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CAR ORGAN TRANSPLANT

- ANTICIPATING ENERGY AND ENVIRONMENTAL BENEFITS OF CLEANER TECHNOLOGIES -

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Dissertação para a obtenção do Grau de Doutor em Transportes

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R e s u m o

Embora não seja suficiente, a transição acelerada para novas tecnologias contribuirá decisivamente para responder aos desafios energéticos e ambientais do transporte rodoviário. Explorámos o Transplante de Órgãos em Automóveis (TOA) como complemento à renovação tecnológica convencional de frotas cujas perdas de benefícios devido à utilização de tecnologias obsoletas são assinaláveis. O TOA corresponde à substituição do sistema de propulsão por novas tecnologias melhorando-se a respectiva eficiência e prolongando-se a sua vida útil.

Analisámos os benefícios ambientais e económicos do TOA comparando cinco ciclos de vida de auto-mobilidade durante 20 anos: manter automóvel, comprar automóveis novos, comprar automóveis usados, comprar automóveis transplantados ou transplantar automóveis particulares. Conclui-se que o TOA pode ser atractivo para o automobilista para além do melhor desempenho do carro. Adicionalmente, estimámos o nível de difusão do TOA na frota Portuguesa e respectivos impactes, concluindo que pode gerar benefícios significativos para a sociedade.

Após analisar as barreiras e implicações do TOA na indústria automóvel, identificou-se a necessidade de mais estandardização e modularização no design e produção de automóveis, viabilizando a compatibilidade intergeracional dos veículos (e, desejavelmente, entre marcas). Finalmente, poderiam surgir novas formas de relacionamento na indústria, por exemplo, 'venda evolutiva de automóveis' em que produtores ofereceriam um TOA programado durante a vida útil do veículo.

Abstract

Road transportation faces multiple energy and environmental challenges. Although not solved, the situation is somehow improving and accelerating the transition to new technologies is central (although not sufficient).

Car Organ Transplant (COT) is explored here as a complementary alternative to conventional technological turnover of fleets by which potential benefits are delayed as obsolete technologies continue to pollute at preceding levels. COT corresponds to replacing obsolete powertrain and ancillary equipments with cleaner technologies. Consequently, car's service time is extended with upgraded and fully-functional technologies.

We analyzed lifecycle environmental and economic benefits of COT by comparing different car-ownership approaches over 20 years: keeping car, buying new car, buying remarketed-car; buying transplanted-car or transplanting own car. We concluded that COT is potentially attractive for owners while improving energy and environmental performance of automobility. Additionally, we estimated the pervasiveness of COT in the Portuguese car fleet and corresponding impacts. We concluded that COT potentially yields significant energy and environmental benefits for society.

Barriers and implications of COT for the automotive industry were identified. Importantly, increased standardization, modularity-in-design and modularity-in-production are necessary. Lastly, new relationships between carmakers and customers may arise like 'evolutionary-car-selling' by which planned COT over time would be bundled to car purchasing.

Keywords/Palavras Chave

Car organ transplant	Transplante de órgão em automóveis
Life cycle analysis	Análise de Ciclo de Vida
Total ownership costs	Custos totais de propriedade
Energy Efficiency	Eficiência energética
Environmental impacts	Impactes ambientais
Sustainable mobility	Mobilidade sustentável

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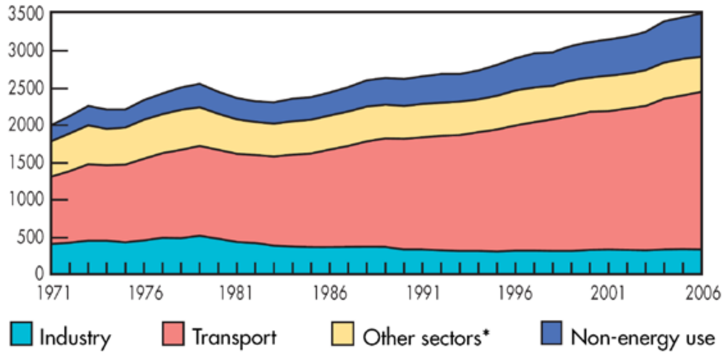
Chapter 1. Introduction, research objectives and thesis outline

1.1. Background and motivation

Current global challenges include, among others, the need to manage energy supply and security, raw material consumption, control solid waste generation, and reduce greenhouse gas emissions and local/regional pollution, while providing infrastructural, economic and social conditions for sustainable development. These challenges are particularly pronounced in the transport sector, where the current dependence on internal combustion engine (ICE) vehicles fuelled with petroleum from politically volatile regions remains a major barrier to overcome. The figure below illustrates clearly the higher growth rates of the world's transport energy consumption while the other sectors of the economy remain relatively stable.



Note: *Includes agriculture, commercial & public services, residential and non-specified other sectors.

Figure 1 . Evolution of Total Final Energy Consumption by Sector (1971 to 2006) (International Energy Agency, 2008)

Private cars account for a large share of those challenges. Under current market trends, car use will perpetuate the current pressure on natural resources and the environment if the automotive industry does not produce sufficiently high-efficient and less material-intensive vehicles or if the international demand for automobility continues its stunning growth nearly 5%/year over 3 decades in the European Union (Eurostat, 2003a) and higher growth rates (15-20%/year) currently occurring in China (Schipper and Ng, 2004).

In response, these energy and environmental efficiency challenges are stepping up research and development in the areas of propulsion technology, including: exhaust gas prevention, alternative fuels (e.g., biofuels), alternative propulsion systems (electric drive vehicle – EDV - either pure, hybrid, or fuel-cell), and materials technology by which the use of lighter materials and developing reuse and recycling technologies is making the automotive industry (progressively) less material intensive. Importantly, passenger cars are in use for more than a hundred years, since the invention of the ICE - end of XIX century. Although the powertrain[1]

[1] We found several definitions of "powertrain" and related terms, such as "drivetrain" and "driveline". In this

operation principle has basically remained the same, it has undergone vast improvements ever since, by which fuel economy of cars has increased by a long way and specific emissions have decreased noticeably. Nonetheless, perfect combustion is still not obtained and, thus, together with large amounts of carbon dioxide (CO_2) and water (H_2O) in the exhaust gases, pollutants are still emitted: carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), oxides of nitrogen (NO_x) and particulate matter (PM) – just to mention the regulated ones. Importantly as well, large amounts of material consumption and waste production are still involved in the production, use and final disposal of cars. Concomitantly, governments are implementing measures for pollution control (for the most part, regulatory instruments like the EURO standards in the European Union) and to reduce carbon emissions by means of increased fuel economy of cars (e.g., voluntary agreement on CO_2 emissions reduction between the European Union and the European, Japanese and Korean automobile manufacturers associations - ACEA, JAMA and KAMA, respectively - as well as policies to promote the decoupling of mobility growth (either passenger or freight) and economic development (refer to the White Paper of the European Commission, 2001, for instance).

Despite the diffusion of more efficient new vehicles, the concentration of air pollutants in many urban areas often exceeds air quality standards (EEA, 2006) and there are strong evidences that climate change is being increasingly induced by anthropogenic emissions of greenhouse gases (GHGs) through global warming (IPCC, 2001, 2007). In reality, higher efficiency of cars is being off-set by increased motorization and mobility and by diverting the technological improvement gains into non-fuel saving vehicle features (e.g., larger vehicles and/or engine size, higher acceleration, air conditioning, among others), while technological breakthroughs take longer to diffuse and become effective, also. In this sense, although problems are far from solved and recognizing that technology isn't the panacea for all environmental impacts of transportation[2] – for example, land occupation by the transport system remains one important issue to tackle – the situation is improving in general and in many respects the question of accelerating technological renewal of fleets towards more efficient technologies seems dominant (Viegas, 2003). In this sense, the transition to a more sustainable transportation system requires a fleet conversion policy that efficiently absorbs new, clean technologies and retires old, high-polluting technologies.

Technological turnover of car fleets has been largely determined by the retirement of older vehicles and replacement by new models. However, depending on the motorization rate of countries and the driving forces for technological change (for example, accelerated end-of-life vehicle retirement policies), the total displacement of older technologies can last from 10 to

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dissertation, "powertrain" and "drivetrain" are considered the same and refer to the combination of major components that make the car run: engine, clutch, transmission, driveshaft, differential and axles, but not the wheels or fuel tank (Nieuwenhuis and Wells, 2003). We include also the depollution equipments (e.g., catalytic converter).

[2] The words "transport" and "transportation" are mostly interchangeable. "Transport" is more often used to refer to the means of movement and is also preferred here for the adjectival form, as in "transport activity." "Transportation" is more often used to refer to the carriage of people and goods in general terms. In the present dissertation, we will use both terms referring to the same concept.

more than 40 years (Grübler, 1990, Grübler and Nakicenovic, 1991). One environmental implication of slower diffusion rates is technological obsolescence of the running fleets and, therefore, benefits from best available technologies (BAT) are fully explored after 10 to 40 years, only. Furthermore, an important share of today's motorized mobility is using older, obsolete and more polluting technologies (for example, refer to data presented by Davis and Diegel, 2006, for the USA), although older vehicles are expected to drive significantly shorter distances over time. If, on one hand, new vehicles are more fuel efficient (considering equivalent models) and include more and better pollution control devices, on the other, pollution control equipment deteriorates over time (Ross *et al.*, 1995, Harrington, 1997, Ross *et al.*, 1998) and so does the fuel economy of engines although to a lesser extent (Ang *et al.*, 1991).

One possible way to shortcut the delay in the diffusion of cleaner technologies would be to make the average lifetime of vehicles shorter by accelerating the turnover of fleets (i.e., increase the entrance of new cars while anticipating the retirement of older vehicles, as mentioned above). However, overall environmental impacts of cars can potentially increase from a lifecycle accounting perspective, mainly due to additional consumption of energy and raw materials or generation of emissions and solid waste from new car production and older cars' scrappage (ECMT, 1999). Kim *et al* (2003) concluded that, all lifecycle stages considered, cumulative emissions of regulated pollutants would be minimized by extending automobile service time: 7 to 14 years for 2000s model years and beyond, while a lifetime of 18 years would minimize cumulative energy consumption and CO_2 emissions. Therefore, reducing the lifetime of vehicles below these values is not the best option if the environmental impacts are to be minimized holistically.

1.2. The concept and research questions

The present dissertation proposes one additional solution as part of an energy consumption and environmental impact reduction strategy for automobility. We named it '*organ transplant' in cars* that aims to extending the service time of vehicles while keeping them technologically up-to-date. This is an analogy between organ transplant medical care in humans and car care. This concept corresponds to replacing any component of the powertrain and energy intensive parts of the car that are technologically outdated, downgraded or malfunctioning while keeping the remaining state-of-the-art and fully operative components and parts, in order to improve its energy and environmental performances and possibly reach 'like new' standards. Putting it simply, replace only what has to be replaced and keep the remainder running while no better options arise. Other authors suggested similar strategies (Ware, 1982, Nieuwenhuis and Wells, 2003, Maxton and Wormald, 2004, SMMT, 2004) as we will explore in Chapter 3. The potential advantages of the concept proposed here, compared to existing conventional alternatives, relate to potentially less energy and raw materials consumption and less emissions and solid waste generation.

This apparently simple and attractive proposal might have some drawbacks that we analyze in the present dissertation. Two main research questions are addressed in the examination of the concept presented here:

(1) Does 'car organ transplant' reduce lifecycle energy and environmental impacts when compared to conventional car ownership approaches (for example, buying new or remarketed cars periodically), and is it attractive for car owners when comparing its total ownership costs to those of conventional approaches? This concept is effective only if the energy and environmental costs of producing the replacing organs (parts and components of a car) and scrapping of those substituted are offset by the gains in energy and environmental efficiency striving from the use of the transplanted organs. Otherwise, we would worsen the overall burden. Still, even if the concept is effective from the lifecycle energy and environmental perspectives, carrying out organ transplant in cars is believed to be largely dependent on its competitiveness in the market place (i.e., 'is it sufficiently attractive to car consumers').

(2) The second research question builds on the conclusions of the first: to what extent are transplant technologies expected to diffuse in car fleets and, consequently, how is 'organ transplant' in cars expected to foster the technological turnover of fleets? Accordingly, what are the corresponding energy and environmental impacts considering whole fleets? As mentioned previously, technological renewal of car stocks occurs with the entrance of new cars (equipped with recent technologies). The rate of diffusion of new cars is nearly 10% of the total car fleet and corresponding technological turnover is expected to increase with transplanted-cars (our hypothesis). The extent of the diffusion of such technologies depends mostly on the competitiveness of transplanted-cars in the used car market considering that they include additional expenses from organ transplants when compared to their equivalent conventional remarketed-models. The degree of energy and environmental benefits from organ transplants depends largely on the pervasive capacity of such technologies but also on the balance between the production of new equipments (and scrappage of older ones) and the efficiency gains (from using them).

1.3. Thesis contribution

The central contribution of this dissertation is to explore thoroughly the concept of organ transplant in cars, including its lifecycle environmental and economic analysis, as part of a strategy for the reduction of energy consumption and environmental impact from automobility. Several advancements are made beyond previous research. Specifically:

- We propose the concept of organ transplant based on the medical care analogy and supported by similar concepts within and outside the automotive industry (e.g., retrofitting, modularity, among others that are reviewed in Chapter 3). We also suggest a possible configuration of a *transplanting kit* and corresponding costs. As explained and described in greater detail later, *transplanting kits* are a collection of 'best available technologies' (BAT) that are transplanted in used cars and by which the cars' energy and environmental efficiencies are expected to increase.
- A framework for analysis is proposed to compare several car ownership strategies over a period of 20 years, instead of the standard static lifecycle analyses of single cars (and model year). In this sense, we compare the following strategies that include the alternative transplanted vehicles: 1) keep the current car; 2) buy a new car; 3) buy a remarketed-car; 4) buy a transplanted-car; or 5) transplant the current car.

- We develop a dynamic lifecycle inventory (LCI) model that builds on the work by Kim (2003). Differently to the author's work that is dedicated to the modeling of the LCI of a single car and restricts his analysis to energy consumption and emissions, our model is applied to different strategies of car ownership (that may include several cars over a period of time) and includes material burdens also. In addition, the model proposed here is dynamic conversely to standard static LC analyses, since our survey is made over a period of time during which several model years are considered and energy or environmental burden coefficients of the different lifecycle stages of cars change over time (e.g., emission factor of the automotive industry during vehicle assembly).
- We extended our LC car ownership modeling by developing economic profiles for each strategy, where environmental damage costs are included. Apart from ranking total car ownership costs, we could estimate net present values and payback periods associated to car organ transplant (with and without environmental damage costs). This analysis rendered one of the most interesting contributions since it demonstrated (considering our assumptions) the viability of the concept both in terms of its environmental effectiveness and from the private consumer's perspective while enabling the remaining research of the thesis.
- We develop an evolution model for the Portuguese car stock based on existing methodologies (we present a literature review of these methodologies in Chapter 6). However, our model is unique in the sense that it includes a discrete-choice model based on proxy-revealed preferences that captures the consumer's behavior towards remarketed cars, in Portugal.
- Realistic figures of consumer's preferences and market penetration of transplanted vehicles are presented:
    - Based on the results of discrete-choice modeling we analyzed the consumer's preferences towards used-car types, including elasticity and willingness-to-pay indicators.
    - We evaluate the pervasive capacity of transplant technologies in the Portuguese stock by comparing a scenario that includes transplanted alternatives to another that assumes a 'business-as-usual' evolution of the stock.

Importantly, we end our research by suggesting in the conclusions further developments concerning the business model of car organ transplant within the automotive industry. Analyzing the business model of the concept is useful to suggesting complementary solutions of car design for automakers, of complementary alternatives for downstream car sales, and complementary car servicing in the aftermarket. Business models include the value propositions offered to the market, identification of possible target customers, description of the type of firms and network of partners potentially involved, and description of the revenue model, the cost structure and the business model's sustainability. Based on the guidelines by Ostenwalder (2004), we propose a business model formulation that will, hopefully, pave the way for a more thorough development.

It is important to emphasize that the contribution of this dissertation is multidisciplinary. From the transportation science perspective, we propose a potentially new concept for the automotive industry, including a comprehensive analysis of its energy, environmental and economic costs. From a methodological point of view, we propose a different approach to car lifecycle analysis by looking at different ownership strategies and incorporating the dynamic dimension of the system instead of the standard static approach. The contribution to the environmental field stems from the results of the models and application to the Portuguese case-study providing guidance for future developments in both policy-making and research.

1.4. Methodology and outline of the dissertation

In this section, we describe the methodology we followed to explore the concept of organ transplant in cars and then we present the outline of the remainder of this document. Although it should be applicable to any country or regional circumstances, the potential advantages of car organ transplant are demonstrated in the Portuguese context, firstly, by analyzing the private car ownership over 20 years and, secondly, by exploring the possible diffusion of transplant technologies throughout the Portuguese car fleet until 2030 and analyzing the corresponding impacts in terms of energy consumption, greenhouse gases and other atmospheric emissions, raw material consumption and generation of solid waste. It should be made clear at this early stage that this dissertation does not include any developments on the mechanical requirements of organ transplant in cars. Regarding the methodology to explore the concept proposed here, our research can be separated into three stages of analysis.

In the first stage, we analyze the problem from the car owner's perspective. We use lifecycle analysis methodologies to evaluate the possible energy and environmental impacts of organ transplant in cars over a period of 20 years. With respect to emissions, we note that we quantify lifecycle emissions of greenhouse gases and regulated pollutants. Whereas greenhouse gases have global effects (particularly through global warming and consequently climate change), regulated pollutants have local effect on air quality (and importantly on public health). Although regulated pollution has local impacts (and therefore each lifecycle stage has a consequence in a different location), our approach bounds those lifecycle emissions of the car to the final user, i.e. the car owner. We centered our analysis on a midsize gasoline-powered car. As referred before, we considered five car-ownership strategies including two that comprise transplanted cars. We include the following lifecycle stages in the LCI model: material production; vehicle manufacturing; fuel refining, transportation and delivery; car use; maintenance and repair; end-of-life disposal. We also applied total ownership costing tools to evaluate the costs of each strategy. The analyses stemming from the methodologies referred here provide the answers to the first research question and are included in chapters 4 to 6 (Part B).

In the second stage, we extend our assessment of car organ transplant to the entire fleet. To accomplish this, we develop a car-stock evolution model that is intended to reproduce a reasonable approximation of the Portuguese fleet's dimension and its technological composition over time (1995-2007). In addition, it serves as a basis for the evaluation of the possible future diffusion of transplanted cars over time. In short, the model forecasts firstly the baseline evolution of car-stock until 2030, i.e. the global demand of cars in Portugal over the same period. To estimate the amount of annual cars sales, we determine the quantity of new cars needed to match demand after deducting the retiring vehicles. The overall technological composition of the fleet over time is obtained by estimating which car types are retired and sold yearly. The scrappage of older vehicles is determined by their corresponding survival curves, while the annual technological mix of new cars is determined exogenously. Finally, to estimate the diffusion capacity of transplanted technologies, which depends on the consumer's preferences and behavior regarding this kind of technology, we develop a discrete choice model to simulate the options of consumers when facing a finite set of used-car alternatives, including transplanted cars. We excluded the possibility that new car buyers would consider buying transplanted cars or transplant their current car. We discuss this issue extensively in Chapter 8.

In both stages above, we calculate energy and material consumption or emissions and waste generation by multiplying the number of each car type with the respective energy/environmental coefficients and mileage curves. Whereas emissions from car use are based on the EMEP/CORINAIR guidelines from the European Environmental Agency (EEA, 2007b), the remaining coefficients were collected from the literature and from industry reports.

We now describe the dissertation's structure that strives mostly from the methodology presented above although the stages of analysis presented above are not necessarily reflected in the dissertation's outline. The present document comprises 11 chapters that are grouped in three separate parts. These parts are framed by the introduction (Chapter 1) at the beginning and the conclusion (Chapter 10) at the end of the dissertation. Chapters can be classified as either background, methodological or policy analytical, although there is some overlap in some cases. The overall outline of the thesis is illustrated in Figure 2 (below). The solid-line arrows in the figure represent the logical sequence of the thesis and how each chapter interrelates with the remainder. The following paragraphs explain this logical sequence in greater detail. The dashed-line arrows in the figure represent a different relation between chapters by which Chapter 9 uses the parameterization of the lifecycle inventory model of Chapter 4 and Chapter 8 uses the parameterization of the total cost ownership model of Chapter 5.

Part A is dedicated to reviewing the problems motivating this dissertation, describing in greater detail the rationale behind our research objectives (Chapter 2) and presenting the key concept proposed here (Chapter 3). Parts B and C are mostly methodological and analytical, although some background is given on specific aspects developed in each chapter.

Part B is mostly dedicated to answering the first research question by exploring the concept of organ transplant in cars over an ownership period of 20 years. In this sense, we propose a model for lifecycle energy and environmental impacts analysis (Chapter 4) and another for economic analysis (Chapter 5), and applied both models to the five car-ownership strategies presented before (Chapter 6).

Part C focuses mainly on the second research question and extends the analysis performed in Part B by extrapolating the results obtained for a 20-years car ownership to an entire car fleet, from today to 2030. Building on the parameterization of the models from Part B, Part C includes the modeling of the Portuguese car fleet (Chapter 7) and of the discrete-choices of remarketed cars (Chapter 8). These models are used to simulate the diffusion of transplanted cars in the Portuguese car fleet and analyses the corresponding energy and environmental impacts, including material burdens (Chapter 9).

Analyses included in parts B and C (summarized above) are somewhat independent and, accordingly, specific background, aims, and methodological details are presented separately for each. Furthermore, the results of each analysis are also discussed separately. This allows the reader to understand and appreciate the main implications of each analysis without necessarily needing to read the entire dissertation. Nevertheless, the dissertation presents, in Chapter 10, a synthesis of the key conclusions related to the overall thematic explored here. Importantly, we try to capture and analyze the possible business logic of car organ transplant in the conclusions and, consequently, propose the grounds for the development a business model (BM) design within the existing automotive environment. As mentioned earlier, the conceptual guidelines for specifying and building the BM follow the ontology proposed by Ostenwalder (2004). Apart from the development of a BM for car organ transplant, we suggest further research developments striving from the work presented in this dissertation.

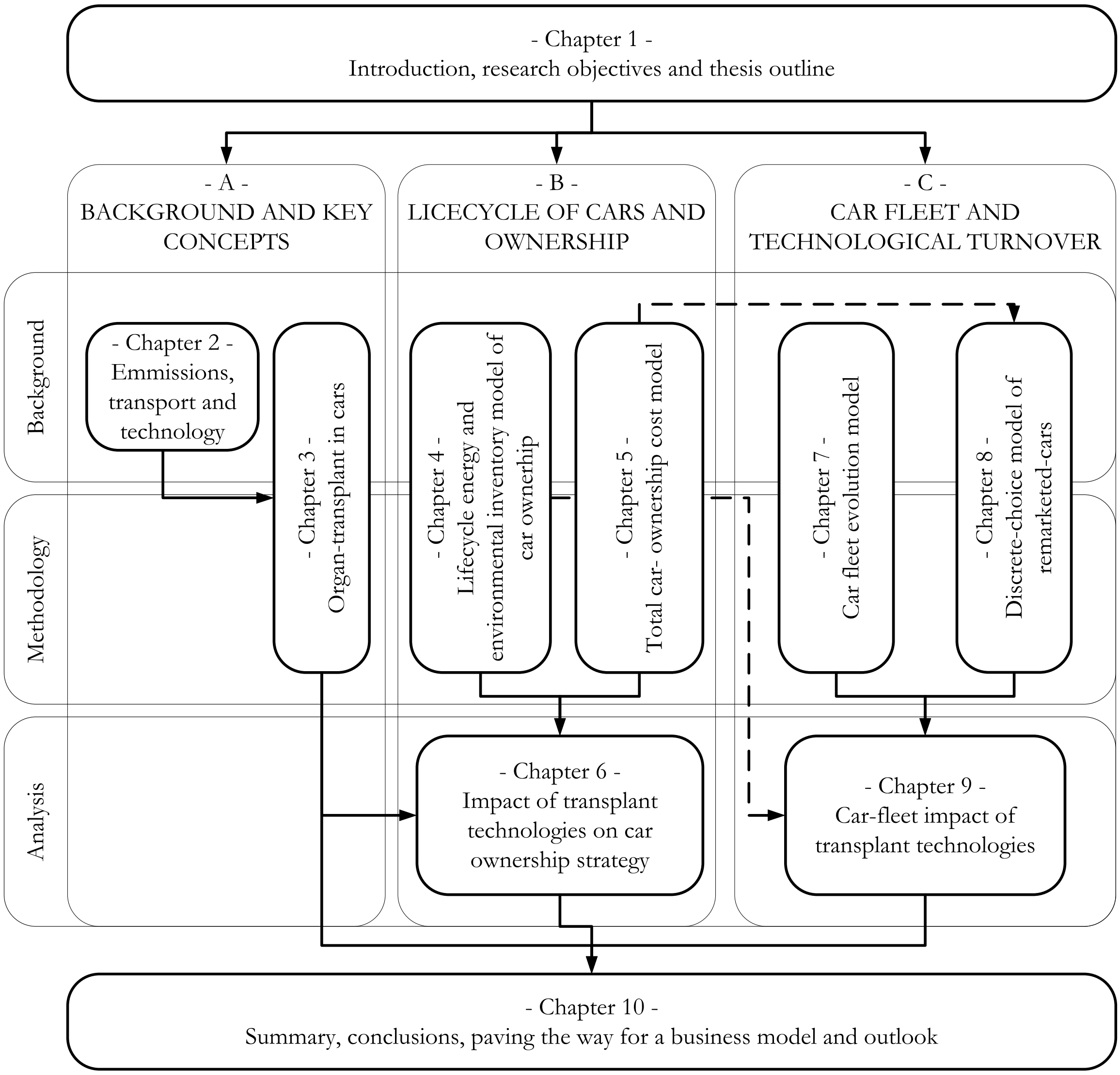

Figure 2. Dissertation organization, main parts and chapter linkages (Source: author)

A. Background and key concepts

Increasing mobility and accessibility, supported by an operating transportation system, are at the foundation of development and growth of the industrialized world. Besides relying heavily on petroleum oil (more then 95%), road vehicles have some important negative environmental impacts. This dissertation focuses on the energy consumption and emissions (both end-use and up-stream) resulting from the use of cars including 'well-to-tank' lifecycle stages, i.e., fuel recycling, transporting and delivering. It also addresses raw material consumption and solid waste generation from the automotive industry (both manufacturers and the aftermarket). Other negative effects that are not addressed here are land use conflicts, biodiversity losses, noise, accidents, not to mention all. As mentioned in the introduction of the present dissertation, we analyze more specifically one possible way to maximize the benefits from technological development by increasing the pervasive capacity of cleaner technologies throughout existing fleets. We called it 'car organ transplant'.

Chapter 2 presents the 'state of the world' regarding the transport system's sustainability problems and identifies the corresponding main sources (section 2.1). Then, section 2.2 identifies the transport environmental problems that could be circumvented through technological fixes and section 2.3 highlights the main challenges that remain unsolved in the longer term. In section 2.4, we analyze the possible ways out of the current transport unsustainable path in a stylized way and section 2.5 highlights the technological changes in the automotive industry that may help to solve or minimize those challenges - both fixes for the existing technologies and the more disruptive technological innovations - that remain unsolved. Chapter 2 ends with section 2.6.3 that focuses on the big inertia of the transport system that is resistant to the faster diffusion of new technologies and that is currently hindering the full-potential of best available technologies to reduce the consumption of energy and materials and minimize the generation of emissions and waste.

Chapter 3 follows and begins with the detailed description of the concept of car organ transplant that we postulate and explore in this dissertation (sections 3.1 and 3.2), including the rationale for its definition and its fundamental technical characteristics, including what parts and components we considered in the '*transplanting kit*' (section 3.2.2). In section 3.3, we give some insights into the technical requirements for organ transplants in cars, although this is not analyzed in detail in the present thesis. Finally, Chapter 3 is completed with section 3.4 where we present similar examples and approaches of our concept inside and outside the transport system.

Chapter 2. Emissions, transport and technology

2.1. Identifying the sources of the problem

According to the World Commission on Environment and Development (WCED), sustainable development has evolved into a guiding principle for a livable future world in which human needs are met without compromising the ability of future generations to meet their own needs (Bruntland, 1987). Accordingly, Daly (1991) argues that sustainable development has to satisfy three fundamental conditions: 1) its rates of use of renewable resources do not exceed their rates of regeneration; 2) its rates of use of non-renewable resources do not exceed the rates at which sustainable renewable resources are developed; and 3) its rates of pollution emission do not exceed the assimilative capacity of the environment. Complimentarily, Ayres (1994) examines the sustainability of our current industrial system by identifying 5 critical questions that are helpful in differentiating sustainable from unsustainable paths. These are illustrated in the following diagram.

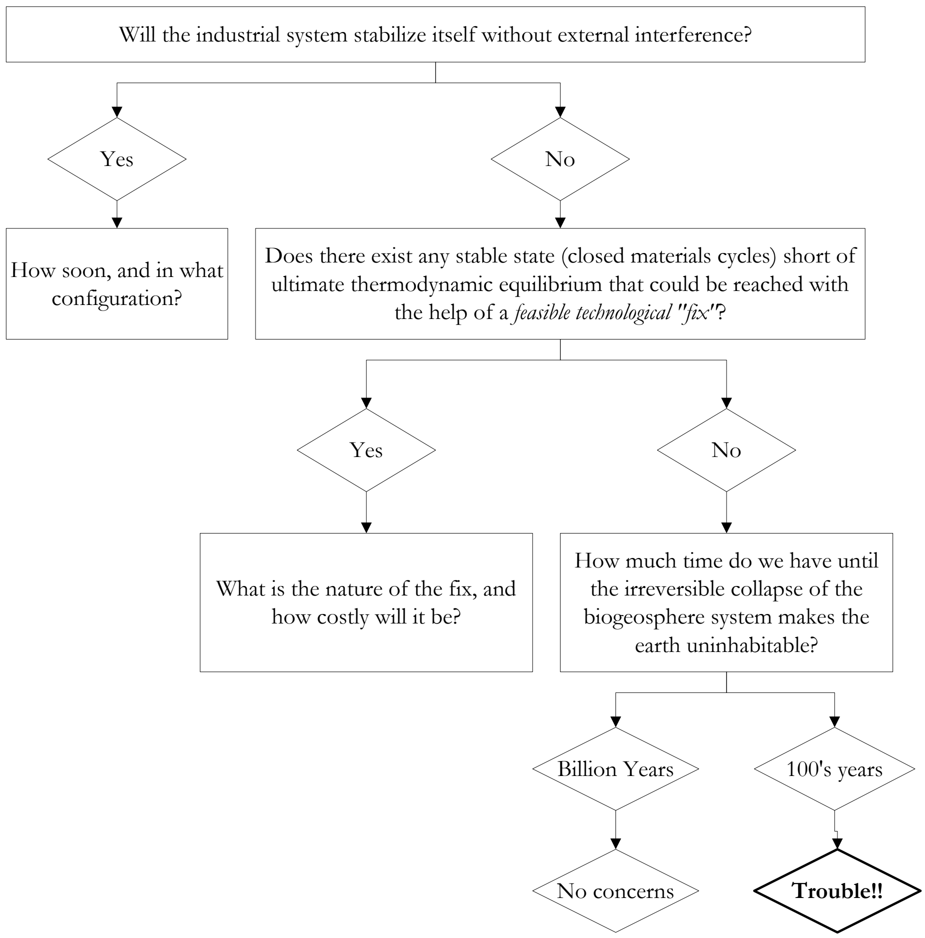

Figure 3. Examining the sustainability of current industrial metabolism (adapted from Ayres, 1994)

Elemental contributions to these questions also pave the way towards more sustainable systems. Addressing the challenge of sustainability encompasses other social, economic and environmental dimensions, and requires a long-term systematic perspective and the integration of many different elements. As put by Deakin (2001), planning for sustainable development aims to attain all three objectives simultaneously and in a just manner. She continues saying that, increasingly, the idea of sustainability has come to be understood as a collective process for considered decision-making and action, and not simply a particular end-state or outcome[3].

As referred in the introductory paragraphs, we stated that the transportation system is at the basis of the development of modern societies. As such, the goal of sustainable development encompasses forcedly a sustainable transport system. One early definition of sustainable transportation[4] was offered back in 1996 by the Organization for Economic Cooperation and Development (OECD, 1996a): "*Transportation that does not endanger public health or ecosystems and meets mobility needs consistent with the use of renewable resources at below their rates of regeneration and the use of non-renewable resources at below the rates of development of renewable substitutes*", pretty much built on Daly's fundamental conditions for sustainable development. Many definitions of sustainable transportation followed becoming more and more encompassing (to mention a few, CEC, 1992, Banister and Button, 1993, Greene and Wegener, 1997, OECD, 2000, Deakin, 2001, OECD/IEA, 2001, WBCSD, 2001, Litman, 2002, WBCSD, 2004). We present the one suggested by the World Business Council for Sustainable Development in the report *Mobility 2030* (WBCSD, 2004)

"Sustainable mobility is the ability to meet the needs of a society to move freely, gain access, communicate, trade and establish relationships [mobility and accessibility dimensions] without sacrificing other essential human [social dimension] or ecological value [environmental dimension] today or in the future [intergenerational]".

Complementarily, the OECD/IEA (2001) describes the three dimensions of sustainable transport as:

- "*Mobility dimension*: The provision of adequate, affordable transport options to satisfy society's needs for access and mobility and to move goods. This includes the maintenance of a sustainable level of oil imports;
- *Social dimension*: The provision of adequate transport services for all members of society in a manner that does not damage the "social fabric" including safety, health, congestion and equal access to services for different groups of the population;
- *Environmental dimension*: The provision of transport services in a manner that does not degrade the environment or hinder people's ability to obtain other needed resources or carry

[3] Corroborating with this idea, Partidário and Moura (1999) explored the concept of sustainability appraisal as part of strategic environmental assessment procedures, by which the only way towards sustainable development is by evolving trial-and-error approaches, intervening in the system early and the best way possible. Selecting the right and explanatory indicators for supporting policy decision-making is one cornerstone issue of this procedure.

[4] Sustainable mobility is a synonym used by the European Commission, first appeared in its *Green Paper on the Impact of Transport on the Environment* (CEC, 1992).

out other needed functions with those resources. A key aspect is the reduction of greenhouse gas emissions."

Considering the goal of this dissertation by which we explore the concept of organ transplant in cars and analyze the potential energy and environmental benefits steming from this concept, we concentrate on the environmental sustainability dimension without losing sight of the more comprehensive concept of sustainability.

Importantly, the Europe's 4th Environmental Assessment Report (EEA, 2007c) clearly states that transportation is one of the four economic sectors whose driving forces are behind the changes in the environment. Together with energy, tourism and agriculture, they cover most of the main environmental issues that society faces. The increase in energy and environmental impacts from the transport system has generally been a result of the effect of a number of demographic, economic, technological, resource and policy drivers. This can be illustrated by decomposing such burdens into some of the key driving variables, based on the IPAT identity proposed originally by Ehrlich and Holdren (1971):

$$Impact = Population \bullet Affluence \bullet Technology \qquad 2\text{-}1$$

In light of this equation, total energy consumption (E_T) can be represented by the following decomposition formula:

$$E_T = Pop \bullet \frac{GDP}{Pop} \bullet \frac{km}{GDP} \bullet \frac{GJ}{km} \qquad 2\text{-}2$$

Here, energy consumption (E_T) is a function of population (*Pop*), per capita incomes (or affluence) (*GDP/Pop*), the level of mobility (*km/GDP*) associated to wealth of population and one technological factor: the amount of energy required for 1 kilometer of mobility (*GJ/km*) depends on the energy intensity of the vehicle (technology in use) and the use of technology (for example, aggressive *versus* economic/ecological driving).

Equation 2-2 applies also to emissions of noxious pollutants (e.g., carbon monoxide or nitrogen oxides) that depend on the vehicle's technology. In these cases, the variable (*GJ/km*) is substituted by (*grams of pollutant/km*). In the case of emissions of gases that depend on the fuels composition (e.g., carbon dioxide that depends on the carbon intensity of the energy used, or sulfur oxides that depend on the sulfur content of fuels) we add the energy-composition factor related to the pollutant analyzed – for example, (gCO_2/GJ) that varies according to the energy type. This factor can encompass the '*well-to-wheel*' lifecycle emissions of the pollution under consideration. Other decomposition formulae could be proposed to symbolize the consumption of raw materials or the generation of waste by the transport system, but for our illustration purpose we refer to energy consumption and emissions.

The relationship presented in the decomposition equation above is highly aggregated and one needs to remember that there are changes in one variable that can induce changes in other variables of the equation. Refer to Figure 4 (below) for an illustration of the clear relationship between mobility and per capita wealth, measured in GDP *per capita*. However, it provides a useful guide to the core driving forces that determine the longer term trends where the transport system might be heading to.

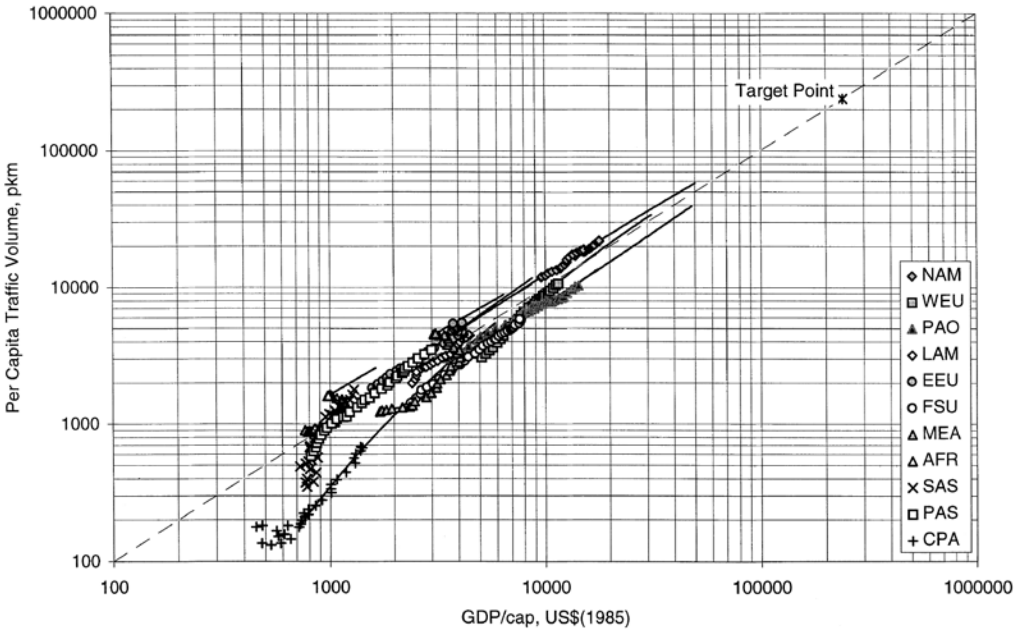

Figure 4. Estimated scenario for mobility and income for 11 regions between 1991 and 2050 (Schafer and Victor, 2000)

Figure 5 (below) illustrates (in a schematic way) the main components of a transport system, their interrelationships and how its current dynamics are intrinsically unsustainable due to the environmental implications related to the use of virgin materials (including energy), the emissions of pollutants and land use conflicts.

Human beings (whether individually or grouped in some kind of organization/structure) are clearly at the basis of environmental impacts, although we could argue that natural phenomenon (such as volcanoes and earthquakes) or extreme events (like tornados or floods) can have disastrous effects on the environment, too. In fact, almost all human activities induce a natural desire for mobility and as such the demand for transportation is commonly referred as *derived demand*[5] (or secondary demand), i.e. it depends strongly on the demand for other activities. It is only the value of the activity at the destination that results in travel. Whether by foot or with some transport technology (e.g., vehicle, lift, escalators, etc.), we all use transport infrastructure and consume energy as the source for motion, which in turn are produced by upstream complementary technosystems that include materials, infrastructure, vehicle and energy

[5] For a more detailed definition and discussion on the concept of transport derived demand refer (for example) to Ortúzar and Willumsen (2002).

industries. In short, they all consume virgin materials (including energy) and produce emissions and waste.

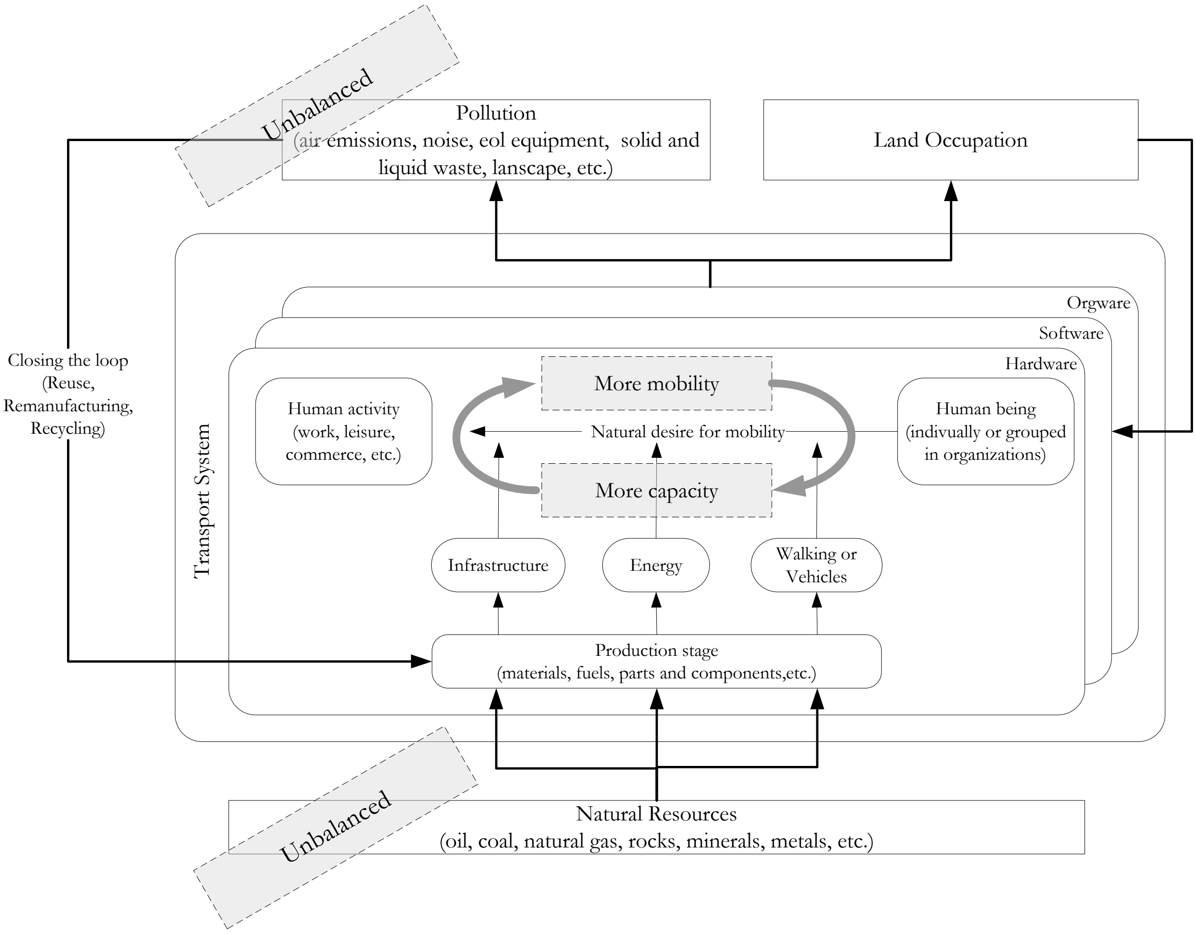

Figure 5. Illustrative diagram of the transport system and its environmental implications (Source: author)

At the other end of the system, we can find the outputs of the transport system's metabolism which, at current intensity, can be classified generically as pollution and land occupation. While pollution can possibly be solved or minimized in the longer run with technology, land occupation involves necessarily restraining the growth of mobility through transport demand management (TDM) instruments and therefore it involves a much more complex task that is to deal with primary decisions and individual mobility options of persons and companies (Viegas, 2008). Restraining mobility growth is one common policy objective and is often referred to as the decoupling of mobility from socio-economic development (for example, refer to the White Paper on Transport Policy by the European Commission, 2001). We will explore this issue in greater detail later in this chapter.

The figure above includes three layers referring to the *hardware*, *software* and '*orgware'* of the transport technosystem. Adapting the extended definition of technology proposed by Grübler (1998), we complete our symbolic characterization of the transport system as follows:

- *Hardware* is the set of manufactured artifacts that constitute the means for mobility and accessibility. For example, cars are powered by fuels and run over roads. Each of these components needs to be manufactured and thus machinery or manufacturing plants are needed, and so forth.

- *Software* corresponds to the knowledge required to design, manufacture, and use technology hardware. For example, knowledge is required to drive the car.
- '*Orgware*' is related to the institutional settings and rules for the generation of technological knowledge and for the use of technologies. In the case of the road transport, this last item is of particular importance since users drive in an open network where they must behave harmoniously and, in this sense, they are informed by the same rules, laws and regulations that are produced and enforced by the states' institutions.

We referred previously that the current dynamics of the transport system are intrinsically unsustainable, in light of Daly's conditions for sustainable development (1991). We identify three main causes: firstly, the transport system relies heavily on non-renewable resources and is not shifting to renewable resources (at least, at a pace similar to that of consumption of the non-renewable resources); secondly, pollution rates exceed the assimilative capacity of the environment; and, thirdly, there is a systemic propensity for induced demand for every increase of capacity (refer to Hills, 1996, for example), as illustrated by the closed loop in Figure 5, by which more mobility induces more capacity that in turn induces more mobility, and so forth. Human beings and the corresponding desire for mobility are at the source of the transport activity and the way mobility and accessibility is provided is at the source of the current unsustainable path (the IPAT identity supports such observation).

Now turning our attention to the contribution of different world regions, Figure 6 (next page) plots regional per capita income against per capita annual mobility (km) for 11 major world regions (as defined by Schafer and Victor, 2000). The relative population of each world region is represented by the area of the circle surrounding each data point. As suggested by this figure, if all bubbles relocate to the position of North American countries (NAM), following the linear relationship between per capita income and annual per capita mobility (Figure 4, p.16)[6], the sustainability issues become even more worrisome. We note that the increase in mobility following wealth growth is not necessarily in the same proportion since, in the longer term, we could envisage a scenario by which more affluent people might not require substantially larger amounts of energy than are used currently as a result of vigorous efforts to promote efficient energy use technologies and lifestyles (refer to "B1 Storyline and Scenario Family" of the SRES scenarios by IPCC, 2000), as illustrated in footnote 6 regarding the case of Japan.

One of the most significant challenges facing the global energy system and climate in the future is the conflict between the potential impact on energy use and greenhouse gas emissions

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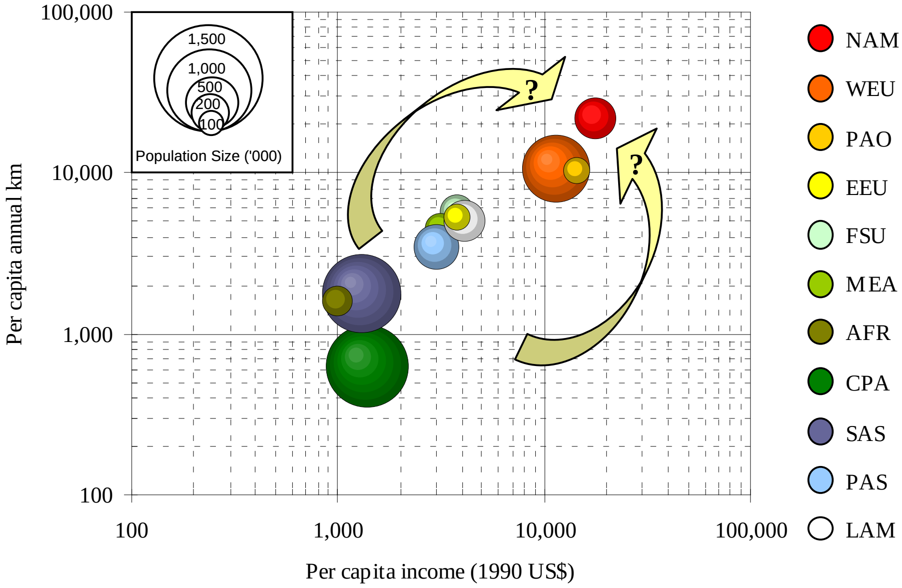
[6] Interestingly, we would expect that Pacific-OECD (e.g., Japan) and Centrally Planned Asia (e.g., China) would experience higher annual travel distances. In the first case, countries, like Japan, have more efficient transport systems relying more on public transportation. In the second, countries such as China are still experiencing strong motorization growth and therefore, at current trends, they might catch up the linear correlation between income and mobility.

of economic development in developing countries, on the one hand, and the economically and socially desirable goal that they achieve levels of prosperity similar to those existing in more developed countries today, on the other (Turton, 2006a). With this respect and looking at the same figure from another angle, we could say that the developed and more wealthy regions drive more, consume more energy and pollute more because of their way of life, their dimension and how their societies are organized (in particular, the dispersed patterns of living of North American countries relying heavily on private cars). In both practical and moral terms, the responsibility to act and the greatest opportunity to fix the problems lie directly with these developed regions and, in this way, enabling the legitimate aspirations of developing countries, eventually.



Note: North America (NAM): Canada, USA; Pacific OECD (PAO): Australia, Japan, New Zealand; Western Europe (WEU): European Community, Norway, Switzerland, Turkey; Former Soviet Union (FSU): Russia, Ukraine; Eastern Europe (EEU): Bulgaria, Hungary, Czech and Slovak Republics, former Yugoslavia, Poland, Romania; Latin America (LAM): Argentina, Brazil, Chile, Mexico, Venezuela; Middle East & North Africa (MEA): Algeria, Gulf States, Egypt, Iran, Saudi Arabia; Sub-Saharan Africa (AFR): Kenya, Nigeria, South Africa, Zimbabwe; Centrally Planned Asia (CPA): China, Mongolia, Vietnam; South Asia (SAS): Bangladesh, India, Pakistan; Other Pacific Asia (PAS): Indonesia, Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand

Figure 6. Per capita emissions, per capita income and population, 1990 (UN Dept. Economic and Social Affairs (http://esa.un.org/unpp/p2k0data.asp, access in 01/08/2008) and Schafer and Victor, 2000)

The unsustainable path of the transport system has other factors of growth (refer to Table 1) apart from the population increase (~6 times since 1800) and economic development (GDP was multiplied by a factor of 70 since 1800). Refer to Grübler and Cutler (2004). In fact, life expectancy has doubled for the last two centuries (from 35 to nearly 70, according to the World Bank's data – http://www.worldbank.org) and the number of working hours were divided by two, leaving 4 times more free time over a life span. In short, we are more numerous, people live longer, work less hours and have higher income (in average). One direct consequence is that people travel more and, at current patterns, consume more energy and pollute more.

Major economic transformations since the late 19^{th} century had enormous impacts in the way people and goods are transported. According to the evolutionary techno-economics, four waves of economic development can be identify related to four industrial revolutions (Freeman and Louçã, 2002). These waves of economic development are often called the Kondratieff waves, named after the Russian economist and statistician (Nikolay D. Kondratyev) noted among Western economists for his analysis and theory of major (50-year) business cycles (Britannica Online Encyclopedia, 2008). The first great transformation happened from an agrarian to an industrial world with the age of cotton, the uprise of the iron industry and water power (where canals had, also, a fundamental role for mass-transportation of heavier and bulkier freight), and Britain was a leading the way. The second wave corresponds to the age of iron railways, steam power, and mechanization. Longer distances could be overcome at higher speeds (increased mobility levels). The third Kondratiev wave is the age of steel, heavy engineering, and electrification. The electrical industry was more directly affected by new developments in science than the railways or textile and paved the way to the establishment of large firms, especially in the USA and Germany. Electrification and the very rapid growth of the steel and related heavy industries enabled Germany as well as the US to overtake Britain and to challenge her supremacy in world trade, colonial possessions, and imperialism, leading ultimately to a naval armaments race between Britain and Germany and to the First World War. The fourth Kondratiev wave is the age of oil, automobiles, motorization, and mass production, which lead to the development of the current high mobility, high accessibility and car based society.

Table 1. Driving forces for transportation growth

Factors of growth	1800	2000	Factor
World population [billion]	1	6	x6
World income [trillion $]	0.5	36	x70
Life expectancy [years]	35	75	x2
Work hours per year	3,000	1,500	÷2
Free time over life [hours]	70,000	300,000	x4
Mobility [km/day] (excl. walk)	0.04	40	x1,000
Global energy use [Gtoe]	0.3	10	x35
Carbon from energy [GtC]	0.3	6	x22

Source: (World Bank (http://www.worldbank.org), Grübler, 1990)

We would classify the last four waves as the 'Industrial Age', as referred by Castells (1998). With the emergence of a new techno-economic paradigm (fifth Kondratieff wave?), we might be witnessing the transition to the 'Information Age' where the fundamental inputs are knowledge-based and are tooled by new information and communication technologies (ICT) (Freeman and Louçã, 2002). ICTs are at the roots of new productivity sources, of new organizational forms, and of the formation of a global economy – understood here as the network of core activities working as a unit in real time on a planetary scale and also referred to as 'network firms' (Castells, 1998, Freeman and Louçã, 2002).

It should be noted that ICT could boost the globalization of the economy because there was the preliminary construction of the complex set of technological infrastructures required for it to function as a unit on a planetary scale and forming this global technosystem: telecommunications, information systems, microelectronic-based manufacturing and processing, information-based air transportation, container cargo transport, high speed trains, and international business services located around the world. The critical organizational form sustaining the current economical and social global system is networking, which can be defined simply as a set of interconnected nodes (Castells, 1998). This networking generated a scaling-up of information flows accompanied by the derived demand for 'physical' transportation of passenger and freight. This scaling-up of transport demand must be addressed soon to avoid potentially disastrous energy and environmental consequences since technological and social changes in the transport and energy systems are relentlessly slow (decades).

In the next section, we review the environmental problems that could be fixed with technology. Thereafter, we will resume the main challenges that remain to be solved in the forthcoming decades.

2.2. The emission problems that could be fixed

Apart from being noisy, consuming large quantities of virgin materials, producing large quantities of liquid and solid waste, and occupying land, Internal Combustion Engine (ICE) vehicles affect the environment since they increase air pollution levels, particularly, carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), ozone (O3) and lead (Pb), as well as particulate matter (PM). We note that greenhouse gases, i.e. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other gases[7], are also exhaust and/or evaporative emissions from cars, but are not considered noxious pollutants since they are not harmful to human health at the levels they are emitted.

Depending on the pollutant considered, transportation can emit more noxious pollutants than any other economic sector of activity. For example, 44% of total Europe ozone precursor are emitted by the transport activity (EEA, 2007c). As a consequence, transportation has been responsible for millions of premature deaths and injuries over the last century. For example, the European region claimed some 127,000 lives (due to respiratory diseases) in 2002 of which about 6,500 were 0-to-14 year old children (WHO, 2004). Many epidemiological studies have assessed and shown the association between noxious emissions and health effects on adults. Refer to annex A.1 (p.357) for a review by the OECD's Environmental Sustainable Transport (EST) project of the main sources, impacts and exceedances of the principal motor-vehicle-related air pollutants (OECD, 1996a). Cars are the main source of CO in most developed countries and nearly 100% emissions in urban areas are caused by road traffic. NO_X emissions

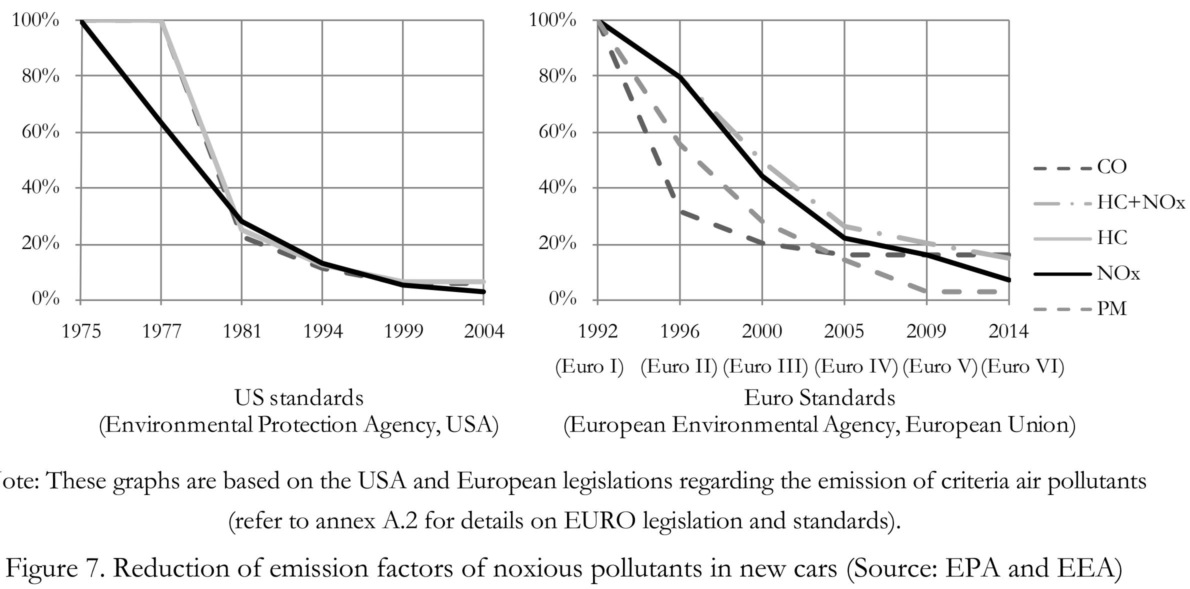
[7] Including chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, chlorocarbons, bromocarbons, iodocarbons, fully fluorinated species, ethers and halogenated ethers (for the full IPCC's list, refer to Table 6.7 of IPCC, 2001).

result mostly from the combustion of gasoline and diesel fuel with significant sulfur content is a major source of sulfur dioxide (SO_2) but also of particulate matter (PM).

Emissions from cars can be categorized into exhaust emissions, evaporative emissions and lifecycle emissions. In the first case, they are the products of burning fuel in the vehicle's engine and emitted from the vehicle's exhaust system. Evaporative losses are produced from gas tank venting, running losses (escape of gasoline vapors from the hot engine) or refueling losses. Finally, lifecycle emissions are produced in activities associated with the manufacturing, maintenance, and disposal of the automobile or during the extraction, refining, transportation and delivery of the fuels themselves.

Over the last few decades, a great deal has been done to reduce noxious emissions and with plans already in the pipeline more can be achieved in the years ahead. To reduce and control emissions from the exhaust system, there are three main options: increasing engine efficiency, increasing vehicle efficiency and exhaust after treatment, i.e. 'cleaning up the emission'. We will review the corresponding technologies later in section 2.6.1 (p.40). As referred above, emissions control measures have drastically reduced emissions per vehicle more than compensating for the increase in the car stocks and in kilometers driven. This reduction in emissions was mostly promoted by increasingly stringent regulation imposed by State's authorities. Refer to Figure 7 for the cases of the USA and European Union, although not exclusive worldwide.

Note that the U.S. and European standards should not be directly compared. The goal of a standard is to limit the average g/km (or g/mile) emission of a certain exhaust component. These figures are, however, very dependent on the driving test cycle applied. Different test cycles are applied in the U.S. and Europe – see Figure 51 (section 4.4.3 - Chapter 3, p.124) for the standard European emission test cycle.



Note: These graphs are based on the USA and European legislations regarding the emission of criteria air pollutants (refer to annex A.2 for details on EURO legislation and standards).

Figure 7. Reduction of emission factors of noxious pollutants in new cars (Source: EPA and EEA)

The USA was the first to produce regulation to controlling emissions from passenger. The Clean Air Act of 1963 was the first federal legislation regarding air pollution control followed by the Air Quality Act of 1967 that was enacted in order to expand federal government activities and also authorized expanded studies of air pollutant emission inventories, ambient monitoring techniques, and control techniques (EPA, 2008). The American Clean Air Act of 1970 was the starting point for stricter regulations and, as a consequence of the severity of problems there, the State of California was given the right to impose more stringent regulations than the federal government. As a section of this act, the Muskie Law[8] required an overall 90% reduction from the current (previously unregulated) levels. Automobile manufacturers were given until 1976 to fulfill those requirements, but this date was moved forwards a number of times and the requirements were first met (in revised form) in 1983 (Wallace, 1995). In 1990, the Californian Air Resources Board (CARB) issued the toughest standards yet. The new standards required all major car manufacturers in California that a certain share of their total vehicle fleet sales be qualified as "Zero Emission Vehicles" (ZEVs) by 1998. In 1990, the only ZEV option assumed available in this time frame was the battery-powered electric vehicle. The time frame and the proportions set by CARB were: "while meeting the fleet average standards, each manufacturer's sales fleet shall be composed of at least 2% ZEVs in the model years 1998 through 2000, 5% ZEVs in 2001 and 2002, and 10% ZEVs in 2003 and subsequent". However, these requirements have since been postponed (refer to CARB's official website for full development on ZEV regulations up-to-today: http://www.arb.ca.gov). Other states in the USA have stated that they will adopt the Californian legislation with some time lag (refer to EPA's official website: http://www.epa.gov). No other country or region in the world has thus far tried to force automobile manufacturers to comply with such stringent emission standards as the state of California.

In the 1970s, the reduction of precursors to ground level ozone, such as HC, CO and NOx, was the main target for policy makers and Japan adopted similar standards and actually implemented them faster than the USA (Fukasaku, 1995): new emission standards of CO, HC and NOx were adopted in 1973 and subsequently revised in 1975, 1976 and 1978. These standards brought down CO and HC emissions to 10% of pre-1973 levels in 1975 and NOx to less than 10% by 1978. Moreover, in order to encourage energy conserving product development, the Ministry of Transport has published fuel consumption requirements of various models since 1976, so that consumers were informed of the fuel efficiency of different models. Later, the new more stringent emission levels also spread to countries in Europe, but only after a strategic battle between EU member states over different standards favoring either the lean-burn engine or the three-way catalyst. Implementing the new more stringent emission standards not only required automobile manufacturers to improve engines and add "tail-pipe" measures, such as the three-way catalyst, but also required fuel companies to improve fuel quality (Wallace, 1995). According to the European Environmental Agency (EEA, 2003), global emissions of particulates and acidifying substances were reduced by 25% between 1990 and 2001, and ozone precursors by 35%, as a result of such emission control measures.

[8] Named after the senator who proposed the law, Ed Muskie.

This said noxious emissions from transportation can be strongly minimized although depending to a large extent on the diffusion of new cars throughout existing fleets. Despite significant decreases of emissions of air pollutants in developed countries, they continue to cause problems for air quality, especially in urban areas. Likewise, less developed or developing countries have severe air pollution problems and most air pollutants are still increasing. For example, emissions have increased in Eastern, Caucasus and Central Asia European countries by more than 10% since 2000 as a result of economic recovery, increases in transport activity, and the lack of effectiveness of air pollution protection policies (EEA, 2007c). Indeed the automotive industry has made great progress in dealing with the problems of noxious emissions, but it still falls short of solving definitively the urban air pollution issue. With this respect, diesel particulate emissions remain an important issue to be solved, although filter collection methods possibly combined with catalytic systems are a promising solution – still, the fuel efficiency of the vehicle is hindered and the soot burned in the filters has to be disposed of (Neeft *et al.*, 1996). Today, the short-term challenge is to public institutions to apply what is already available and to find the proper means to accelerate the technological turnover of car fleets wherever needed, i.e. predominantly in urban areas where air pollutant concentrations are worrying and where populations are more exposed to those noxious emissions.

As we will address in Chapter 3, much has been achieved in the cutback of energy consumption and environmental burdens related to the upstream and downstream lifecycle stages to car use. For example, regulation has been introduced in the material's production industry. In addition to the environmental challenge of further reducing the air pollution levels in the short-term, long-term challenges have to be addressed. The following section reviews the two main global challenges for the transport system and the automotive industry in particular, i.e. energy supply and security, and climate change deriving from global warming induced by anthropogenic greenhouse gas emissions.

2.3. Long-term challenges of the transport system

As referred in the 3rd and 4th Assessment reports by the Intergovernmental Panel for Climate Change (IPCC, 2001, 2007), there is strong evidence that global warming is being enhanced by anthropogenic GHG emissions. Although an exact concentration level "that would prevent dangerous anthropogenic interference with the climate system" (Article 2, UNFCCC, 1992) has yet to be determined, "if it remains below 450 ppm of CO_2-equivalent, there is a 50% probability that the global temperature rise will not exceed 2 degrees Celsius above pre-industrial levels" (IPCC, 2007). In 2006, the six GHG included in the Kyoto Protocol have reached 433 ppm, which is an increase of 155 ppm compared to the pre-industrial level.

Transport is a fast growing emitter of GHG emissions (see figure below for the EU27, although similar trends occur for most of the OECD countries) and, while it contributes with approximately a fourth of global emissions (International Energy Agency, 2008), 90% come from road vehicles, predominantly cars. For every liter of gasoline consumed by a vehicle, about 2.4 kg of CO_2 are emitted to the atmosphere, which annually corresponds to approximately 2-3 times of the weight of a medium car[9]. For diesel it is 2.7 kg but we note that diesel powered engines are more energy efficient than gasoline and the final outcome of CO_2 emissions per kilometer is more favorable to diesel fuelled vehicles. Additionally, emissions in emerging markets tend to grow disproportionally fast due to their economic development but also because people cannot afford the latest and cleanest vehicle technologies that are entering the car markets in the developed world, today, nor is the quality of their fuels as high and their vehicles as well maintained.

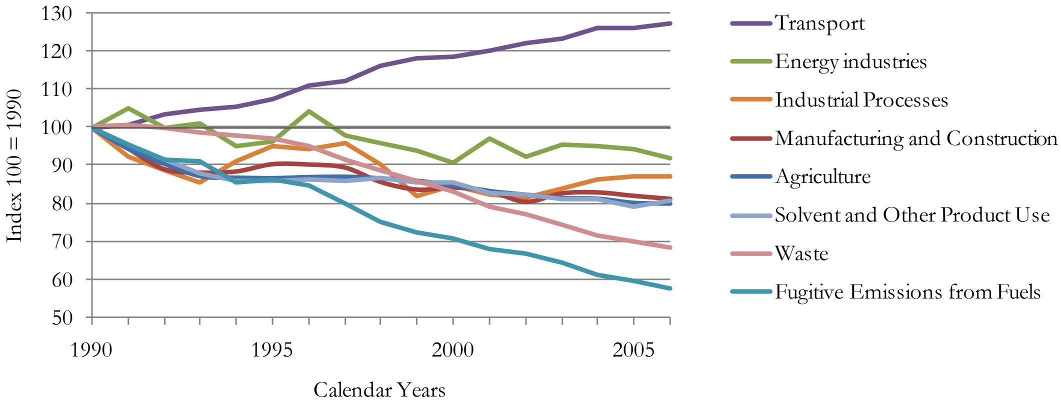


Figure 8. EU27 greenhouse gas emissions by sector, 1990-2006 (based on data from Eurostat, 2008)

Transport is the fastest-growing user of oil worldwide. World oil reserves are finite and oil extraction and production has also its limits. The exact time when oil production will peak[10] is very controversial and many papers/reports have addressed this issue (Rogner, 1997, Campbell and Laherrere, 1998, Duncan and Youngquist, 1999, Duncan, 2001, Zittel *et al.*, 2002, among others). They all agree that conventional oil extraction capacity could peak within the first decades of the 21st century. Although conventional wisdom argues that new discoveries are adding sufficient reserves as consumption grows, current trends suggest that it will surpass production capacity and resources and therefore will possibly generate an oil supply security problem. Still, according to Turton and Barreto (2006), there should be enough oil reserves for 45 years of global reserves, by 2050 (which is often cited in the literature). The following figure shows the modeling results of a study on long-term energy supply security by these authors. Importantly, their exercise includes conventional oil reserves but also unconventional oil reserves and resources (e.g., heavy oil, tar sands, oil shale, deepwater, etc.) that can substantially increase the overall oil availability. According to Rogner (1997), unconventional oil reserves and resources could nearly double today's total oil availability. In such cases, the issue becomes whether these primary sources can compete with alternative sources like coal, nuclear, hydrogen and renewable energies.

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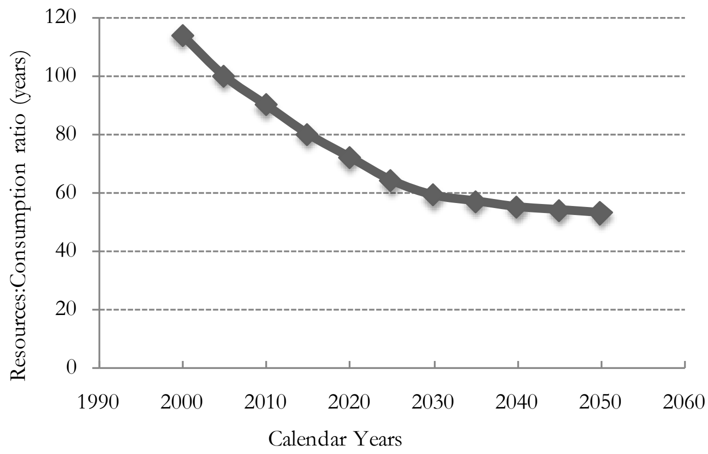
[9] Assuming an annual mileage of 15,000km, a fuel consumption of 8lt/100km and a curb weight of 1,300kg.

[10] The lifecycle of oil production can be divided in three main stages: "pre-peak" during which there is a continuous production increase, "at peak " or "plateau" when production is stagnant, and " decline" when there is a continuous declining production (Zittel et al., 2002).

Ultimately, the current indefinite maintenance of oil supply security must have some responses to ensuring sustainable resource consumption. Eventually, diversification through a shift from oil and natural gas to a combination of coal, uranium, biomass, hydrogen and other renewables should be seen as the first step in a long-term transition (Turton and Barreto, 2006).



Note: The authors use the resources to consumption ratio to measure oil supply security, expressed in years.

Figure 9. Past and future world oil Resources:Consumption ratio (adapted from Turton and Barreto, 2006)

In the case of transportation, this shift involves a whole range of technological and social changes, including (Turton, 2006b):

- transport technology transitions by which it is foreseeable that initially internal combustion engine shift to hybrid-electric vehicles and, eventually, towards hydrogen fuel cell vehicles, also (we note that much uncertainty exists regarding radical technological transitions);
- fuel production and other requirements that involve the production of alternative fuels (mostly alcohol and hydrogen-based) and the creation of production and distribution infrastructure required for large-scale deployment of these fuels (these pose a number of challenges); and
- Social and market changes are slow and, therefore, they require a multi-instrument based transport policy (Vieira *et al.*, 2007) to encourage a transition to a more sustainable energy system and overcome those social and market barriers.

One additional feature increasing the complexity in dealing with the risk of a disruption to energy supply is the current overall dependence of OECD countries on oil supplied from politically volatile regions (as illustrated in the figure below).

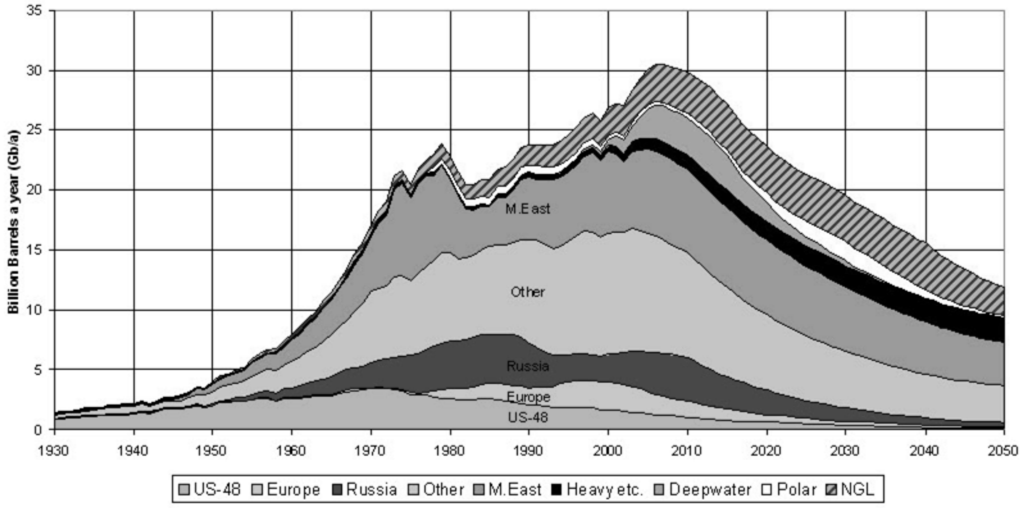
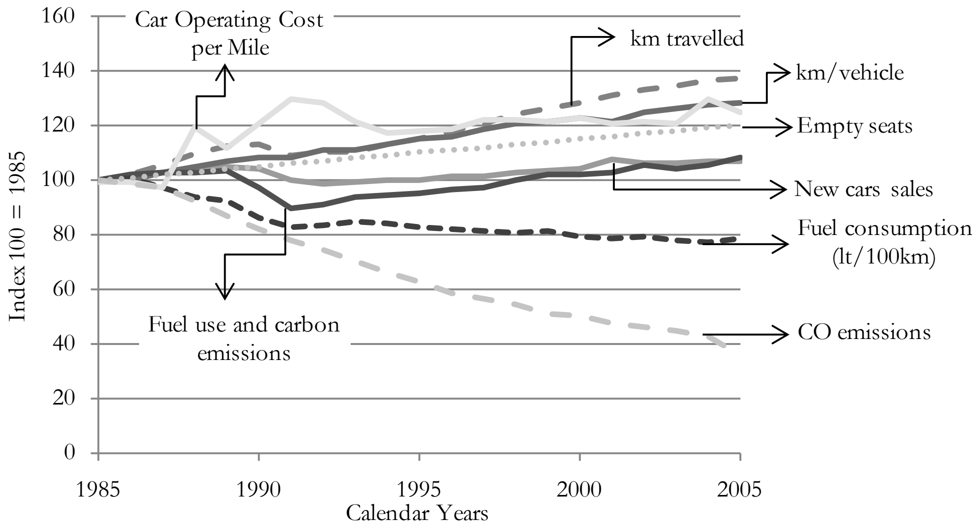


Figure 10. Past and forecasted geography of world oil production from 1930 to 2050 (ASPO, 2004)

All in all, if local air pollution from transportation can possibly be minimized through technological fixes in a foreseeable time horizon, it has become clear that in face of finite fossil fuel reserves and resources and the need to reduce the emissions of GHG, the use of petroleum oil cannot grow forever. These challenges strive mostly from the fact that technology has not yet solved the energy shortage problem and corresponding GHG emissions, i.e. the reduction of per kilometer fuel consumption is largely outweighed by the increasing mobility levels. As illustrated in the following figure, although cars are more efficient, there are more cars sold yearly, people drive longer distances, and cars are driven with fewer occupants. Interestingly, car operating costs (including variable and fixed costs) did increase in the 1985-1990 period but, since then, it stabilized (in the USA). And, although there is an urge to shift away from passenger cars, the cost of using them is not increasing visibly.



Note: Car operating costs are expressed in constant 2007 USD.

Figure 11. Relentless path of total energy consumption and car use despite the gains in fuel economy (adapted from Davis and Diegel, 2006, for the US automobility)

Figure 4 (p.16) illustrates how mobility growth is strongly correlated with economic development. Interestingly, there are two "universal laws" by which personal mobility seems to be bounded: fixed budgets of time – slightly more than 1hour/day – and money – 10-15% of household income (Schafer and Victor, 2000). However, the distances travelled and the vehicles used make the difference between the more developed and the developing countries. For example, American citizens travel nearly 70km/day while a British person would travel 30km/day and Tanzanian villagers would travel less than 10km/day (WBCSD, 2001). Furthermore, the modal mix of passenger travel estimated by Schafer and Victor (2000) clearly shows that cars dominate mobility by far in more developed western countries.

Finally, evidence shows that land use patterns and related mobility strongly determine the energy and carbon efficiency of urban areas. Figure 12 (below) illustrates the strong correlation between urban density and transportation energy consumption (Newman and Kenworthy, 1989), which suggests that higher density generates lower kilometers travelled and therefore exhibits lower energy consumption. Policy makers and urban planners, in most developed countries, have accepted this view as one solution for air quality problems, although this has been disputed mainly because of the feasibility of 'compacting' long established urban areas or simply due to the fact that people might not want to live in high density areas (for example, refer to Mindali *et al.*, 2004).

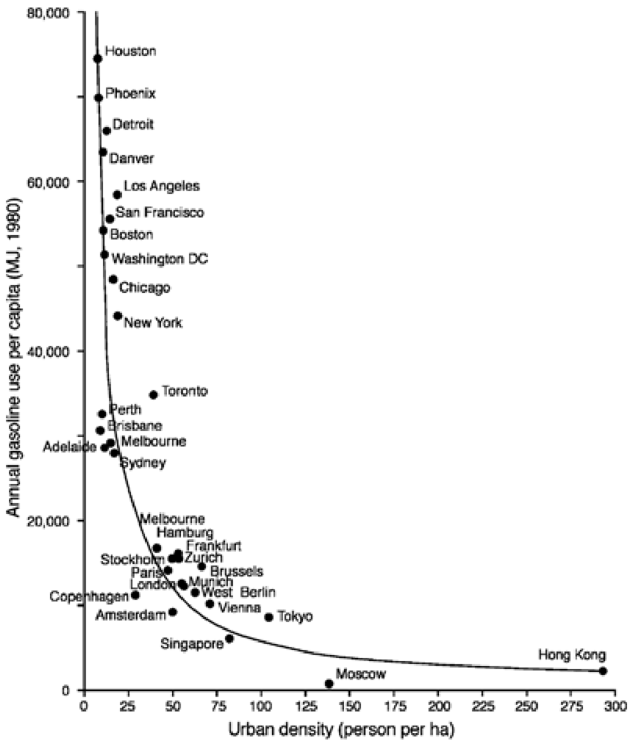


Figure 12. Gasoline use per capita versus urban density, 1980 (Newman and Kenworthy, 1989)

Moreover, the relationship between urban structure, transport emissions, and population exposure to air pollution, can be controversial. Ferreira *et al.* (2005) analyzed the population exposure to air pollution in urban areas, combining air pollutant concentrations at different microenvironments and population time-activity pattern data, and compared different urban structures: from the scenario of urban sprawl to the opposite scenario of a compact city with mixed land use. Results indicate that although compact cities provide better air quality compared to disperse cities, they have greater exposures and thus higher health risk, due to the higher population density.

These are the facts behind the unsustainable path of the transport system supporting current economic development. The overall conclusions on what are the main challenges the transport system faces in the longer-run are clear. If mobility is to be preserved enabling growth at acceptable economic, environmental and political costs, i.e., sustainably, either we limit the use of oil (through technology and mobility management) or we change current fuels to renewable resources with low carbon content and low polluting emissions (which requires significant technological changes, also), or both. The problem is that we are looking at diversified and complex set of possible substitutions and combinations of solutions. The option as to how this might be done is explored in the next section, in a schematic way.

2.4. Potential ways out of the unsustainable path

As we already mentioned, sustainable mobility is not a particular end-state or outcome of the transport system. Instead it consists of a collective process towards less resource-intensive and polluting system that requires decision-making and actions to reduce the need to travel (less trips), to encourage modal shift towards more efficient technologies, to reduce trip lengths and to encourage greater efficiency in the transport system (Banister, 2008). In order to identify some potential ways out of the unsustainable path of the transport system, we can categorize instruments into five of types: (CE) capacity expansion (whether through more vehicles and infrastructures or by increasing their performance), (P) pricing mechanisms, (R) regulation, (I) information and (LU) land-use management.

Figure 13 (p.31) illustrates how each of these might possibly be used to act on the demand and supply side of the transport system (except for information). This figure is based on the previous diagram we proposed for the transport system (Figure 5, p.17) and illustrates where (in the transport system) we could intervene in order to reduce the energy and environmental burdens. Clearly, technological fixes (left-column of the table of the same figure, which are reviewed in greater detail later in section 2.6) are more attractive from the policy-making perspective, since problems can be tackled without involving primary decisions and individual mobility options of persons and companies, while at the same time the notion of "progress" is upheld, and jobs are created to produce and sell the new components and the new cars fitted with the new technology. Still, it does not solve some of the problems.

An example is the 'rebound effect' induced by increased efficiency of vehicles. According to Herring (2006), improving energy efficiency lowers the implicit price of energy and hence makes its use more affordable, thus leading to greater use. When the 'rebound effect' is greater than 100%, exceeding the original efficiency gains, economists refer to the Jevons Paradox. It is the proposition that technological progress that increases the efficiency with which a resource is used, tends to increase (rather than decrease) the rate of consumption of that resource. William Stanley Jevons observed that England's consumption of coal rocketed after James Watt's coalfired steam engine greatly improved the efficiency of earlier designs ("The Coal Question", 1965) since it became more cost effective leading to the increased use of the steam engine in a wide range of industries. This in turn increased total coal consumption, even as the amount of coal required for any particular application fell (Britannica Online Encyclopedia, 2008). In such cases, induced mobility must be tackled differently.

In this sense, transport demand management is required to promote a more sustainable mobility. In the middle-column of the table of Figure 13, we list some actions for mobility management:

- Land-use policy measures to <u>reduce trip lengths</u> (and, possibly, avoid motorized mobility),
- <u>Modal shift</u> towards more adequate and efficient vehicles, and
- Reduce (or eliminate) the need to travel by <u>substituting</u> it with non-travelling activity.

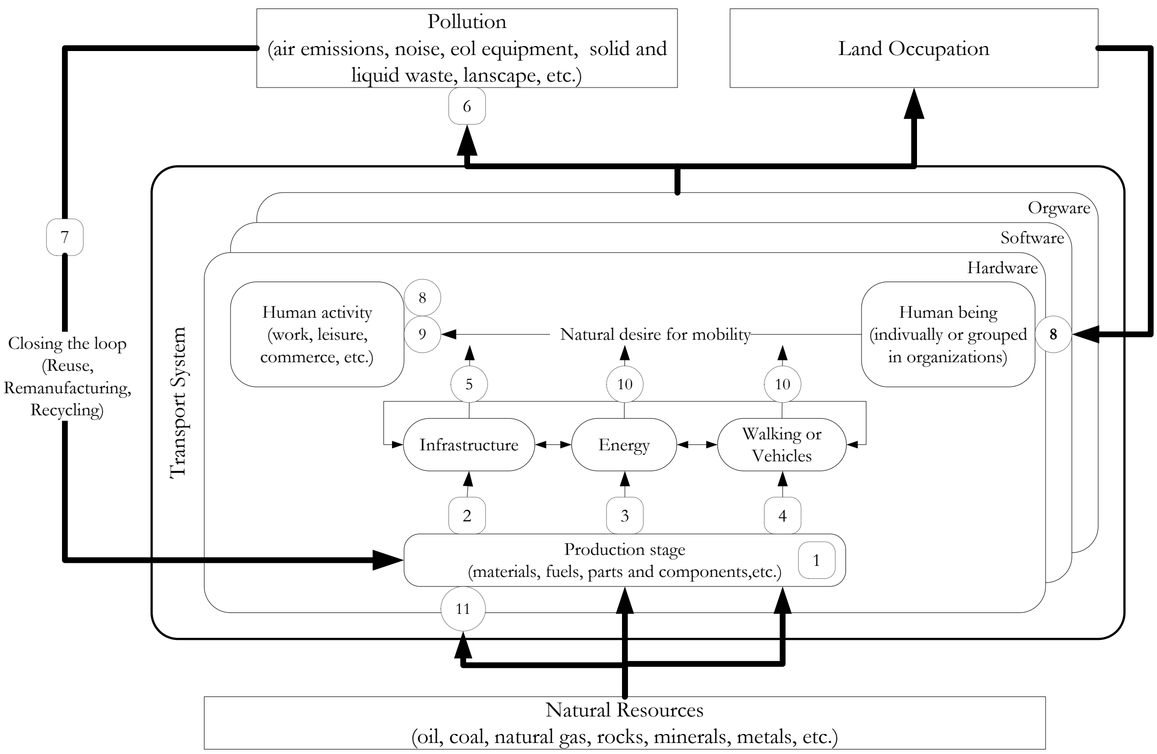
Regarding the last bullet, the combination between transport and information and communication technologies (ICT) can bring substantial substitution of trips (e.g., Internet shopping, mobile working). However, the final outcome is dubious in that the final balance between trip substitution and generation is not clearly on the reduction side. For an extensive list of examples on transport demand management instruments refer to the Victorian Transport Institute Web Encyclopedia (VTPI, 2003) or to the "Handbook of Transport and the Environment" edited by Hensher and Button (2003) which is a source of considerable material and reference lists of key information in this area.

While ICT enables the substitution of trips (by avoiding or reducing its intensity, e.g. home delivering after internet shopping), it can also generate more spontaneous travels (e.g., booking last minute holiday overseas). Complementarily, ICT can also be used for transit flow optimization: for example, intermittent bus lanes (Viegas and Lu, 2004), ramp metering (Haj-Salem and Papageorgiou, 1995), capacity reserve, connecting cars in highways, among others.

The right-column of the table in Figure 13 presents some 'fixes' that can be introduced to address the infrastructural aspects of the transport system and additional behavioral issues that wouldn't fit within the remaining group of actions presented before. These refer to reducing the lifecycle energy and environmental burdens of:

- The automotive industry. As we will address in Chapter 3 (section 4.4.2, p.121), the energy intensity per vehicle produced can be halved through lean production (for example, Toyota's program of "Green, Clean and Lean Factory" in France, Toyota Europe, 2001).
- The road infrastructure. In this respect, actions can be held from the strategic level – assessing environmental issues (including land use constraints) together with technical (civil engineering) and economical aspects when deciding upon the large scale layout of road networks – until the construction of infrastructure, i.e., after environmental assessment of the project, include all minimization measures (e.g., acoustic barriers) and implement an environmental management system of the construction yards. Complementarily, the design

of the road itself can introduce recent technologies related, for example, to pavement characteristics in order to minimize noise from tire-to-road contact.



	Increased efficiency through technological fixes (only)		Reduced demand through mobility management		Infrastructural and behavioral actions
2	Infrastructure engineering (e.g., pavement composition and design)	8	Land-use policy to reduce trip lengths (and, possibly, avoid motorized mobility) through regulation (e.g., urban environmental zones) and pricing mechanisms (e.g., congestion charging, parking prices) to influence the choice of residential, work and business locations.	1	Increase efficiency of material production and automotive industries
3	Fuel technologies (e.g. sulfur content, biofuels)			7	Industries for reusing, remanufacturing or recycling materials and components.
4	Vehicle technologies (e.g., new propulsion technologies, continuous variable transmission, stop-and-go)			10	Fiscal instruments to influence consumer's preference for more efficient fuels and vehicles (e.g., carbon-levied taxes)
5	Increase the stability of transit flows (e.g., eco-driving, intermittent bus lanes - IBL, ramp metering, capacity reserve)	9	Influence modal choice to shift mobility towards more appropriate and efficient transport means (e.g., mass transit for commuting trips) through pricing mechanisms and, possibly, reduce the need to travel by using ICT (e.g. Internet shopping).	11	Project assessment (incl. Environment Impact Assessment) to determine the need, the adequate mode and of the infrastructure in face of expected demand.
6	After treatment (e.g., acoustic barriers, catalytic converters, particle filters, etc.)				

(Note: Round-squares refer to technology-driven fixes and circles refer to transport demand management instruments)

Figure 13. Transport system's threats and possible ways out (source: author and adapted from Viegas and Moura, 2006, Viegas, 2008)

- Reusing, remanufacturing and recycling industries. Industrial ecology is the interdisciplinary field that covers a wide spectrum of solutions to progressively close the loop of industrial metabolism and reusing, remanufacturing and recycling are important tools for the dematerialization of the economy (refer to section 3.1 for detailed review of these concepts, p.55). However, much has to be done in order to increase the overall performance of the system. For example, the European Parliament has brought the principle of "extended product responsibility" to the Directive 2000/53/EC, by which the auto industry must comply with technical requirements for car design as well as minimum recycle and recovery rates for end-of-life vehicles (ELV). This regulation is expected to induce changes in the infrastructures required for ELV processing, and presents a challenge to maintain such economically viable infrastructure (Ferrão and Amaral, 2006). According to the authors, less than 75% of EOL vehicles are recycled today. In order to comply with the targets of more than 80% recyclability, recycling of an additional amount of mass per ELV is required, which will have to include other materials such as plastics, rubber and others. This has strong implications in the car design stage in order to optimize the dismantling stage after the car's service life.
- Car consumer preferences – Fiscal instruments can be used to influence consumer to choosing more efficient vehicles and fuels by, for example, levying taxes on carbon intensity (such as was enforced for car purchasing in Portugal since 2007 with the Law nº 53-A/2006, 29th of December).

As mentioned in the introduction of this dissertation, although problems are far from solved and recognizing that technology isn't the panacea for all environmental impacts of transportation, the situation is improving in general and the transition to a more sustainable transport system requires action from policy decision makers to implement and enforce the available port-folio of solutions. With respect to the main core activity of the system addressed in this study, i.e., the use of cars, the reduction of energy and environmental burdens requires a fleet conversion policy that efficiently absorbs new, clean technologies and withdraws old, high-polluting technologies, i.e., increasing technological turnover of fleets.

2.5. Diffusion of new technologies and the big inertia of car stocks

2.5.1 Development and deployment of new technologies

The Schumpeterian[11] theory of economic development postulates that each time some technological cycle reaches its saturation level, a new paradigm arises and creatively determines

[11] Joseph Schumpeter (1883 –1950) was an economist and political scientist. His is the author of the theory of entrepreneurship whose innovative entry in the stabilized markets was the force that sustained long-term economic growth. As a consequence, innovation would potentially destroy the value of established companies that enjoyed some degree of monopoly power, aka 'creative destruction' (Britannica Online Encyclopedia, 2008).

the end of the previous technological system or provokes its concept reformulation (Schumpeter, 1934, Andersen, 1999, Grübler *et al.*, 1999). Following Grübler *et al.* (1999) and Rogers (2003), Figure 14 (below) schematically illustrates the development and deployment of technologies together with the 'learning cost' curve and categories of adopters.

Typically, technological change starts with the invention process, which is the creation of an idea and is often the product of fundamental and applied research. Innovation follows and is characterized by the first practical application of an invention in the form of development and demonstration projects in industrial laboratories. Afterward, the new technology is typically employed in niche markets where it has substantial performance advantages over existing technologies (this is when senescence of older technologies starts, sooner or later). The first commercialization in niche markets allows manufacturers to "learn by doing" and "learn by using" which leads to further improvements in performance and cost. Pervasive diffusion of the technology follows by extending it to broader markets until it reaches saturation, eventually. Senescence follows when a new and better competitor takes the market share or redefines performance requirements, thus changing consumers' expectations and preferences.

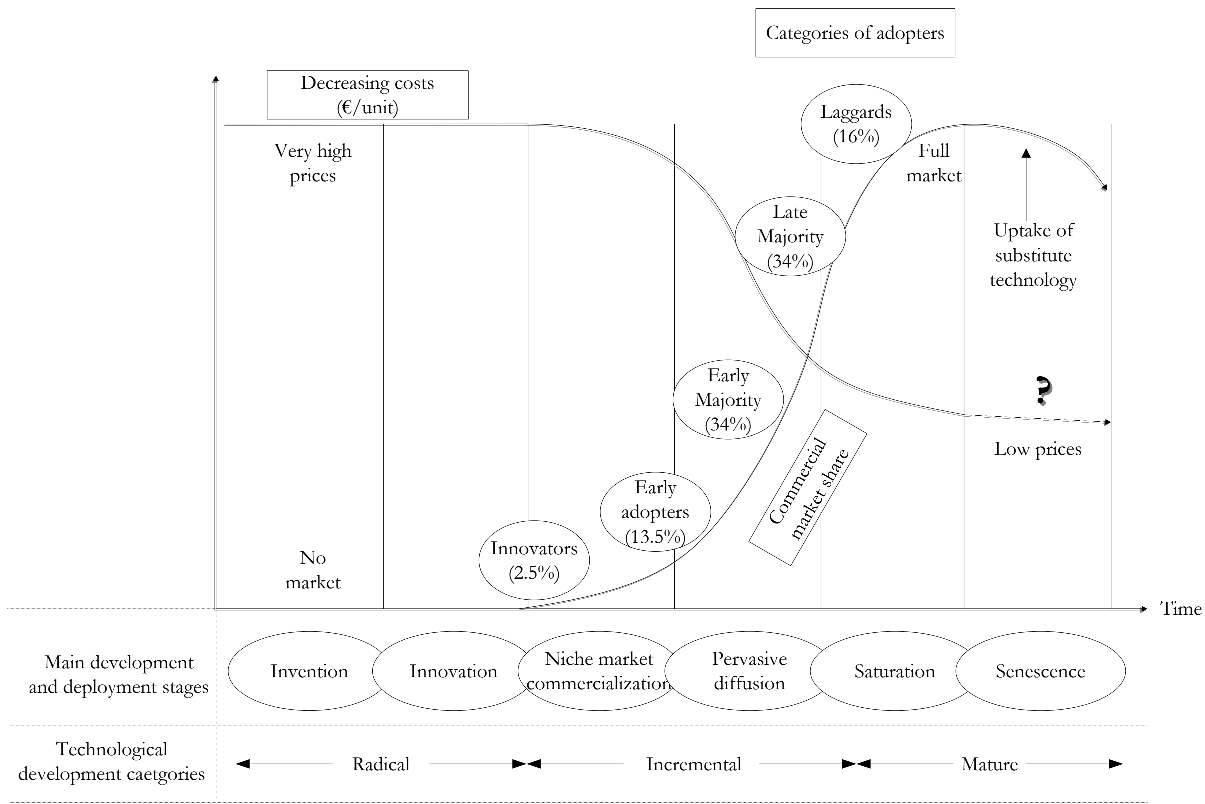


Figure 14. Schematic illustration of the development and deployment of technologies, learning cost curve and categories of adopters (Grübler *et al.*, 1999, Rogers, 2003)

As explained by Grübler *et al.* (1999), each of the six stages of technological development have key underlying mechanisms that we summarize hereafter:

- Invention – seeking and stumbling upon new ideas, breakthroughs, basic research;
- Innovation – applied research, development and demonstration (RD&D) projects;

- Niche market commercialization – identification of special niche applications, investments in field projects, “learning by doing", close relationships between suppliers and users;
- Pervasive diffusion – standardization and mass production, , “learning by using", economies of scale, building of network effects;
- Saturation – exhaustion of improvement potentials and economies of scale, arrival of more efficient competitors into market, redefinition of performance requirements; and
- Senescence – domination by superior competitors, inability to compete because of exhausted improvement potentials.

One important aspect in the process of technological development is the technology learning process we referred before (through “learning by doing” and “learning by using”) by which, typically, production costs are brought down with cumulative production and use of the technology. The more often a specific technological artifact is produced, the more manufacturers learn about making the technology: design improvements, streamlining and optimizing the productive chains (shortening production times also), using fewer (or cheaper) inputs, and increase the scale of production (possibly). As illustrated in the figure above, costs start declining during the niche market commercialization of the technology when manufacturers learn how to “make things better”. If it becomes competitive, then the pervasive diffusion initiates and much of the learning opportunities arise from standardization, mass-production and economies of scale, i.e., reducing costs by building and using faster and larger units (Grübler, 1998). During the saturation stage, learning opportunities are rare and production costs stabilize. McDonald and Schrattenholzer (2002) present a comprehensive overview of surveys conducted on technology learning processes for energy technologies and arrived at a quite uniform learning rate by which the costs decrease between 11 to 35 percent with each doubling of cumulative experience (expressed, for example, in quantity of applications). Many studies have addressed the expected mass-production costs, and corresponding conditions for technology deployment, of more radical automotive technological developments (Rogner, 1998, Arthur D. Little, 2002, Ogden *et al.*, 2004, Tsuchiya and Kobayashi, 2004, among others). Rogner (1998) analyzed the learning costs of Proton Exchange Membrane Fuel cells (aka PEMFC) and referred that a few hundreds of thousands would have to be produced before costs decline below US$150/kW. More ambitiously, Tsuchiya and Kobayashi (2004) estimated that production costs of PEMFC (approximately US$45/kW) could compete with today’s mature ICE technology (approximately US$30/kW, Edwards *et al*, 2006, for example) when cumulative production would surpass 5 million units (possibly by 2020).

Technology development in the automotive industry has been based on three main paths (Grübler, 1998, Geerlings and Rienstra, 2003):

- Incremental steps that are (1) improvements over existing technologies (e.g., shifting from 4 to 5-gear transmission) or (2) remanufacturing of existing solutions (e.g., introduction of biofuels in current fossil fuels). Importantly, no single improvement by itself will have a dramatic effect, although their combined effect is important. We note that this is extremely relevant for our research, since the concept of car organ transplant can be defined as a continuous incremental improvement over the vehicle's service time (whether it is programmed by the car maker or by initiative of the car owner).

- Radical development that involves (3) concept-rethinking (e.g., fuel cell propulsion).
- Technology is mature when no further significant developments occur.

Importantly also, the deployment and diffusion of new technologies largely depends on the type of adopters. Rogers (2003) identified five categories of adopters (illustrated in Figure 14) on the basis of innovativeness, which is the degree to which an individual is relatively earlier in adopting new ideas than other members of a social system. Potential adopters emerge with the niche market commercialization. Firstly, innovators and early adopters start using the new technology and, according to Roger's classification, they differ mostly on their degree of venturism. After this first stage of deployment (i.e., niche markets), the new technology enters a period of very rapid diffusion when the early majority joins the previous adopters. At this stage, the new technology has typically reached 50% of the market share. Thereafter, there is a slowdown in the adopting rates and most potential adopters (late majority) have switched to the most recent technology when the technology reaches its maturity (saturation). Laggards are the last to come and are typically most skeptical to novelty.

There are two main forces that are emphasized to explain the apparent slowness of the beginning of technology diffusion process (Jaffe *et al.*, 2001, Rogers, 2003):

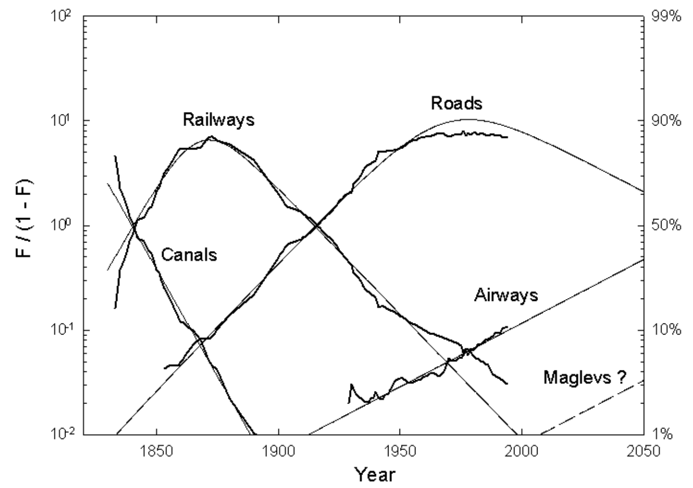
- Adopting a new technology involves risk, requiring considerable information, both about the generic attributes of the new technology and about details of its use;
- First-movers may face higher costs, which tends to delay the uptake of technologies, also; and
- Potential technology adopters are heterogeneous, so that a technology that is generally superior will not be equally superior for all potential users.

Based on the previous paragraphs, we would argue that the more niche markets are explored for the commercialization of a new technology, the greater should be the probability for that technology to diffuse faster, for the same reasons explained before: more "learning by doing", more "learning by using", greater potential for economies of scale, and so on. Again, this is important in the context of our research since exploring the possibility of car organ transplant, a much larger universe would arise to implement the new technology, i.e., introducing the new technology in used-cars and not only in new models that hardly correspond to 10% of total fleets. We will analyze the pervasive capacity of transplanted technologies (as advocated in our research) in Chapter 9 (p.257).

We generically explained how new technologies emerge and, potentially, diffuse within some technosystem. Associated to the process of technological innovation is the consequent process of technological change within that technosystem. In the next section, we review the technological change in the automobile system.

2.5.2 Technological change in the automotive technosystem

In the past 200 years, the transport system has embraced a new means of transport every 50 years or so, according to the long-cycles of technological evolution (refer to the following figure). The takeoff of each cycle is clustered within certain historical epochs (Ausubel *et al.*, 1998, Andersen, 1999) and apparently determined by multiple and complex factors pushing technological breakthroughs, although the main causes are related to the need for faster transport means, overcome longer travel distances and avoid congestion of existing systems (Grübler, 1990, Ausubel *et al.*, 1998).



Notes: Squiggly lines represent observed values and the smooth lines were estimated with the logistic substitution model. 'F' is the fraction of total length or the market share.

Figure 15. Shares of the actual total length of the US transport infrastructure (presented in Grübler, 1990)

Interestingly, history of social and technological innovation has a large abundance of "nonstarters", i.e. examples of potential technological breakthroughs that failed to diffuse altogether (Grübler, 1998). Electric and steam-powered cars are two examples of nonstarters that the automotive industry ruled out as early as the beginning of the 20th century. The choice of technology for its prime mover narrowed quite quickly to the ICE engine which proved to be increasingly reliable, easy to use and repair, and cheap to mass-produce – with this respect *Fordism*[12] paved the way to the success of the machine that changed the world (Womack *et al.*, 2007). Interestingly, "*The machine that changed the world*" is the title of the landmark study of the automobile industry (International Motor Vehicle Program - IPVM) directed by James Womack, Daniel T. Jones, and Daniel Roos, at the Massachusetts Institute of technology (2007, 1st ed. from 1990). Importantly, when mentioning 'machine' they are certainly referring to the vehicle

[12] *Fordism* introduced innovative shop floor techniques in automobile manufacturing. In short, breaking down complicated tasks in many smaller and simpler ones, allowing unskilled labor to replace skilled labor, and cutting training time so employees could easily and quickly be replaced. However, it was Edward Budd's 'all-steel body-chassis' that facilitated automation in manufacturing of the modern automobile and enabled mass-production required for economies of scale (Nieuwenhuis and Wells, 2003).

artifact but also to the complete lean production system that they argue is at the source of profound changes in the world, by shifting away from the Ford's mass-production approach. We present the principal car manufacturing systems later in section 3.2.3 (p.69).

Understanding the development patterns of the automotive industry requires the identification of the main technological interdependencies between the systems with which automobiles interact. With this respect, the production and distribution of petroleum to fuel ICE was one of the major industrial developments of the 20th century (often termed the 'Oil Age'), contributing to the build-up of the current automobile technosystem. Today, our mobility depends to a large extent on cars and on the oil industry with its exploration, refining and massive distribution infrastructure. As explained by Grübler (1998), we are "locked-in" in a particular development pattern of the automotive industry accruing from the accumulation of past decisions that are difficult (and costly) to change. Effectively, there are significant increasing returns to adoption of energy technologies deriving from economies of scale, learning and networks, which downscale the production costs of matured technologies and, hence, make it harder for new technologies to compete due to higher production cost. The present automobile "lock-in" results from a previous "path dependency" of technological development that began with different initial conditions and determining factors (e.g., economic, institutional, infrastructural and technological) that, by then, were essential for the system's economic and social growth. As a consequence, the potential for environmental improvement of the transport system that could be achieved through the diffusion of the more radical and much cleaner technologies that are available today is stalled.

Today, the operative diffusion of proven technologies[13] in car fleets is currently driven by the retirement of older vehicles and replacement by new models. Importantly, the rate of technological turnover is constrained by the car density of the fleet in that the latter decreases as car density approximates the one-car-per-inhabitant mark, which corresponds to the saturation of car fleet (as explained in detail in section 7.2, p.206). The turnover also depends on driving forces for technological change, for example, government regulations regarding earlier retirement of EOL vehicles. Additionally, it is observed that technological diffusion in car stocks varies also with the type of technology being introduced. Figure 16 illustrates the diffusion of new technologies in the US car industry from 1950 to 1985. The total displacement of older technologies can last more than 10 years when technological change is fast, e.g., disc brakes, radial tires, electronic injection and environmental control technologies. Conversely, it can reach 50 years in the cases of slower changes, e.g., automatic transmission, power steering and air conditioning (Grübler, 1990, Grübler and Nakicenovic, 1991).

[13] According to the nomenclature presented in the previous section, these correspond to incremental technologies that overcame the niche market commercialization and reached the pervasive stage of diffusion.

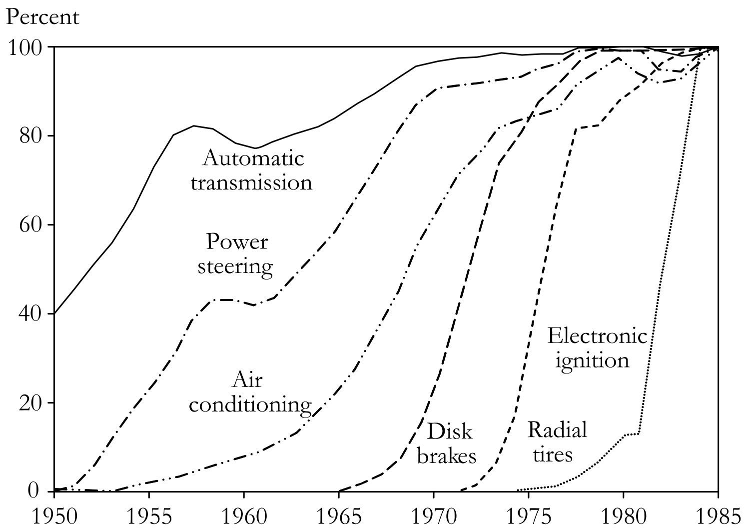


Figure 16. Diffusion of new technologies in the US car industry, in percent of car output (Grübler, 1990, Grübler and Nakicenovic, 1991)

Figure 17 analyses the introduction of environmental control technologies in the US automobile fleet from 1960 to 1990. Differently from previous examples of diffusion of car technologies that depends mostly on their comparative advantage over other technologies (expressed in producers and consumers preferences), the deployment of environmental technologies is driven by government regulation. In such cases, diffusion follows inherently the car stock's ('population') dynamics (i.e., transformation). In fact, the introduction of the new technology is forced by emissions standards and, hence, the percentage of cars produced/sold with that technology varies instantaneously from 0 to 100 percent of the car fleet in that same year. Using demography nomenclature, each new standard creates a new cohort of the car population. As showed in the next figure, the total displacement of a these technologies is about 10 years (like we mentioned before), which comes with no surprise if we consider a constant annual 10% new car sales of the total fleet.

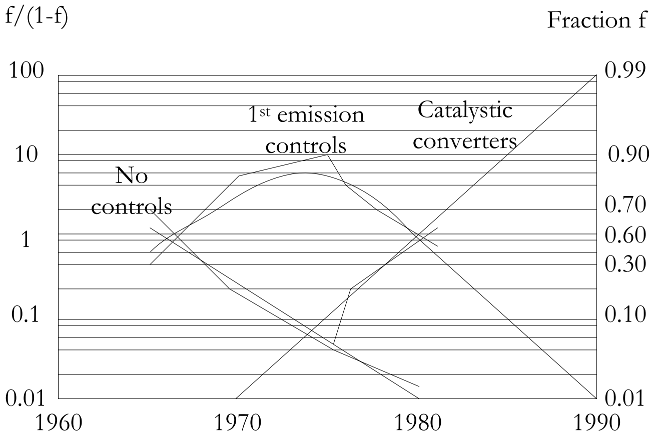


Figure 17. Substitution of cars with emission controls (Nakićenović, 1985)

However, the outcome of the desired effects of these technologies can last longer since, on one hand, the annual sales of new cars are often below 10% and, on the other, energy consumption and emissions are subject to other factors, such as upsizing of the total fleet or rebound effect of demand – just to mention two examples. In Figure 18, we compared the indexed evolution of total NO_X emissions by the EU15 road transportation with the evolution of the corresponding EURO standards. We detected large delays (up to 20 years) between the beginning of a new standard and the moment when the fleet's average emissions reach the same level. The longer period is strongly influenced by the continuing use of inefficient, higher-polluting older cars (although annual mileage decreases with car age and thus the bulk of emissions from older cars could be lower than recent model years).

As we mentioned before, one environmental implication of these slow diffusion rates is that potential benefits accruing from more efficient technologies are fully exploited only after 10 years (at the best). This is one cornerstone argument for the wide application of the concept we explore in this dissertation by which car organ transplant (or, technological transplant) might accelerate the diffusion of cleaner technologies while keeping the remaining and up-to-date components of the car running. The concept proposed here might potentially shortcut this relentless process by introducing new technologies into used cars and therefore expand the universe of application of the cleaner technologies above 10% of the total fleet, yearly. As this could hardly be imposed by regulation on used cars, this would be subject to the consumers' preferences in that they would have to support the corresponding organ transplant expenses. We will analyze this in detail in part B of this dissertation.

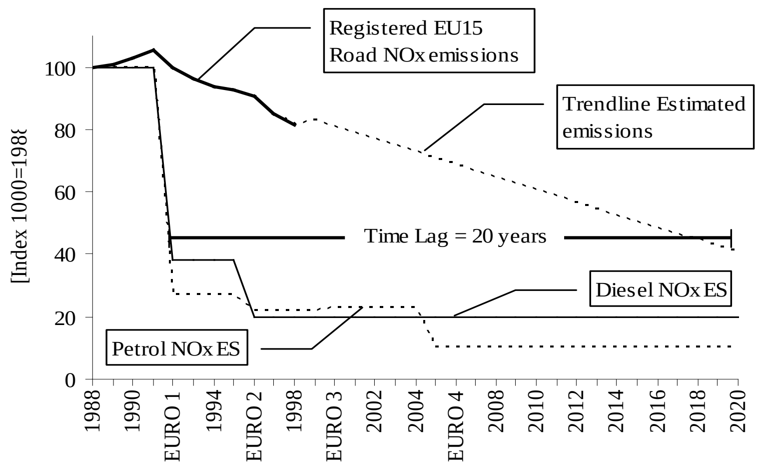


Figure 18. Delay between the introduction of EURO 1 standards and the effective reduction of the average emissions of total EU fleet (adapted from Ntziachristos *et al.*, 2002)

In the next section, we shift our review towards the technological solutions that can potentially contribute to meeting those challenges, whether these are fixes for the existing technology (incremental innovation) or more radical alternatives that might be available in the longer run (few decades). We also overview some of the technological roadmaps presented by the automotive industry aiming to tackling the challenges outlined in previous sections.

2.6. Technological change in the automotive industry

There are many Internet sources – for example, US EPA's site, http://www.epa.gov/otaq/fuels.htm, and EU EEA's site, http://themes.eea.europa.eu – that review the set of technological possibilities to enhance the energy and environmental performance of vehicles and fuels. Complementarily, a broad literature has been published over the last decades on the means to improve fuel and vehicle's efficiency and on the comparative analysis of the corresponding lifecycle burdens (Interlaboratory Working Group, 1997, Weiss *et al.*, 2000, DeCicco *et al.*, 2001, Delucchi and Lipman, 2001, Hackney and de Neufville, 2001, Delucchi, 2003, Lipman and Delucchi, 2003, ECMT, 2005, Edwards *et al.*, 2006, Cheah *et al.*, 2007, just to mention a few). These documents vary in the extent of the technological innovation considered: from simple incremental fixes using betterments of existing technologies (without implying burdensome transformation of the remainder technosystem mostly related with the production and distribution fuel infrastructures) to more radical innovation that implicate other parts of the technosystem. In the next section, we describe the main technological fixes for the existing technology.

2.6.1 Fixes for the existing technology

When considering near-term reduction targets of fuel consumption and GHG emissions from cars, the technological solutions are necessarily those available today or in the near-term and these are inevitable incremental technological developments. In this sense, electric-drive vehicles (namely, plug-in hybrid electric, battery electric or hydrogen fuel cell vehicles) are considered to be more radical alternatives (although they are important technologies for realizing vehicle fuel consumption reductions) and are addressed in the following section.

Regarding fuel technologies, there are three main categories of solutions: improved existing fuels, alternative fuels or alternative energy carriers (namely, electricity and hydrogen). We list the first two groups hereafter with a short explanation of each technology (Bosch, 2004, http://www.epa.gov/otaq/fuels.htm and http://themes.eea.europa.eu):

- Reformulated gasoline (aka, RFG) is fuel blended to burn cleaner by reducing smog-forming and noxious pollutants.
- Ultra-low sulfur diesel (aka, ULSD) is a diesel fuel with substantially lowered sulfur contents. As of 2006, almost all of the petroleum-based diesel fuel available in Europe and North America is of a ULSD type.
- Oxygenates are fuel additives (alcohols and ethers) that contain oxygen which can boost gasoline's octane quality, enhance combustion, and reduce exhaust emissions.
- Renewable fuels (aka, biofuels) are produced from plant or animal products or wastes, rather than from fossil fuels. The best known renewable fuels today are ethanol and biodiesel. It has now been a few decades since ethanol has been blended with gasoline in many countries across the world. Ethanol blends at higher volumes, such as 85% ("E85"), are available also for use in specially designed "flexible-fuel vehicles" (which allow a vehicle to operate on a mixture of gasoline and ethanol that can vary from 0 percent to 85 percent ethanol and which are quite popular in Brazil). European Union has recently enacted a directive ("European Biofuels Directive" – 2003/30/EC) by which a target of 5.75% of all petrol and diesel for transport purposes (calculated on the basis of energy content) should be replaced by biofuels, until 31 December 2010.

- Natural gas is used mainly in its compressed form (CNG) but can also be used in its liquefied form (LNG). It consists primarily of methane (90%) with a mixture of other hydrocarbons. It is derived from gas wells or in conjunction with crude oil production. To obtain the liquefied version, the gas must be cooled considerably and stored in insulated tanks. Special refueling stations are needed in order to sufficiently pressurize the gas for in-vehicle storage since natural gas is most commonly used in the compressed form.
- Synthetic fuels are produced from coal, natural gas, and low-value refinery products into a high-value, clean-burning fuel through the Fischer-Tropsch synthesis, which is a catalyzed chemical reaction in which a mixture of CO and H_2 is converted into liquid hydrocarbons of various forms. However, these synthetic fuels do not offer any advantage in terms of the GHG gas emissions over traditional oil since its primary source comes from fossil fuels. Still, they offer important emissions benefits compared with diesel, reducing NOx, CO, and PM.

Apart from fuel technology savings, tailpipe emissions can be controlled with increasing engine efficiency, increasing vehicle efficiency, or cleaning up the emissions. Table 2 presents a list of some existing or promising incremental technologies that can be used to meet such objectives (based on the technical features presented in Bosch, 2004, RENAULT, 2007). In annex A.3 (p.360), we describe succinctly each of these technologies.

Table 2. Incremental technologies to promote energy and environmental efficiency (Bosch, 2004, RENAULT, 2007)

increasing engine efficiency	increasing vehicle efficiency	cleaning up the emissions
• Engine control unit (ECU) • Controlled Auto Ignition (CAI) • Homogeneous Charge Compression Ignition (HCCI) engine • Stratified charge engine • Turbochargers • Camless engine • Camshaft angle variator • Common rail (CR) • Multi-injection diesel engines • Piezoelectric injectors • Robotized gearbox • Continuously variable transmission (CVT)	• Reducing friction through aerodynamic design, gearbox and tire optimization, and minimization of cylinder and valve sliding frictions. • Engine downsizing • Reducing friction • Shedding weight	• Catalytic converters • Particulate filter • NOx filter • Selective catalytic reduction of NOx • Exhaust Gas Recirculation (EGR)

Furthermore, vehicle fuel economy can also be improved by reducing the power consumption by ancillary equipments or components. Some examples are: electrically driven oil and water pumps, electric power steering, efficient alternators, efficient air conditioners and heat pumps, fast warm-up technologies, idle-off systems, 42 volts electrical systems, adaptive cruise control (ECMT, 2005).

The list of technologies refers to examples of incremental developments that can be used today without requiring structural changes on the overall technosystem. These are the technologies (including those ancillary equipments or components) we would consider to be transplantable in existing used cars and for which intergenerational compatibility should be conceived. There are obvious drawbacks. For example, as car electronics evolve new models are equipped with more electronic control units (so-called ECUs) that might not exist in older vehicles (at least, all of them). These ECUs are fundamental pieces that communicate with the engine's management unit (EMU). The EMU provides real time management of some fifty engine function parameters which is achieved by continuously analyzing the signals sent by those ECUs from different parts of the vehicle (e.g., accelerator position, engine mode, occurrence of knock, pressures, temperatures, etc.). Accordingly, the EMU decides the optimal engine adjustment and acts on the numerous actuators (e.g., fuel throttle, fuel injectors, exhaust gas recirculation valves, turbocharger blade positions, etc.), which will place the engine in the optimal operating condition. Similar operations are executed for the control of emissions (catalytic control through the lambda probe measurements and the sensor in the particulate filters). Clearly, even though these are incremental technologies, strong limitations might arise for the intergenerational compatibility required for organ transplant, unless specific modules are designed for older vehicle models. We would argue that costs could be worthwhile for more popular car models (e.g., Golf VW).

We present in the next section more radical innovations that require new production and distribution infrastructures.

2.6.2 The really new technologies

While the really new technologies will eventually be required to move away from conventional mechanical engines and the corresponding fuel infrastructures in order to driving automobility towards higher sustainability standards, the present research did not include the possibility of transplanting radical innovations in older vehicles. Still, we do not rule out such possibility in the longer term. In a 'drive-by-wire[14]' paradigm of the automotive industry and with the increased

[14] 'Drive-by-wire' in the automotive industry is a term inspired by the aviation 'fly-by-wire' by which electronic and computerized control systems replace the traditional mechanical and hydraulic control systems, using electromechanical actuators that ensure the human-machine interface while keeping the conventional car control systems – e.g., pedal and steering wheel (Bosch, 2004). The traditional components such as the steering column, intermediate shafts, pumps, hoses, fluids, belts, coolers and brake boosters and master cylinders are eliminated from the vehicle (Automotive News, 2007).

modularity in the design of cars (Helper *et al.*, 1999, Camuffo, 2000, Orsato and Wells, 2007), ‘plug-out & plug-in’ modules appear even more attractive than current thermal ICE where thermodynamic and mechanical barriers can become harder to overcome (as rightfully discussed by Whitney, 2003, in his analysis on the limits to modularity).

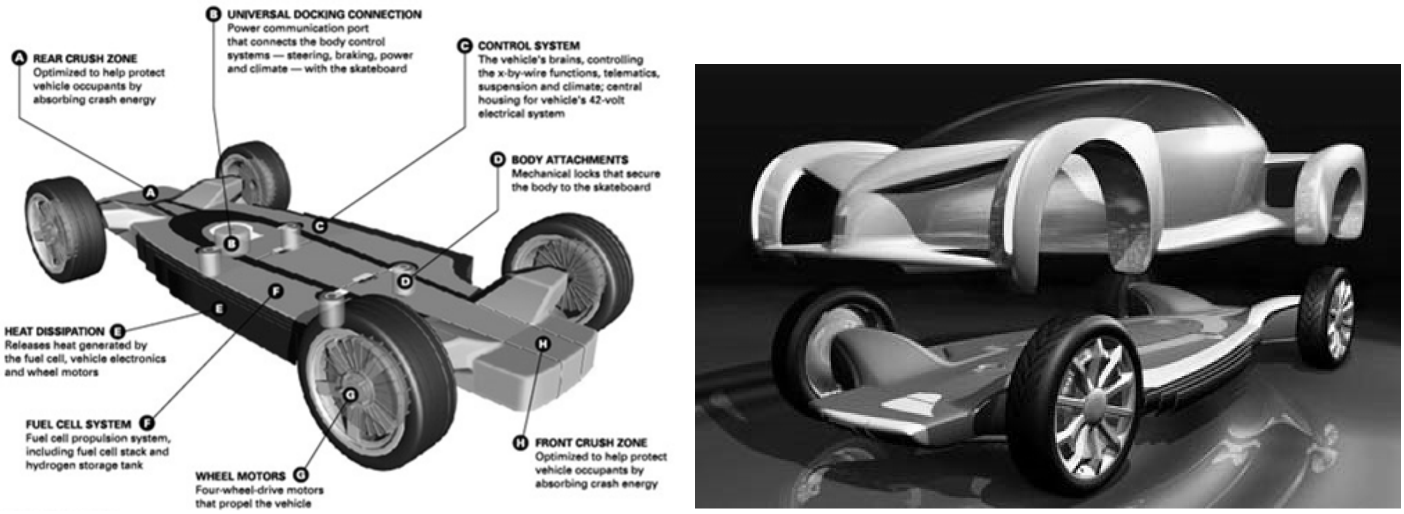
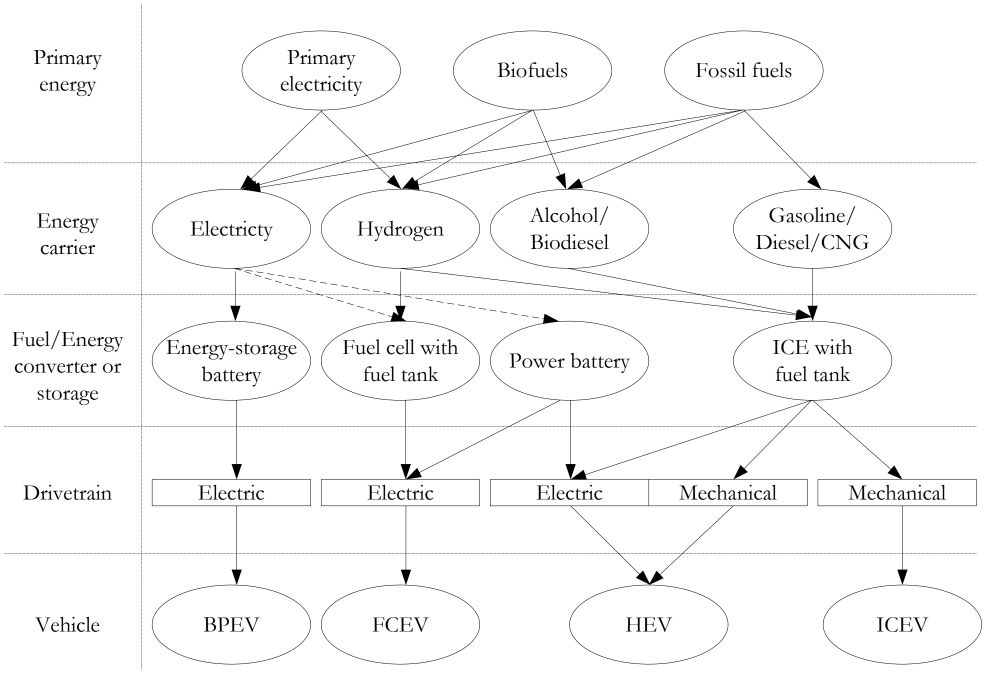


Figure 19. Autonomy’s skateboard platform (http://www.gm.com – General Motors, Inc.)

GM’s AUTOnomy concept car and its ‘skateboard platform’ (http://www.gm.com) materialize these principles. The ‘skateboard’ platform concept illustrated in Figure 19 is a flat base unit (15 cm thick) that contains the entire fuel cell powertrain and holds the wheels, suspension and other items. It is itself an autonomous mobile structure and has four body attachment points and one central ‘docking point’ by means of which a body structure can be attached to it. As mentioned by Nieuwenhuis and Wells (2003), fuel cell technology and electric powertrain allow very flexible packaging in a way not possible with conventional ICE systems. The authors add that the AUTOnomy concept reintroduces the separate chassis and body structure designed by Henry Ford on the Model T and departs from the monocoque structure introduced by Edward Budd.

While larger technological gaps in ICE solutions can lead to more difficult (or possibly rule out) bridging of newer components in much older vehicles, with electric propulsion and control systems it would resume to computerized management systems and electronics, i.e., sensors, wires, plugs, docking points (and so on) to bridge all components together and make the car operate harmoniously.

The radically new technologies refer mainly to shifting from liquid energy carriers (conventional or alternative fuels) to electricity and hydrogen. Electric-drive vehicles (EDV) are very promising technological breakthroughs although it is expectable that they will slowly enter the car market since they suffer to different degrees from a lack of market experience and high costs (Turton, 2006b). These can be hybrid (HEV), plug-in hybrid (PHEV), fuel-cell (FCEV) or pure battery-powered (BPEV) electric vehicles.



Note: Dashed arrows refer to the possibility of batteries being recharged directly from the grid with plug-in systems.

Figure 20. Main streams of conventional and alternative technologies from primary energy to powertrains (adapted from Arthur D. Little, 2002, Ahman, 2003)

We now make a brief review of the main streams of car radical innovation from the primary energy sources to the end-use vehicles. The components that are unique to alternative vehicles are related either to fuel conversion and energy storage or the powertrain. The crucial components are the electric powertrain, the fuel-cell system, and the battery, which vary according to the type of EDV. The electric powertrain consists of an electric motor, a generator, and power electronics for control. It applies to all EDVs. HEVs or FCEVs use smaller batteries – storage of 0.3-1.5kWh with a total power capacity of around 30kW – than BPEV that require higher energy storage and power capacity and, as such, larger batteries – storage of 30kWh with a total power capacity of 60-80kW (Arthur D. Little, 2002, Ahman, 2003, Ogden *et al.*, 2004). The components can be combined into vehicles according to the figure above. We discuss hereafter the main features of each of these technologies, including the main barriers to implementation.

Battery powered electric vehicle (BPEV). The barriers to the introduction of the BPEV are fivefold: low range (lower than 80 kilometers with currently available batteries), high battery weight, limited battery life, long recharging duration and high cost for it to be competitive on the market. New battery technology – lead acid, nickel metal hydride (NiMH), and lithium-ion (Li-ion) – could give the BPEV enough range (nearly 200 kilometers) with lower weight (less than 50kg), but the question remains whether batteries will reach the cost target of US$150/kWh (or 120€/kWh) and the recharging time of 3-6 hours (Chalk and Miller, 2006). Medium term cost assessments suggest that mass-production costs for NiMH and lithium batteries would be between 160-350 USD/kWh (or 130-300€/kWh) (Lipman *et al.*, 1999). Furthermore, a large-scale use of BPEVs would require a new electric infrastructure, appropriate home-charging appliances and public fast-charging stations. The cost of this infrastructure could be high although it corresponds to an upgrade of the existing electric network.

Hybrid electric vehicle (HEV). In many respects, hybrid-electric powertrains provide the better of two worlds. The electric motor produces its maximum torque at 0 rpm and therefore is particularly fit to moving vehicles from a stand-still. Complementarily, ICE produces its maximum torque at higher rpm and therefore is suited for stable transit flows. The technology for HEVs with advanced and energy-efficient ICEs is available on the market today. Examples are Toyota Prius and Honda Insight (costing approximately 30,000€). These models use parallel-hybrid systems which are better suited for electric-motor use in urban 'stop-and-go' driving cycles and for IC engine use out of town in more stable operation and higher rpm. Alternatively, series-hybrid systems can be used and these are composed by a smaller ICE that charges the electric motor and stores energy in the batteries, avoiding large and heavier battery packs. This is a more promising technology as it yields very real benefits in fuel consumption and emissions while retaining the existing fuel supply infrastructure (Nieuwenhuis and Wells, 2003). Today's HEVs use gasoline, but can easily use methanol or ethanol and perhaps hydrogen also. More advanced series-hybrids are being developed. One example is the Human Oriented Sustainable Transport (HOST, http://ltces.dem.ist.utl.pt/host, access in 11th of October 2008). It is a hybrid-series multi-platform vehicle being developed by a consortium involving three universities and Research Centers (CRIPS from the University "La Sapienza", KTH Royal Institute of Stockholm and Instituto Superior Técnico from Lisbon) and several industry partners (e.g., Volvo). Propulsion is supplied at the wheels by four independent electrical motors placed inside each wheel, allowing it to be a truly 'all-wheel-drive' vehicle. These electrical motors receive their energy from batteries and supercapacitors (for acceleration peak power). In order to create a truly 24h usable vehicle, a hybrid-electric architecture with a series configuration is fuelled by an 800cm^3 diesel engine.

Fuel cell electric vehicle (FCEV). A fuel cell uses an electrolytic reaction in reverse by using oxygen (from air) to split hydrogen molecules (that are fuelled into the vehicle) into protons and electrons to produce an electric current and by-products, i.e. water and some heat (operating temperature is between 60 to 100ºC). Typically, fuel cell uses platinum group metal or alloy to catalyze this reaction. This technology appears in a number of different types, but the chosen standard for transport applications is the Proton Exchange Membrane Fuel Cell – PEMFC (Nieuwenhuis and Wells, 2003). The two most important challenges for fuel cells are cost, durability and hydrogen production and distribution. The cost for automotive ICE is about 30€/kW. Current fuel cell systems are estimated to be some five times higher in cost. There are estimate for high-volume manufacturing and learning through mass-production and economies of scale can reduce costs. Still, this would double the cost of today's ICE technology (Arthur D. Little, 2002, Ogden *et al.*, 2004). Major contributors to high costs are the electrocatalyst, the membrane and the bipolar plates. Regarding durability, the performance of current systems decreases substantially after about 1000 hours of operation, which is less than 15% of current ICE standard service time (Chalk and Miller, 2006). This is a major challenge to overcome. With respect to production and distribution of hydrogen, there are many possible solutions as illustrated in the previous figure. However, current 'well-to-tank' lifecycle analyses suggest that the most carbon efficient solution are to reform hydrogen from ethanol produced from corn (biofuels in Figure 20), from reformulated gasoline or methanol from natural gas, i.e. the fossil fuels referred in the figure (Arthur D. Little, 2002, MacLean and Lave, 2003, Ogden *et al.*, 2004).

Finally, as the distribution system for hydrogen is only at the pilot-scale, technological development, transportation and distribution costs for hydrogen (including compression and storage) are far higher than those for conventional fuels (Arthur D. Little, 2002).

We note that 'vehicle-to-grid' technologies in cars – term coined by Kempton and Letendre (1997), aka 'V2G' – might reduce operation costs of EDVs by adding new features to the typical car functions. Noticeably, cars are idle assets for 90-95% of their service time (i.e., the useful service time is 1-3 hours/day, in average). EDVs (and more particularly, BPEVs with their large batteries) could potentially play a major role as complementary and decentralized energy storages to the electricity grid and used mainly for load management, e.g., regulation services and backup for peak time energy demand (Kempton and Tomić, 2005a, Moura, 2006). Turton and Moura (2008) modeled the possible diffusion of V2G technologies over the longer term and results indicate that V2G systems may have the potential to transform both energy and transport systems in profound ways, by promoting the deployment of alternative vehicle technologies; reducing inefficient investment in conventional electricity generation (such as coal power plants); and supporting the installation of renewable electricity sources (by representing a potential additional and decentralized storage for intermittent energy producers). Again, this technology would require important reforming of the current electricity grid, namely installation of electrical plugs in parking sites and electrical service upgrades to the residential or commercial building site (a higher capacity distribution board and possibly larger – higher capacity – line to the power pole) (Kempton and Tomić, 2005b).

Apart from EDVs, the 'Air Car' might be a promising option also (http://www.theaircar.com). Patented by Guy Nègre, the 'Air Car' can be powered solely by compressed air, or combined (as in HEVs) with gasoline/diesel/ethanol or electric motor and regenerative braking. Initially, the engine works like a normal ICE in that it draws air in. It then mimics a diesel engine by compressing this air. Where it departs from this conventional logic, is that in the next phase air is injected from compressed air tanks stored on board. The small injection of air is enough to move the piston downwards for the power stroke. Compressed air is economically competitive compared to conventional fuels. 'Air cars' could be sold at around 10,000€ (possibly, starting in 2009). The production and distribution infrastructures of compressed air are prevalent.

Finally, the Hypercar from Amory Lovins' Rocky Mountain Institute (Lovins and Cramer, 2004) aims to include radical innovations of the automotive industry, synergistically, by starting the new concept car's design from a clean sheet. Hypercar vehicles are ultralight (using advanced-composites-intensive body structure), ultra-low-drag, hybrid-electric vehicles (optionally based on fuel cells) with highly integrated, simplified, software-rich design (enabling electronic vehicle dynamics control). The *Revolution* fuel-cell concept vehicle was developed by Hypercar, Inc.[15] in 2000 to demonstrate the technical feasibility and societal, consumer, and

[15] Hypercar, Inc. is a spinoff company generated from the Rocky Mountain Institute to commercialize Hypercar concept enabling technologies.

competitive benefits of holistic vehicle design focused on efficiency and light weighting. It was designed to have breakthrough fivefold increase in fuel economy or reduction of emissions (see Figure 21).

Figure 21. Revolution concept car photo (Lovins and Cramer, 2004)

With respect to the 'Air Car' and the 'Hypercar', they both are concept cars that have attracted venture capital investments that are typically provided to less mature companies, for the launch, early development, or expansion of a business. Both concept cars have yet to prove their commercial viability.

We reviewed these really new technologies to differentiate incremental from radical technological developments. As we mentioned, the concept we explored here includes incremental improvements, although it is not impossible to transplant radical innovations into older vehicles. For example, we collected many websites addressing private initiatives of electric conversion of conventional ICE cars:

- (http://www.electric-car-conversions.info, http://www.electriccarsociety.com/ and http://www.evconversions.ca/ (accessed in 11th of October 2008) presents guidelines for ICE vehicle's electric conversion; and
- http://www.canev.com/ and http://www.electroauto.com/ (accessed in 11th of October 2008) are companies that provide conversion kits for specific and more popular models.

The availability of future technologies (whether incremental or radical innovations) potentially influences the path towards a more sustainable transport system. However, their emergence is influenced by decisions made today that determine the path dependency of technological development (as mentioned before). In addition, it is the existing techno-economic system that determines the timing of emergence and large-scale deployment of those technologies, also influenced by the political, economic and social context. As pointed by Grübler (1998) and Freeman and Louçã (2002), the transition between techno-economic cycles has demonstrated to occur with significant political and social turbulence and the assimilation of a major new technology into the social system gave (historically) rise to tensions and structural crises of adjustment, both at national and international levels (e.g., the Great Depression of the 1930s while the automotive industry was booming).

Technology roadmapping is a technique that is used within industry to support strategic and long-range planning and therefore serves the purposes for technology development and deployment. We now briefly review the concept and some examples from the automotive industry.

2.6.3 Technological roadmaps in the automotive industry

While traditional roadmaps are used to navigate and to reach a spatial target (destination), technology roadmapping defines a trajectory of technological development through time to meeting certain performance objectives within a fixed timeframe. Garcia *et al.* (1997) defined technological roadmapping for a given set of needs (that have to be adequately identified beforehand) as:

- A way to develop, to organize, and to present information about the critical system requirements and performance targets that must be satisfied by certain time frames.
- It also identifies technologies that need to be developed to meet those targets.
- Finally, it provides the information needed to make trade-offs among different technology alternatives.

Accordingly, the process of roadmapping generates roadmaps and these can take various forms, ranging from 'technology-push' strategies – i.e., based on the capabilities of the new technology and looking for implementation opportunities – to 'market-pull' oriented – i.e., aiming for customer defined product (Phaal *et al.*, 2004). A generic roadmap looks like a time-based chart, comprising a number of layers that typically include both commercial and technological perspectives. More comprehensive approaches do include additional layers of information such as was done in the Foresight Vehicle program by the British Society of Motor Manufacturers and Traders (SMMT, 2002, 2004). In this case, sub-maps for societal, technological, environmental economic, political and infrastructural themes were also included. In a general sense, roadmaps enable the evolution of markets, products and technologies to be explored, together with the linkages and discontinuities between the various perspectives.

Kappel (2001) reviewed a number of roadmaps in use by a range of US companies and concluded that "despite the long-term view promised by roadmapping, roadmaps in practice typically gave serious consideration to next product generation (beyond the one currently under development)". As put by Nieuwenhuis and Wells (2003), "they tend to be driven by what we have today, rather than by what we want tomorrow".

We present hereafter three examples of technology roadmaps for the automotive industry that go beyond considering just incremental technologies ('what we have in the near term') by including more radical innovation ('what we can have in the middle and long terms'). Firstly, we refer the Foresight Vehicle roadmap for the British automotive industry; then, we present some insight to the FURORE technology research roadmap for the European automotive industry (issued by the European Automotive Research Partners Association – EARPA); and, finally, we describe with more detail the sustainable automotive roadmap to 2050 proposed by the Centre for Automotive Industry Research (CAIR) from the Cardiff University (http://www.cardiff.ac.uk/carbs/research/centres_units/cair.html).

Foresight Vehicle (SMMT, 2002, 2004). Foresight Vehicle (FV) tries to assess the shape and nature of automobility around 2010-2030 by incorporating some important challenges that the British society will face with respect to environment, safety and security, but also those exclusive to the automotive industry that related with consumer choice, mobility needs and the economic context. Thereafter, the roadmap identifies the types of technologies needed to bring that vision about. Its primary tasks is to make sure the UK automotive supply, Research and Development (R&D) – including the key UK contract R&D sector – and assembly base are prepared and competitive for that future automotive industry. In order to achieve these strategic targets, the roadmap sets a number of targets that need to be met and also incorporates some future visions starting from 2020 and beyond. In addition, it offers individual sub-maps for **S**ocietal, **T**echnological, **E**nvironmental, **E**conomic, **P**olitical and **I**nfrastructural themes (they called it the STEEPI approach, from the initials of these headings). Within each sub-map, there are three streams for "Market/Industry trends and drivers", "Uncertainties" and "Performance measures/targets" that serve as indicators for monitoring the overall development suggested by the roadmap. Figure 22 shows the performance measures and targets regarding the technological improvements required to reach the future road transport system. Figure 23 shows the details regarding the 'speed to market and costs' improvements for future engines and powertrains. Similar details exist for all other aspects of the engines and powertrains, but also for the other technological items.

For example, the roadmap highlights that technology to reduce design and development time of engines and powertrains, and improve the manufacturing process, have a significant role to play in reducing time to market and costs, therefore improving competitiveness. In this sense, advanced computation techniques are required which will aid virtual engineering, in areas such as modular design, combustion emissions and calibration.

		0-5 years	5-10 years	10-20 years	Issues
Technology	Engine and powertrain	Improve thermal and mechanical efficiency, performance and drivability, reliability, durability and **speed to market/cost**, and to reduce emissions, weight and size.			Improved efficiency and emissions reduction.
	Hybrid, electric and alternatively fuelled vehicles	Develop viable alternative energy and power systems, including evolution of conventional engine systems and new alternative solutions, including consideration of infrastructure and fuel.			Alternative fuel availability. Capacity to generate 'biofuels'.
	Advanced software, sensors, electronics and telematics	Improve vehicle performance in terms of control, safety, adaptability, functionality, reliability, intelligence, driver support and integration.			Infrastructure and vehicle system developments linked. Reduction of accidents is key.
	Advanced structures and materials	Improve safety, product configurability, flexibility and value, and to reduce costs and environmental burden of vehicle, in terms of weight, durability, re-use and recycling.			Priority to achieve simultaneous emissions, economy and safety. Re-use/recycling a constraint on development
	Design and manufacturing processes	Improve the performance of the automotive industry sector, considering the full lifecycle from design to end-of-life, including manufacturing and business processes and systems integration.			Flexible manufacturing capable of servicing different industrial sectors. Simulation of reliability and durability.

Figure 22. Performance Measures and targets for the 'technological' theme (SMMT, 2004)

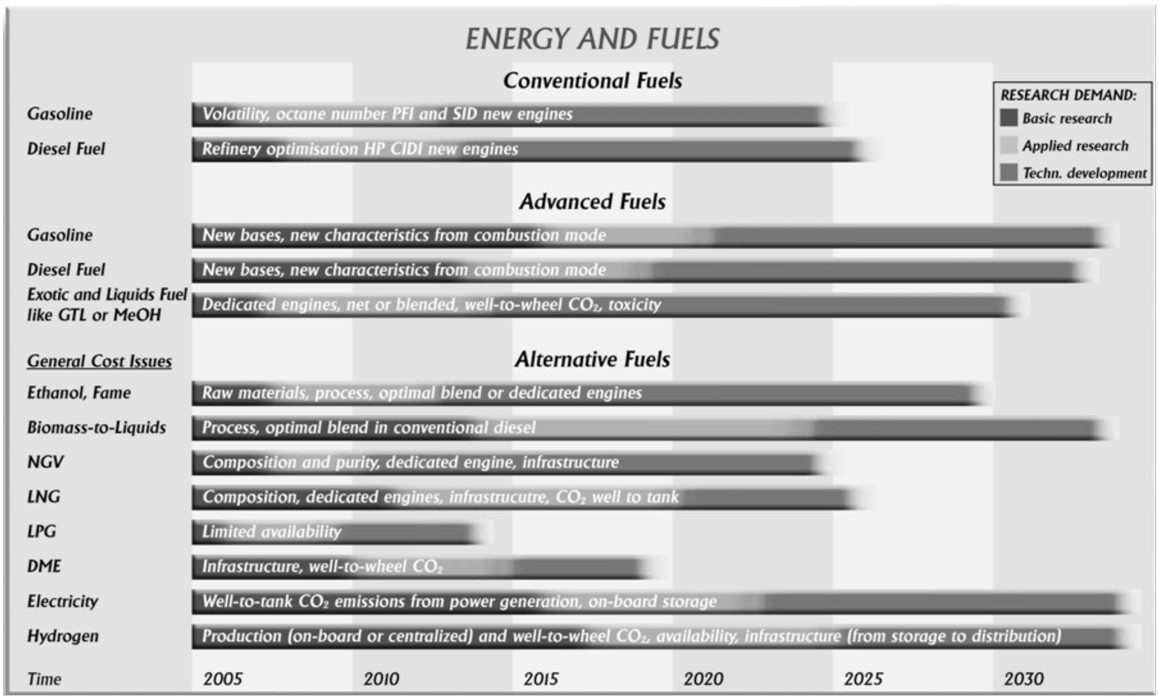
Engines and powertrains	0-5 years	5-10 years	10-20 years
Speed to market/cost	Knowledge capture and management systems	- Automated drivability calibration - Modular engines and transmissions - Advanced transmissions allowing wider application of engine types - Virtual emissions engineering and calibration - Increasing use of plastics/composites in transmissions	

Figure 23. Improvements required in the 'speed to market and costs' of engines and powertrains (SMMT, 2004)

FURORE (EARPA, 2004, http://www.furore-network.com, access in 16/10/2008). The overall objective of the FURORE Thematic Network is to establish a platform for the creation of an Automotive R&D Technology Roadmap describing breakthrough technologies for the next generation of vehicles for the year 2020 and beyond. The network is focusing predominantly on technologies for road vehicles powered by ICE, but also analyses the potential of breakthrough technologies in comparison with alternative fuels and systems such as hybrids and fuel cells. Focused on RTD organizations and Universities, the FURORE Network forms a hub linking the significant and growing number of Community, national and industry funded Networks concerned with future vehicle technologies.

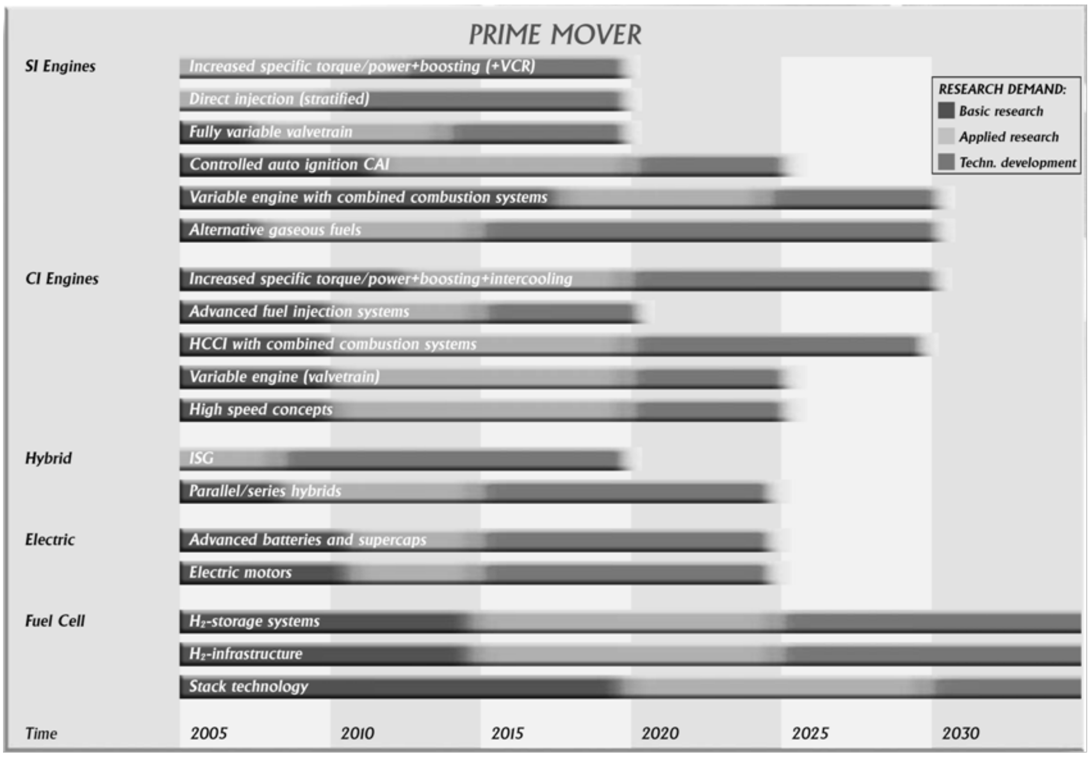
The roadmap defined here starts with the characterization of what could be the vision of the automobility by 2020 and beyond, based on the foreseeable social and political requirements (pretty much what was done with the FV British program). Thereafter, they define their view on future European traffic, energy and environmental scenarios resulting from the assumptions related to the vision defined previously. Both the vision and views of future scenarios generate performance targets to be achieved, for example, vehicle performance in terms of fuel economy and emissions. Finally, the technological developments required to achieving performance objectives with respect to energy, fuels and powertrains are outlined and the technological breakthroughs are identified. The latter correspond to radical innovations necessary to meet more stringent performance targets.

The following figures present the FURORE's roadmaps for energy and fuels (Figure 24) and powertrain (Figure 25) technologies from 2005 to 2030 and illustrate the research required to pursue the technological development endeavors. The bar charts of these figures show the most important key technologies for each area. The bars explain the time which is necessary for basic research (black), for applied research (light grey) and for final technical development resulting in market launch (dark grey). As the definite date cannot be predicted exactly, the transition of colors between these categories is smooth.



Note: 'GTL' refers to Gas-to-liquid fuels generated by Fisher-Tropsh chemical reactions; MeOH refers to methanol fuel.

Figure 24. Roadmap of energy and fuels technologies (EARPA, 2004)



Note: 'VCR' refers to 'Variable compression ratio'; 'SI' refers to 'Spark Ignition'; 'CI' refers to 'Compression Ignition'; 'HCCI' refers to 'Homogeneous charge compression ignition'; 'ISG' refers to 'Integrated Starter Generation' system.

Figure 25. FURORE's roadmap of powertrain technologies (EARPA, 2004)

CAIR program (Nieuwenhuis and Wells, 2003). The Centre for Automotive Industry research (CAIR) have outlined a vision of a sustainable automotive world (see Table 3, p.54). Rather than planning forward from the present as the visions sustaining the roadmaps presented before, they used their vision of a sustainable mobility paradigm to work back from, i.e. back casting process. This vision is to be achieved by 2050 and therefore several milestones and corresponding intermediate targets were defined. In this sense, technology development deadlines were identified such timeframes to preparing the enabling legislation, fiscal changes, social changes, planning changes, organizational changes, and so on. Likewise the FV program, a monitoring and auditing tool is set out with intermediate targets for tracking progress towards the desired goals. The ultimate goals that embody CAIR's vision for a sustainable mobility and respective technological, social and political combined changes can be summarized in the following diagram.

Ultimate goals		Technological, social and political combined changes
• Perfect urban air quality • Near zero fatalities on road • Near zero congestion • Zero consumption of non-renewable resources • A genuine democratic structure with localised decision-making • Rebuilt communities	⇔	• Intensive use of human powere in the form of bicycles and advanced HPVs • Use of benign, zero emission, public transport modes • Banning motorised personal transport from urban areas • Requirement of all transport modes to be ZEVs • Greater use of teleworking • More localised service provision • Other travel need reduction measures

Figure 26. CAIR's roadmap ultimate goals and required technological, social and political combined changes (adapted from Nieuwenhuis and Wells, 2003)

The road from the point where we stand today until CAIR's vision is materialized requires radical changes in all layers that symbolically constitute the transport system in Figure 5 (p.17). Fortunately, the technological layer does not need to be invented from scratch as there are already a number of trends visible within the automotive industry (as we overviewed in previous sections) that point in the direction they suggest. The problem lies on the pace by which such innovations occur and respective diffusion. Moreover, the software and orgware of the transport system must also adapt to those innovations or, to a large extent, induce greater changes in the technological side. The authors suggest a set of trends that must be reinforced:

- Ever-tightening emission targets,
- More ambitious CO_2 reduction agreements between the governments and car makers,
- Moves toward weight reduction,
- Technology trends making lower volumes more viable,
- Market introduction and take-ups of HEVs,
- Experimental introduction of FCEVs,
- High level of investment in FCEV technology by major players, and
- Impending safety standards (namely, for pedestrian impact safety).

It is clear, at the moment, that the necessary changes for the transport system to reach its desired standards of sustainability involve neither just technological measures nor just managing transport demand, but also a whole range of harmonized changes that include social, political, organizational, legal and regulatory aspects. Once an endeavor involves such a wide array of agents, stakeholders, organizations and institutions, technology roadmapping (or similar tool) emerges as a very adequate tool to bringing all the pieces together in one single set of possible shared trajectories, although it has never been attempted on such an ambitious scale (Nieuwenhuis and Wells, 2003). Adapting roadmapping to such a comprehensive approach in order to reaching sustainable mobility requires multinational companies, institutional and, possibly, multi-governmental additional involvement. In this sense, roadmapping would surpass by a long way its conventional range of action, which has been blueprinted by technology industries (Phaal *et al.*, 2004).

Car organ transplant fits into the roadmaps presented before due to its close relation with important concepts presented in the section: lifetime 'refitting' capability of vehicles, modularity in design, design for the environment, dematerialization of the automotive industry, etc. In Chapter 3, we discuss this issue in greater detail.

2.7. Summary and conclusions

We reviewed the transport environmental problems that could possibly be fixed through technology while identifying the main challenges that remain unsolved in the longer term. We highlighted some ways out of the current transport unsustainable path, both through technology and transport demand management, in order to decoupling mobility growth from economic development. We listed the technological changes that are likely to emerge in the automotive industry – both incremental and radical technological developments – that may help to solve or minimize those energy and environmental challenges. However, we recognize that the transport system has a big inertia and that it is resistant to the fast diffusion of new technologies. This downside of the transport system is currently hindering the full-potential of best available technologies to reduce the system's consumption of energy and materials and minimize the generation of emissions and waste.

Ultimately, the main issue is how to accelerate the pace of technology diffusion. As referred before, this dissertation explores the hypothesis that car organ transplant can potentially increase the overall energy and environmental performance of the transport system and more particularly of automobility, by accelerating the diffusion of best available technologies in existing car fleets.

After reviewing the relevant background principles of industrial ecology for the concept explored here, Chapter 3 presents our conception of car organ transplant. We also analyze some potential mechanical drawback that may arise and hinder the concept's broader applicability. Finally, we end this chapter by comparing this concept to similar practices currently undergoing in the automotive industry (e.g., retrofitting, car repowering, and so on) and other sectors.

Table 3. CAIR sustainable roadmap to 2050 (Nieuwenhuis and Wells, 2003)

Elements	Present (2003)	2003-2010	2011-2020	2021-2030	2031-2040	2041-2050	Vision
Market and social	Markets asking for increasing visible differentiation: environmental concern growing but not translated in buyer behavior	Growing cost of high CO_2 vehicles boosts demand for low CO_2 vehicles; urban congestion and pollution increasingly unacceptable	Developing countries also demand low CO_2 cars now popular in industrialized countries	Car use demand outstrips car ownership demand in established markets	Car park hits fundamental structural limits in established markets	Social prestige of car falls rapidly	Customers use motorized modes responsibly; demand for durable products dominates
Regulation and incentives	Tightening IC emissions; zero emissions vehicles (ZEVs) mandate in California; EU EOL directive.	**Bellagio Principles** adopted globally; EURO V, VI	Bellagio principles guide regulation; all cars ultra low emissions vehicles (ULEV); super ULEV; or ZEV	Bellagio principles implemented; all new cars SULEV or ZEV	ZEV applies to all new cars; LCA guides regulation	Materials become focus of regulation	EOVs or ZEVs for all new cars based on LCA
Product technology	Heavy inefficient ICE steel monocoque cars; some niche products non-Budd; some low CO_2 cars	Increasing use of HEVs; 1st FCEVs; CO_2 reduction leads to car weight reduction	Weight reduction trend continues; on board H_2 storage problem solved	Number of ZEVs produced exceeds ICEVs	All new cars are ZEV; durability up to 25 years; modular **refit** becomes priority	All new cars are Environmentally-optimized vehicles (EOVs); purpose-specific vehicles and/or modular design	Lightweight environmentally-optimized ZEVs; improved human-powered vehicles (HPVs)
Production technology	Large centralized factories sourcing and supplying globally; some non-Budd plants	Budd system adapted to lower volumes; composites and aluminum to higher volumes	Growing demand for lightweight cars leads to 1st volume non-budd car plants	Mass production of 'skateboard' structures starts	Rapid prototyping becomes viable production technology	Production-only factories become unviable	Microfactories deal with assembly, sales, service, upgrades, ELVs
Infrastructure	Gradual decline in road building; ICT seen as solution; petroleum-based fuels dominate supply system; cities clogged by motorized vehicles; some car bans	Widespread introduction of ICTs; road charging growing rapidly	More and more urban space reclaimed from cars; limited H_2 network appears	Reversal of spatially extensive society; start of decentralized economy	H_2 production 50% from renewable; car use controlled by active ICTs	H_2 production 100% from renewable	Only benign modes in urban areas to reduce congestion, pollution; supply of solar/wind power for ZEVs; comprehensive HPV/bike and light rail (LR) networks

Note: a) When the authors refer to 'refit' in the table above, in our dissertation we called it 'organ transplant'; b) The Bellagio principles were agreed upon by consensus by a group of regulators and experts to synthesize the best regulation regarding the automotive industry in the search for a more harmonized regulation throughout the world. If stringent regulation can be understood by some as 'protectionism', the Bellagio team has found that by harmonizing the standards upwards would generically reduce costs and increase benefits (Energy Foundation, 2002).

Chapter 3. Car organ transplant

Concepts that are relevant to our research are: sustainability since we seek to contribute for the development of the transport system towards sustainable mobility; technological diffusion because technology is central to the discussion of sustainable mobility and, also, because the concept proposed here might potentially accelerate the diffusion of cleaner technologies in car stocks; systems thinking as our methodological approach follows the lifecycle analysis of the automobile and its related systems (e.g., fuel's lifecycle, aka 'well-to-wheel'); and industrial ecology seeing that we embrace a concept that aims to potentially increase efficiency and reduce wastes throughout the vehicles lifecycle by changing the way it is designed, manufactured and serviced and, as such, involves concepts like product life extension, slower consumption and dematerialization.

In Chapter 2, we addressed both theories of sustainable mobility and technological diffusion. Now, we overview the theory of industrial ecology, while the concept of systems thinking and lifecycle analysis are discussed in Chapter 3 (Part B) where we perform and compare the lifecycle inventory of different scenarios of car ownership, including the alternative of car organ transplant. Besides explaining our conception of organ transplant, this chapter explores how the concept explored here is informed by industrial ecology and, as such, might constitute a contribution to a more sustainable transportation system and, in particular, to sustainable automobility.

3.1. Industrial ecology informs the concept

Industrial ecology is a biological metaphor presented by Frosch and Gallopolous from General Motors in the Scientific American journal (Frosch and Gallopoulos, 1989). By doing so, the authors contributed to the revival of the concept that had previous important contributions. The earlier attempts to defining similar concepts go back to the mid-19th century and are due to systems ecologists like Odum, Margalef and Hall (for a complete historical review, refer to the paper by Erkman, 1997). They had the intuition of the industrial system as a sub-system of the biosphere when studying biogeochemical cycles and, therefore, the first closest term was 'industrial ecosystem'.

Industrial ecology is intrinsically related to the theory of sustainable development and is one possible path that could provide real solutions to meet the sustainability requirements. In fact, it advocates that instead of just improving methods of waste treatment and disposal – the classical and outdated end-of-pipe approach – we look for the best opportunities to reduce waste throughout the total material cycle from virgin materials to finished products and to end-of-life products, transforming waste into usable by-products as much as technologically feasible. To do this, industrial ecologists first analyze how the industrial system works, how it is regulated, and identify all interactions with the biosphere. Then, on the basis of what we know about the natural ecosystems, they explore ways to restructure the industrial system to make it compatible with the way natural ecosystems function (Erkman, 1997). In a sense, it aims to convert the entities that have been major sources of environmental damage into agents for greater environmental well being.

Importantly, industrial ecology took on an institutional identity with the establishment of the Journal of Industrial Ecology (http://www.yale.edu/jie/), which is a peer-reviewed international quarterly owned by Yale University and published by MIT Press, as well as of the professional and scientific society, the International Society for Industrial Ecology.

Among many definitions available in the literature, Erkman (1997) found that all authors more or less agree on at least three key elements of the industrial ecology perspective:

1) "It is a systemic, comprehensive, integrated view of all the components of the industrial economy and their relationships.
2) It emphasizes the biophysical substratum of human activities, i.e. the complex patterns of material flows within and outside the industrial system, in contrast with the current approaches which mostly consider the economy in terms of abstract monetary units, or alternatively energy flows.
3) It considers technological dynamics, i.e. the long term evolution (technological trajectories) of clusters of key technologies as a crucial (but not exclusive) element for the transition from the actual unsustainable industrial system to a viable ecosystem".

While industrial ecology refers to the field of knowledge, industrial metabolism refers to the industrial process itself, by which a "whole integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes in a (more or less) steady-state condition" (Ayres, 1994), which in simple terms comes to saying that what goes in – materials (e.g., minerals, biomass, etc.) and energy (e.g., fossil fuels) – must come out, eventually – air emissions, waste, etc. The definition proposed by Robert Ayres refers exclusively to the physical understanding of the system. We would argue that technology (including hardware, software and orgware) contributes with important inputs to the system and decisively influences how labor is put into work to convert raw materials and energy into finished products and wastes, thus influencing the efficiency of the system.

Complementarily, Ayres and Simonis (1994) state that "*there are only two possible long-run fates for waste materials: recycling and re-use or dissipative loss*". The more materials are recycled, the less they will be dissipated into the environment, and vice versa. We would define dissipative losses as those irreversibly produced through the simple dispersion of energy and materials into neither recoverable nor usable by-products. For example, air emissions are dissipative losses that result from the conversion of fossil fuels into usable (mechanical) and non-usable (thermal – that is also a dissipative loss) forms of energy.

Figure 27 (below) illustrates the industrial metabolism by which material loops connect four boxes that, symbolically, represent the natural environment (Box 1) that provides raw materials and commodities (Box 2) for production purposes and that takes delivery of waste from every human-related activity. Productive capital (Box 3) involves a complex collection of interdependent technology systems (as alluded before in Chapter 2) to provide society with final products (Box 4) that are consumed. The consumption left-overs go back into the natural environment (Box 1) in all its states of matter, i.e. solid, liquid or gaseous. Looking more closely to Box 4, we note that final products have four outflow alternatives: (1) wasted back into the environment (as mentioned earlier); (2) reused without any reprocessing; (3) reused after reprocessing (e.g., remanufacturing, reconditioning, refitting, etc.); or (4) partly reused after some retrofitting or organ transplanting. The last alternative outflow differs from the previous in that the final product is partially renewed, whether retrofitted with few new components (e.g., substitution of the catalytic converter with a newer model) or transplanted with new major organs (e.g., new model of engine or transmission). We will discuss this in more detail in the next sections.

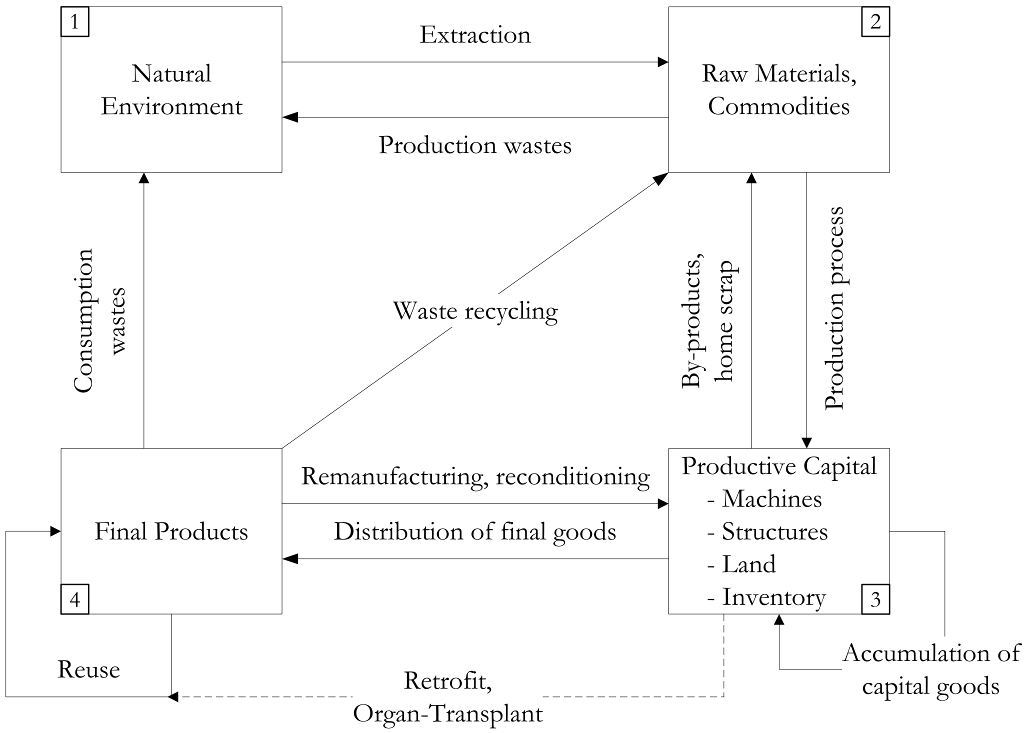


Figure 27. Four box scheme for industrial material cycles (adapted from Ayres, 1994)

We mentioned before that the industrial ecologist explores ways of restructuring the industrial system in order to close the loops of material flows as much as technologically feasible. In this sense, several, strategies and methodologies/tools are being developed in order to achieve this complex objective. We present now some examples that are not intended to be exhaustive (for a complete review on industrial ecology refer to the handbook edited by Ayres and Ayres, 2002):

- Eco-efficiency (strategy) was coined by the World Business Council for Sustainable Development (WBCSD) in its 1992 publication "Changing Course" (Schmidheiny, 1992) and refers to a management philosophy that encourages business to search for environmental improvements that yield parallel economic benefits not only by accounting for the input resources (materials, energy, water, land) but also by relating them to products, services or benefits produced. The procedures advocated here relate to “demanufacturing” or “remanufacturing” – that is recycling the materials in their products and thus limiting the use of raw materials and of energy to convert those materials.

- Dematerialization and Decarbonization (strategy). The first refers to the reduction in the quantity of materials flowing throughout the economy while the second addresses the reduction of carbon content of energy used to accomplish a task.
- Product life extension (strategy) is a design strategy by which the product’s useful life is extended and resources are saved and there is less waste generated, because fewer units are needed to satisfy the same needs (Keoleian and Menerey, 1993).
- Extended producer responsibility (which include systems such as ‘product take-back’ or ‘product stewardship’) (strategy) is a strategy designed to promote the integration of environmental costs associated with products throughout their lifecycles into the market price of the products. This means that firms that manufacture, import and/or sell products and packaging, are required to be financially or physically responsible for such products after their useful life (OECD, 1996b).
- Analysis of material and energy flows (methodology/tool) in industrial and consumer activities. By doing so, we are able to identify how the economic, regulatory and social factors might influence the use and transformation of resources, including the effects of these flows on the environment.
- Life cycle analysis (methodology/tool) is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, the corresponding environmental impacts, including the entire life cycle, i.e., extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal (Consoli *et al.*, 1993). Refer to Chapter 4 where we review this methodology in detail.
- Design for the environment (DfE or ecodesign) (tool) refers to a variety of design approaches that attempt to reduce the overall environmental impact of a product, process or service, where environmental impacts are considered across its lifecycle, starting as soon as these are being conceived. It should be noted that DfE features in a product can only facilitate – and not ensure – recycling. Other complementary solutions must address the final disposal stage of products. Eco-industrial parks are one example.
- Eco-industrial park (”industrial symbiosis”) (tool) is a community of manufacturing and service businesses located together on a common property. Members seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues. For example, wastes from one unit can be transformed into by-products that are used as inputs in another unit of the ‘eco-park’. This is one management approach to closing the loops of industrial metabolism.

The concept of car organ transplant explored here could be included in this list (it is represented by the dashed arrows in Figure 27). Together with retrofitting, remanufacturing, refitting, reconditioning, recycling and reusing (not to mention all), it can potentially refrain the voracious automotive industrial metabolism. By adopting such practices, the service time of cars is potentially extended (unless abrupt interruption occurs, e.g., car crash). Consequently, virgin materials are saved (or at the least, their extraction is delayed) and waste materials are minimized (including dissipative pollution). We will explain why this concept is informed by industrial ecology after we present the concept (car organ transplant) in greater detail in the next section.

3.2. Car organ transplant

As addressed in Chapter 2, every technology that is part, component or artifact of a system follows a lifecycle that begins with its introduction and diffusion stages. Maturation follows and it ends in some type of unavailability or senescence. It is then replaced by a new, updated and (desirably) more performing and cleaner technology. Replacement of older by newer technologies, i.e. decreasing and increasing market shares, respectively, occurs during periods of coexistence that ensure a smooth transition between technologies and also prevent stock disruption of parts and components needed to maintain the functionality of older technologies while the new ones pervade.

Car owners do not control the supply of the critical components of their vehicle (e.g., ICE or transmission). In effect, they do not have the ability to influence the technological content of the car during its service time and, as such, they can use technological improvements by the automotive industry only when new car models reach the retail market. The conventional procedure is: the car owner sells or scraps the used car and buys a new one and accepts the new supply of the technological components that it comprises, given that these 'go with the package'.

Importantly, the significant improvements in the quality of cars, over the past decades, lead to greater reliability and longevity as key mechanical components and bodywork last longer. In view of that, car makers typically warrant spare parts production over 10 years or so (which can go up to 30 years for critical spare parts), after serial production is ended and technological obsolescence of cars becomes a potential problem for car owners (Maxton and Wormald, 2004). As a matter of fact, car parts and components are interchangeable within each car generation but not necessarily between model years, i.e. inter-generational compatibility is not ensured by car makers, while intra-generational compatibility is naturally planned when designing cars.

In a word, cars remain technologically unchanged throughout their service life since upgrades are not commercially available (unless they opt for car tuning – also known as car customizing– or some other kind of home-based or at least small scale car transformation), while lifetime tends to be extended as a consequence of technological improvements. As we referred in the previous chapter, the diffusion of new technologies can take up to 40 years before they fully displace older technologies. In face of the energy and environmental challenges that force the development of more efficient and cleaner equipments, there are apparently two opposing trajectories: while cars last longer, the urge for the diffusion of new technologies implies faster technological turnover of fleets that, in turn, might generate increased consumption of raw materials and lead to more solid waste, if turnover depends on the existing 'scrap and buy new' paradigm.

Alternatively, we propose a system by which cars could be partially upgraded through the transplant of new technologies in order for the system functionality to become more energy efficient and cleaner without having to displace the full car. We now present our conception of car organ transplant.

3.2.1 The concept

Vehicles are comprised of many individual components (i.e., specialized or general elemental constituents of a vehicle – e.g., ABS wheel speed sensor or valves, respectively), aggregated in parts or modules (i.e., assembly of general and specialized components concentrated in one location of the vehicle – e.g. seats) and systems (i.e., groups of components that are linked by function and therefore can be located in several parts of the vehicle – e.g. safety systems) (Rupf and Grief, 2002, Nieuwenhuis and Wells, 2003).

Organ transplant in cars corresponds to replacing parts, modules and systems of the powertrain (including depollution equipment) and other energy intensive ancillary equipments (e.g., air conditioning) of the car that are technologically outdated, downgraded or malfunctioning while keeping the remaining components and parts that are state-of-the-art and fully operative, in order to improve its energy and environmental efficiency and possibly reach 'like new' performance standards, over its service life.

Putting it simply, replace only what has to be replaced with best available and more performing technologies and keep the remainder running while no (much) better options arise. The only changes advocated here point towards better efficiency of the car as a whole and do not include, for example, horsepower improvement (like practiced in car tuning) that would result in increased fuel consumption and emissions factors. Structural changes to the body or chassis are not assessed (for example, substituting some body parts with lighter materials) although they are expected to contribute decisively to improved fuel efficiency of cars (refer to technological roadmaps mentioned in the previous section). We use organ as a generic term for those components, parts and systems that compose the overall transplanting kit (refer to next section).

Car organ transplant has been explicitly or implicitly mentioned by other sources. For instance, the Foresight Vehicle (FV) Program (SMMT, 2004) refers that "*vehicle longevity precludes the economic rapid take-up of new technologies which will have significant impact on emissions and safety. Retrofit capability of technology is a challenge as an intermediate step before introducing more radical solutions*". The same report also mentions that "*technologies aiming to increasing service life, whilst enabling the upgrading of emissions and safety systems, will be needed*". The SMMT recognizes the argument that current diffusion of innovation and the corresponding technological turnover rates hinder the potential benefits from new technologies and advocates a transition period during which vehicles should integrate new technologies (the incremental type) before the really new innovations take-up market shares. Complementing this idea, Nieuwenhuis and Wells (2003) suggest that "*the latest powertrain items and other new technologies could be fitted at various points during the car's life*". They add that extending the lifetime of products is the expectable trend in view of the extension of the lifetime of car parts performed by the automotive industry and in face of more stringent environmental regulations that will arise. Complementarily, Graedel and Allenby (1997) suggested that "*in the future, it is likely that engines, transmissions, suspension systems, electronics, body components, and other parts will be designed so that they can be removed and replaced as easily as can today's portable radio batteries*". They continue saying that increased modularity in car design and manufacturing "*will allow for both technological advances – with concomitant increases in economic and environmental efficiency – and product life extension, thereby reducing the velocity of materials flow through the automotive sector*".

In a general sense, all sources mentioned above argue that partial technological upgrading of cars would be an advantage in the future. Moreover, achieving such task requires a different, more modular, approach to building cars than the current mainstream and the automotive industry should make part of such a change of car making paradigm. We will discuss this issue later in this chapter.

In order to investigate the expression used here, i.e. 'organ transplant', we quote Merriam-Webster dictionary's definition of *transplanting* (Merriam-Webster Online Dictionary, 2006):

"1: to extract and reset in another situation;

2: to remove from one place or context and settle or introduce elsewhere;

3: to transfer (an organ or tissue) from one part or individual to another"

We would argue that our conception of technological organ transplant corresponds to the third definition proposed here that suggests the analogy between medical care and car care. Additionally, we quote Britannica Online Encyclopedia's definition (2008):

"Transplant in medicine corresponds to removing a section of tissue or a complete organ from its original natural site and transferring it to a new position in the same person or in a separate individual. Originally, the term was borrowed by surgeons from horticulture. Both approaches imply that success will result in a healthy and flourishing transplant, which will gain its nourishment from its new environment."

Pursuing Britannica's explanation, there are four different types of medical transplants:

- Autotransplant is made from one part of the body and transplanted to another site in the same individual (e.g., skin tissue from leg to arm);
- Isotransplants are made between identical twins or highly inbred animals (e.g., kidney from one twin to the other);
- Allotransplant (or homotransplant) comes from a donor to a recipient of the same species (e.g., heart from human to human).
- Xenotransplant (or heterotransplant) is performed between individuals of different species (e.g., cardiac valves from pig to human) or inert manufactured transplants can also replace human organs.

According to the medical description, autotransplants and isotransplants cannot be rejected by the recipient while allotransplants are usually rejected unless special efforts are made to prevent this. Finally, xenotransplants are usually destroyed very quickly by the recipient. The following table presents our understanding of correspondence between the medical transplants types and technological development stages potentially involved in car servicing, including car organ transplant.

Table 4. Correspondence between car servicing and medical transplant types

Type of transplant	Level of rejection	Type of technological development	Comments	Example
Autotransplant	Cannot be rejected	No correspondence	No correspondence	No correspondence
Isotransplant	Cannot be rejected	Spare parts	No technological development occurs and therefore isotransplant would correspond to conventional servicing or repair by which spare parts are easily interchangeable.	Replacements of ICE with original ICE.
Allotransplant	Usually rejected special efforts are made to prevent this	Incremental innovation	In face of incremental innovation, some inter-generational incompatibility may arise, if not addressed properly. Some adaptation may be required.	Replacements of ICE with new model year ICE. For example, new mounts for engine fitting may be required to preventing the transplanted engine to stagger.
Xenotransplant	Total rejection and transplants are usually destroyed by the recipient	Radical innovation	With radical innovation, inter-generational incompatibility issues will most probably occur. Major transformations are required.	Replacement of ICE, fuel tank and electric/battery system with a full-electric propulsion system and battery-pack. Complete conversion is needed.

From our point of view, car organ transplant corresponds to allotransplant, if analyzed from the rejection standpoint, in that some adaptation might be required to fit the new technology in the older recipient and ensure its full functionality.

There are additional concepts that are complementary to car organ transplant, which correspond more adequately to the remaining medical transplant types. We note that these are not analyzed in this dissertation:

- <u>Renovation</u> consists in "restoring to a former better state (as by cleaning, repairing, or rebuilding)". Remanufacturing car parts and components (Smith and Keoleian, 2004) or repowering (Engine Repower Council, 2006) are also forms of renovation since the purpose is to bring the technology to its original state.

- Retrofitting consists in "installing new or modified parts or equipment in something previously manufactured or constructed".
- Conversion can be defined as "altering the physical or chemical nature or properties of some object or equipment for more effective utilization".

All definitions were taken from Merriam-Webster Online Dictionary (2006). Renovation is more related to isotransplant since, typically, it is rather close to conventional car repairing. Finally, conversion corresponds more to xenotransplant since it implies major and structural changes to accommodate radically new organ transplants and ensure full functionality of the recipient vehicle. Otherwise, the recipient would not function, i.e. it would be 'rejected'.

In a sense, retrofitting and car organ transplant could be considered identical and, if so, why would we suggest a new term? The main reason for differentiating organ transplant from retrofitting is that the latter is a term typically used for replacing smaller components of cars, namely, replacing older catalytic converter with newer models, and it usually involves minor adaptations (if any). To our understanding, retrofitting corresponds to minor organ transplant and would fit somewhere between isotransplant and allotransplant. Car organ transplant aims at substituting entire subsystems of the car (including depollution equipments) that could bring major improvements in its energy and environmental performance. Alternatively, we could call it 'extended retrofit'.

Another interesting related concept is car tuning (or car customizing). Car tuning can be defined as car modification aiming to personalize vehicle to better suit the owner's preferences, whether these refer to improving performance or styling. As defined by the European Tuning Organization[16] (ETO, 2008), the corresponding tuning equipment (also referred to as 'specialty equipment') refers to "everything added to a car after it leaves the assembly line that is designed to improve the performance, look or enhance the comfort of a vehicle". As advocated in the car tuning associations, environmental performance and energy efficiency of cars has been tuned up through the reprogramming or introducing new electronic control unit (ECU). They called it "Eco tuning" that, somehow, is equivalent to organ transplant in cars.

In practice, car organ transplant would involve new conceptions of car:

[16] The association represents an important industry with several thousand of employees and generating several billions Euro's of sales turnover throughout the continent. In a recent development, the ETO has been officially recognized as a European organization following its status for the past several years as an active working group. Germany has the largest European tuning industry and according to the German car tuners association (Verband Deutscher Automobiltuner – VDAT, http://www.vdat.org/, access in November 7th, 2008), which turnover sales are estimated to amount to 4.5 billion €, totaling approximately 1,000 companies. The American counterpart is the Specialty Equipment Market Association (SEMA) that, in 2000, represented a US$29 billion retail market of specialty equipment provided by 5,727 member manufacturers (SEMA, 2001), corresponding to nearly 15% of the American automotive aftermarket - US$211 billion, according to the Automotive Aftermarket Industry Association (http://www.aftermarket.org, access in November 7th, 2008).

- Design and manufacturing – with this respect, increased modularity in the automotive industry might become a requirement as mentioned above;
- Ownership – particularly, greater awareness and credit to the lifecycle total ownership costs that would include environmental damage costs, and
- Serviceability – in that car maker, suppliers and the aftermarket agents would have to offer commercially viable transplanting kits ensuring ease, duration of the process itself and cost-effectiveness of organ transplant (refer to section 3.2.2 for a full description of transplanting kits).

We referred in the previous section that car organ transplant is informed by industrial ecology principles. As a matter of fact, organ transplant is explored in this dissertation as a strategy of product life extension by which the service time of vehicles is prolonged while keeping the overall system technologically up-to-date at reduced energy and environmental lifecycle expenses. Recalling the definition presented above, this is done by replacing the outdated, downgraded or malfunctioning parts while keeping the remainder fully functional. Referring to Robert Ayres' diagram of industrial metabolism (Figure 27, p.57), car organ transplant can be defined as a physical process that jointly delays (1) the final disposal of materials back into the natural environment in the form of waste, and (2) the need for more raw materials and using the corresponding energy to convert them. As such, the car fleets will potentially be dematerialized and decarbonized since the service time of longer-lived products save resources and generate less waste and because fewer units are needed to satisfy the same system's automobility needs. While Part B of this dissertation addresses these issues by analyzing five different strategies of car ownership over 20 years through lifecycle analysis (LCA), Part C extends this analysis to an entire car fleet. Material and energy flows could also be analyzed with and without car organ transplant in place and quantify the corresponding impacts (this could be included in further research developments to the concept proposed here).

As suggested in the concept of extended producer responsibility (EPR), manufacturers must ensure high use of products and materials in the form of re-use and recycling and the effective collection and environmentally-sound treatment of the remainder products. Complementarily, EPR should bring the achievement of another complementary tool, i.e. design improvements of products (earlier, we called it 'Design for Environment' – DfE) as manufacturers would improve the material and energy flows surrounding the lifecycle of their products, in order to optimize the overall manufacturing system, close the loops of energy and material flows, make recycling an easier task to pursue and reduce the overall lifecycle product costs. With respect to design for recycling, Graedel and Allenby (1997) advocate seven streams of action: 1) minimize the use of materials; 2) minimize materials diversity (particularly in the case of plastics); 3) choose desirable materials (which we know that were recycled or are more prone to being recovered); 4) make the car modular; 5) eliminate unnecessary complexity; 6) make it efficient to disassemble; and 7) make the materials easy to recover.

For the reasons presented before, car organ transplant can also be an advantageous strategy for car makers and suppliers once the EPR is fully implemented and the corresponding tracking systems are in place. As the manufacturer incurs in additional cost at some stage in the future, it must be attractive to minimize this cost by increasing the car's life expectancy and postponing the point at which the end-of-live vehicle is disposed.

We note that the European directive for end-of-live vehicles - ELV (2000/53/EC, 18th of September 2000) builds on the same principles and much responsibility is returned to car producer both on the costs of ELV final disposal and on the design for preventing waste production or easing the reuse and recycling of parts and components. Another implication is that whilst primarily geared towards selling new cars the industry may have to work out a way of keeping the cars technologically updated in order to comply with the more demanding environmental regulation. As pointed out before, this can be done through increased modularity in the design and manufacturing of cars and extending the conventional approach of car servicing by including technological organ transplant in used cars.

Conceptually, we would consider four causes or major opportunities for car organ transplant that would not forcedly mean that the whole car should be substituted (adapted from Woodward, 1997):

1) *Physical life* – The period over which the parts and components may be expected to last physically or when replacement is physically required. For example, the typical physical life of an ICE is 300,000 km for a gasoline cars (or 500,000 km for diesel cars), and that of a transmission is 115,000 km.
2) *Technological life* – The period until technical obsolescence dictates replacement due to the development of a technologically superior alternative. We also include here the replacement due to unsatisfactory performance of the existing equipment that cannot be solved by conventional servicing. For example, components may not be adequately reliable or the car owner is not pleased with its performance, either due to design flaws, maintenance problems or legal constraints on the car use. For very old vehicles, there may also be problems regarding the availability of spare components and/or personnel with know-how on the old technology.
3) *Economic life* – The period until economic obsolescence dictates replacement with a lower cost alternative. This does not necessarily mean the equipment is unsafe or unfit, but it could have economic consequences by decreasing the vehicle's performance in terms of fuel consumption or maintenance needs in the short term or the corresponding replacement could bring benefits with reasonable payback periods.
4) *Social and legal life* – The period until human desire or legal requirement (regulatory change) dictates replacement. The first case applies to car owners that look for better performance or more modern aspect of vehicles (for example, car tuners looking for more powerful engine). In the second case, regulators may impose new safety and environmental requirements that involve standards that current vehicles do not comply with.

It is important to mention at this early stage that styling and aesthetics of more recent cars influence resolutely consumers' decision for which make, model and brand to choose. In this sense, the social life of the vehicle is to be understood in the perspective of 'fashionable live' of the car. This is corroborated by the review from Train (1986) by which the author compared compensatory discrete choice models of new and used cars and found that there was a surprising consistency among the models reviewed in that vehicle's vintage appears as a factor chiefly affecting consumers' decisions. Importantly, class/vintage variables presented statistically significant and positively signed parameters. Assuming that fashion is closely related to vintage (which is reasonable), this conclusion by Train has important implications in our research in the sense that car consumers would prefer more recent or new models, discarding transplanted cars. As discussed later in this dissertation (section 9.2), we assumed in our modeling exercise that consumers preferring new cars would not consider transplanted cars. Hence, we decided to model the discrete-choice of remarketed cars to evaluate the rate and extent of diffusion of transplanted technologies and, by doing so, we excluded the customers of new car. As a result, our modeling exercise is somewhat conservative with this respect.

All situations described here dictate replacement of equipment but not necessarily organ transplant (in that the replacing organ corresponds to a Best Available technologies – BAT), although the last two might become important determinants for car organ transplant in sensible areas. For example, increasing legal requirements concerning air quality in urban areas lead to the delimitation of environmental protection zones in urban areas in some countries (Feychting *et al.*, 2002, Browne *et al.*, 2005). This kind of restriction to car use combined with incentives to the use of cleaner technologies – for example, reserve capacity for cleaner models in suburban highways and sharing BUS or HOV (high-occupancy vehicle) lanes – and with increasing fuel prices, might drive car owners towards organ transplant, if the corresponding serviceability is attractive, i.e. short duration of transplant (possibly, few hours), cost effectiveness with reasonable payback periods and few (or no) procedural and legal hurdles.

3.2.2 Transplanting kit and some basic technical requirements for organ transplants

While car organ transplant is the concept explored in this dissertation, 'transplanting kit' corresponds to the artifact whose description and characteristics are presented in this section. These are the characteristics that are used for modeling purposes throughout the dissertation, namely for the models of lifecycle inventory and total ownership cost.

The following figure illustrates the composition of the transplanting kit by which components are classified according to the parts they belong to and we also refer their corresponding functional integration in the car. Parts are classified according to the subsystem they are related to. We used the classification proposed by Delucchi *et al.* (2000) and Maxton and Wormald (2004). We emphasize that this composition of the transplanting kit is not unique in that other configurations would naturally be acceptable, for example, including less parts and components for replacement. We opted for using a more complete set of components in order to ensure the likelihood of one chief assumption of our research (we will refer to it along the present dissertation) that is '<u>transplanted vehicles are considered to reach like-new energy consumption and emission factors</u>'. Accordingly, the selection of parts and components for the transplanting kit was based on the direct influence these might have on the energy and environmental efficiency of the car and, in short, they include the components of the powertrain, electronic command and control, climate control and exhaust systems (including after treatment devices).

We also included additional transplanting equipments and materials that would naturally be involved in conventional servicing. Finally, we note that all electronic sensors of the recipient vehicle should be replaced in order to ensure the full functionality of the new systems (for instance, the new engine and the corresponding ECU).

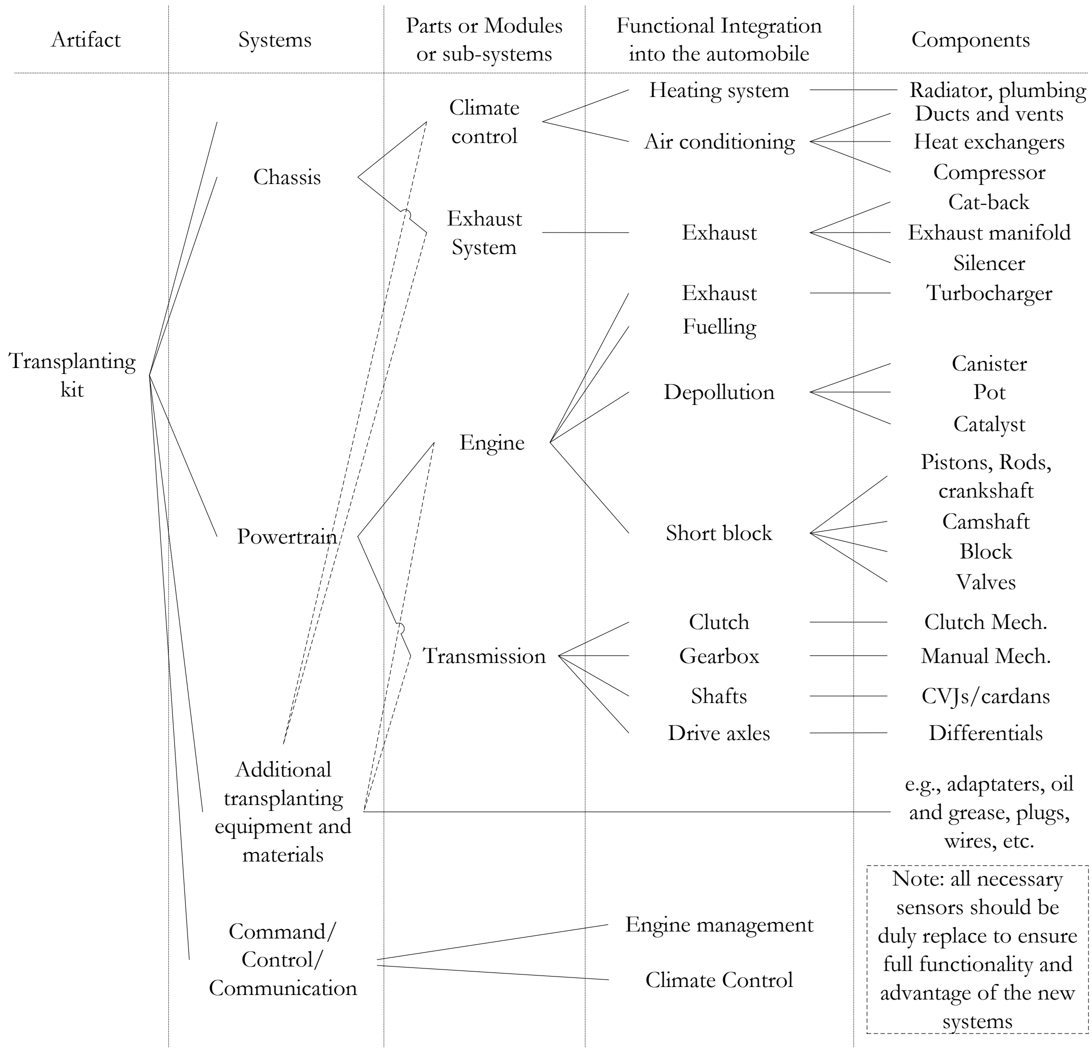


Figure 28. Parts and components of a transplanting kit (source: author based on the classification by Delucchi *et al.*, 2000, Maxton and Wormald, 2004)

We will now overview some basic technical requirements for car transplant that also lead to the final layout presented in the figure above (see Table 5). These were mainly identified based on Clarke's (1990) review of classical powertrain swaps in the US and on the author's tips and techniques for more successful endeavors, although there are many websites where detailed explanations are available for swap operations for a wide range of vehicle models (or more radical conversions, as we mentioned in the previous section – e.g., ICE to electric powertrain conversions). Although the technical requirements for powertrain swap vary depending on the extent of the technological dissimilarities between car models, the following short list of equipments (and ancillary parts) is not exhaustive but usually included.

Table 5. Parts and components required for a powertrain swap (source: author based on Clarke, 1990 and other internet sources)

Subsystem	Part	Component	Comment
Powertrain	New engine	All components attached to it (cylinder head, piston, rods and crankshaft, camshaft, fuel injector, alternator, distributor, air condition pump if necessary, among few remaining).	Most of the popular engines for cars are readily available in "long block" form, i.e., a fully assembled, brand-new engine with cylinder heads installed, directly from the automakers themselves, possibly making transplanting operations easier and quicker.
		Environmental control system	Swapping the old catalytic converter is important, otherwise the existing system might act as a 'cork' to the new powertrain (apart from not being the best available technology).
		Cooling system	The cooling system might also need an update for preventing the engine to overheat. This is probably unnecessary if the engines are equivalent in cylinder capacity and power.
		Fuel pump	For some more radical swaps, the existing fuel pump might not suffice to meet the needs of the new engine. At the very least, the pump of the new engine should be used.
	Adequate transmission	Clutch, gearbox, shafts, Shift Linkage, drive axles, etc.	The transmission must be adequate in that it must bolt up to the engine's block.
Chassis	Existing Platform	Mounts	Mounts that came with the new engine or custom mounts when the new engine is not directly compatible with the existing engine structure.
		Exhaust system (including the exhaust manifold, silencer, etc.)	
Command, control & communica-tion	New Engine Control Unit[17] (ECU)	Adequate sensors located in different parts of the car (sensors for mass airflow, oxygen, throttle position, coolant temperature, voltage, manifold absolute pressure, engine speed, etc.).	Before emissions laws were enacted, it was possible to build a car engine without microprocessors. With the enactment of increasingly stricter emissions laws, sophisticated control schemes were needed to regulate the air/fuel mixture so that the catalytic converter could remove a lot of the pollution from the exhaust. This might bring intergenerational compatibility issues if not all sensors are available in recipient vehicle or if these cannot be installed easily, quickly or at reasonable costs.

With respect to the details on the physical composition (i.e., materials and weight) and economical characterization of the transplanting kit considered in the present research, we refer the readers to sections 4.4.5 (p.134) and 5.3 (p.161), respectively. Transplanting kits are

[17] An Engine Control Unit (ECU), also known as Engine Management System (EMS) or Powertrain Control Module (PCM), is an electronic system, fundamentally a computer that controls the ICE by reading several sensors in the engine and exhaust system, and using the information to control its ignition systems. ECUs allow greater fuel efficiency, better power and responsiveness, and much lower pollution levels than earlier generations of engines (Bosch, 2004).

estimated to weigh approximately 330 kg (which varies depending on the car type) and are mainly composed by iron and steel (>70%) since, on a weight-basis, the more important parts are the engine and transmission. With respect to the production cost of transplanting kit, we estimated that these would reach approximately 5,000€ depending on the car type considered.

After presenting the concept of car organ transplant, the description of what we assumed a transplanting kit is and some technical requirements for organ transplant, we present a brief insight into the possible mechanical hurdles that may arise when performing such transplants. As mentioned earlier, it is not a primary objective of the present thesis to analyze this issue in detail.

3.2.3 The automotive industry: structure, main players and systems of production

The automotive industry has reached a mature stage after 100 years of technological, industrial, managerial and organizational developments. Maturity is evident by the slowing down of world car production. Figure 29 (below) illustrates this slow down (6% from 1950 until 1995 and 1% until the end of the 20th century). The early years of the 21st century show an uprise trend in car production but most is due to the Asia-Oceania countries that showed an 8% annual growth (where China's 30% growth is striking) compared to the stagnation of Europe's (2%) and America's (0%) production. This slowdown (compared to the first 100 years average growth) is naturally driven by economic cycles but also by industry consolidation and the nature of competition, where cost, speed, variants and the rush into the few growing regions and segments are prominent (Nieuwenhuis and Wells, 2003, Maxton and Wormald, 2004, Seidel *et al.*, 2005, Orsato and Wells, 2007).

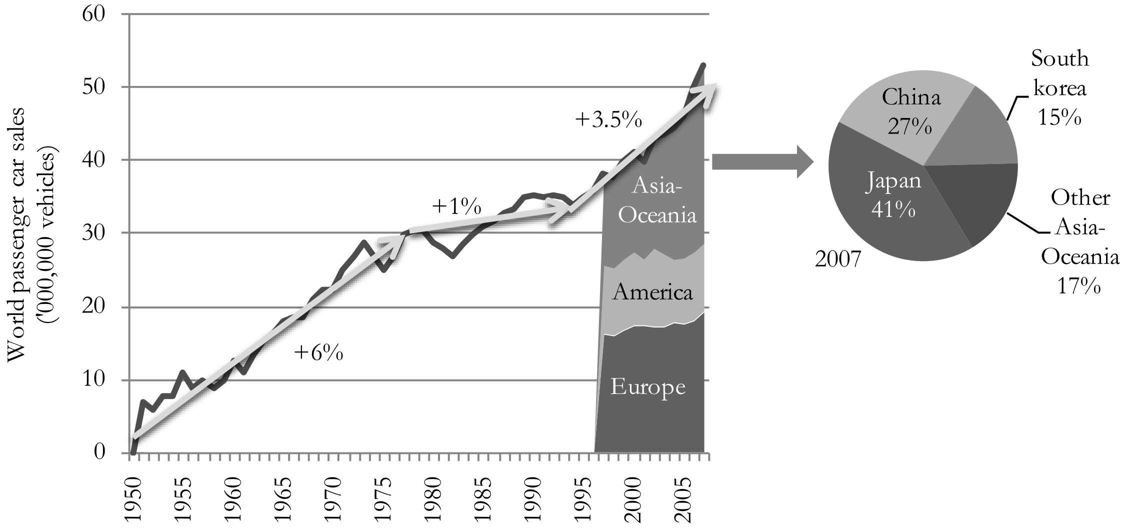


Figure 29. World passenger car production (Source: author based on Maxton and Wormald, 2004, OICA, 2008)

Before concluding on how organ transplant in cars might possibly fit into the automotive world, let us present the structure, main players and systems of production of the current automotive industry. Presenting the automotive industry in just one section of the dissertation falls short of completeness and, hence, should be perceived as an illustration of the fundamentals that are more significant to the concept explored here. For instance, among today's players, which are those that might be involved in organ transplant in cars? What are the production systems that might facilitate organ transplant in cars, i.e. parts and components interchangeability and intergenerational compatibility?

Who are the players in vehicle manufacturing? Nieuwenhuis and Wells (2003) distinguish three broad types of manufacturer:

- <u>High volume, full range producers</u>, typified by Ford, VW, Fiat, Toyota, Nissan and GM who are extensive holdings. These companies are in the centre of the market, producing at the highest volumes and lowest prices (more than 4 million vehicles a year, each), with a wide range of general purpose cars for mass consumers. These car makers compete on the basis of unit cost reduction through economies of scale.
- <u>Specialist producers</u>, typified by Mercedes, Volvo, Audi, BMW and Lancia. These companies occupy the upper market niches with larger or higher performance vehicles that demand higher prices. They compete on the basis of differentiation and cost recovery, offering a compromise between exclusivity, quality and utility. Consumers are willing to pay premium prices because of reputation and image.
- <u>Niche producers</u>, typified by Lotus, Alpine, TVR and Ferrari. These companies offer exclusivity and extremes of performance, particularly in sports cars, but often at the cost of uneven quality, limited practicality and considerable financial burden.

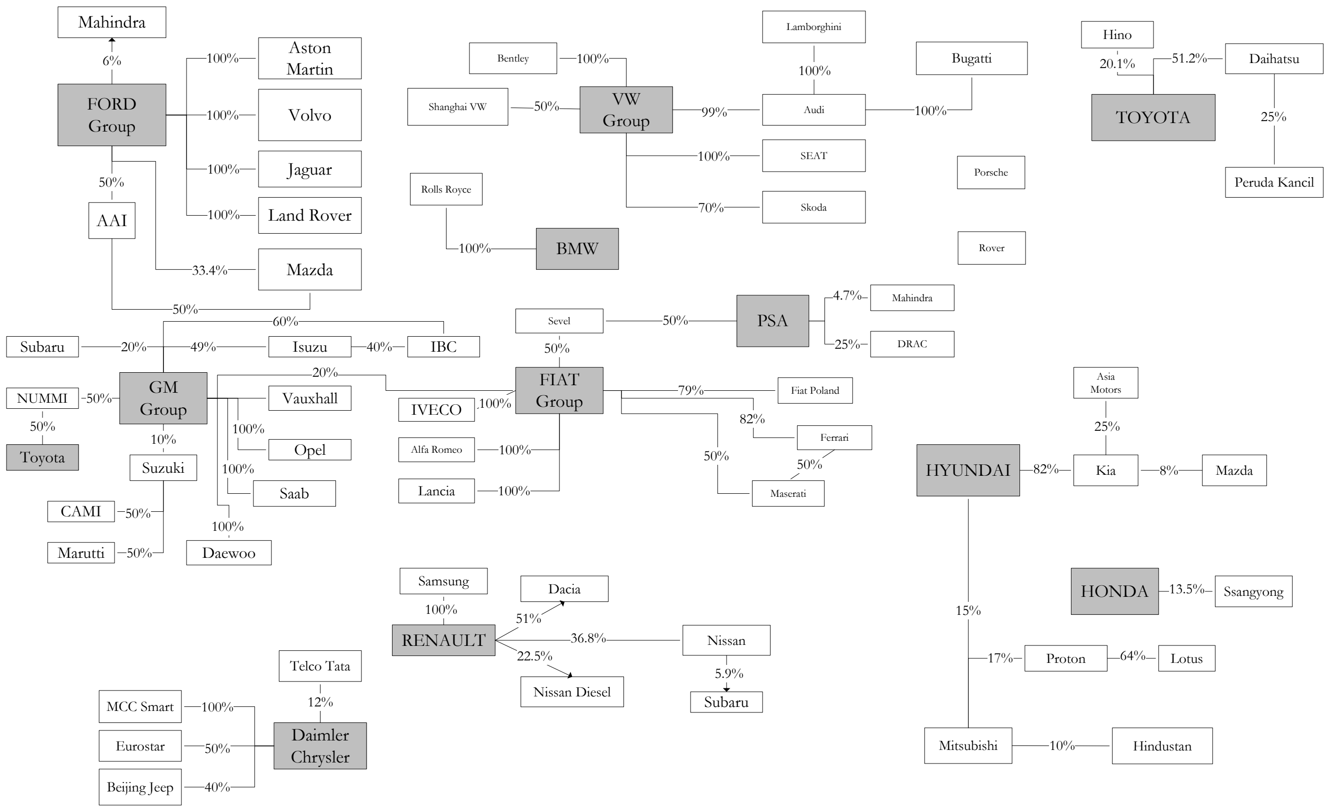


Figure 30. The financial structure of relationships in the global automotive industry (Nieuwenhuis and Wells, 2003, updated)

Figure 30 illustrates the equity links between car manufacturers and today's intricate and complex global financial structure of car manufacturers. This global picture is a result of periods of consolidation and mergers (or acquisitions) of car manufacturers that were mostly motivated by the importance of securing global presence of the biggest and ensure large-scale markets.

Figure 31 (below) symbolically illustrates the structure of the automotive industry and the corresponding downstream service sector (i.e., aftermarket). We will start by describing the car manufacturing structure and players (bottom-up in the figure), and follow with a short explanation of the aftermarket (top-down in the figure).

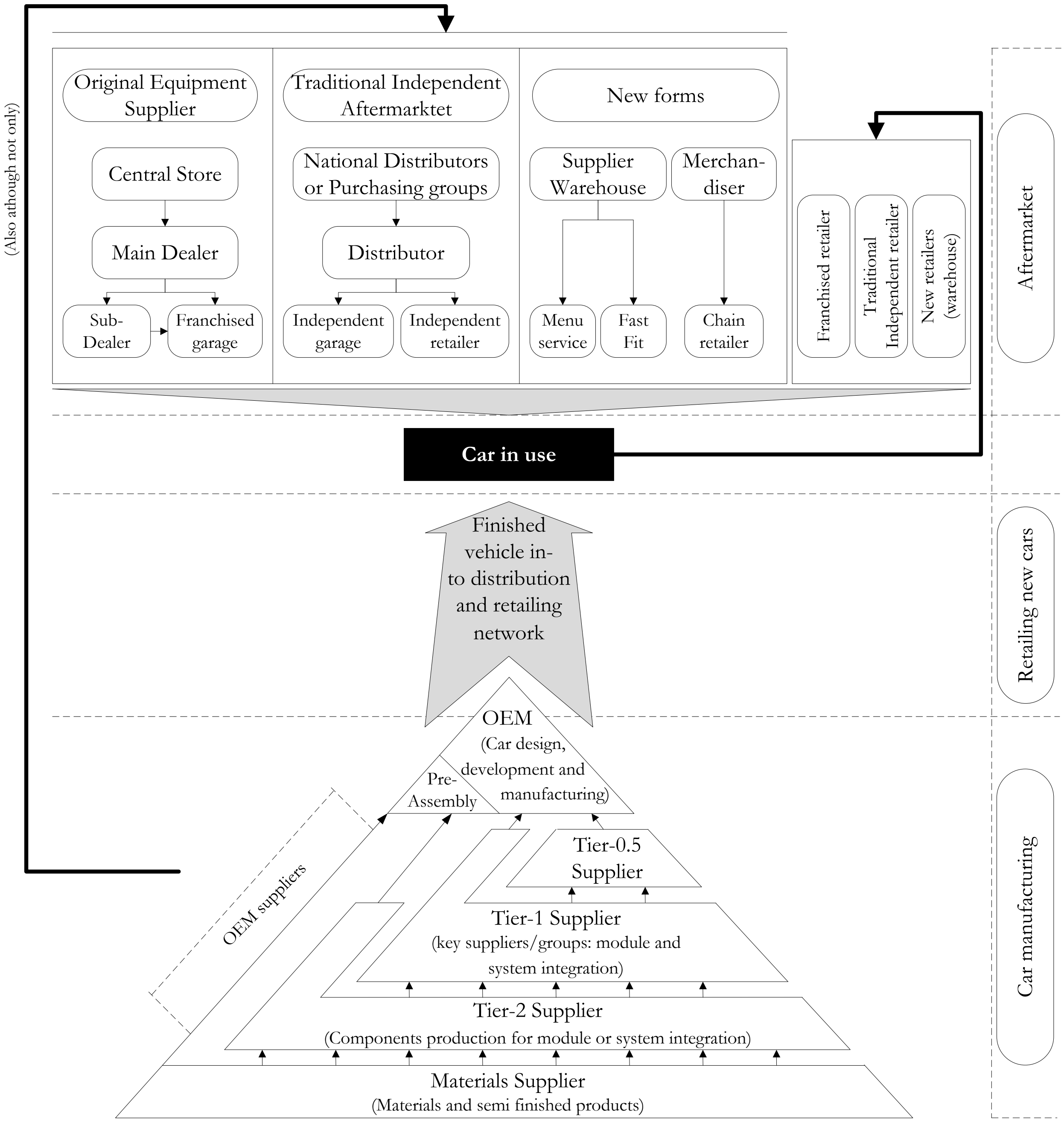


Figure 31. Simplified generic structure of the automotive industry and aftermarket (based on Nieuwenhuis and Wells, 2003, Maxton and Wormald, 2004, Arantes, 2005)

Aside from the core items of the vehicle body structure and the engine (usually produced by the car makers), independent companies supply the materials and components that constitute the vehicle. Suppliers of components are referred to Tier-2 suppliers whereas Tier-1 companies supply parts, modules or sub-systems. Tier-1 companies supply directly to OEMs and are linked by collaborative Research and Development (R&D). Tier-2 companies supply components to both Tier-1 companies and OEMs.

Car makers are increasingly outsourcing parts and modules in order to reduce production costs and their pre-assembly burdens (and thus shifting the pressure for costs cutting to the Tier-1 and Tier-2 suppliers), and concentrate on the design and development of new products, coordinating the manufacturing supply chain, and marketing and dealing with customers (Womack *et al.*, 2007). Accordingly, there is an emergence of module or 'full-service' suppliers, also known as Tier-0.5 companies, such as Magna, Bosch, Lear, Delphi and Denso. Tier-0.5 are large multi-location companies, able to supply car makers anywhere in the world and have advanced technology capabilities and are significant innovators (Nieuwenhuis and Wells, 2003, Arantes, 2005). The shifting of production from OEMs to suppliers is reflected on the origin of value added of the final car. Today, the vehicle manufacturers only control 25% of the value of the product coming out of their assembly plants and the remaining 75% of value-added is in control of their suppliers. In 1955, it was the other way around (Maxton and Wormald, 2004). In fact, suppliers are now large companies that compete with the car makers they supply in terms of market relevance (e.g., total annual sales). As shown in Figure 32, supplier companies occupy 18 positions over the first 35 (when there are more than 70 different car makers, worldwide).

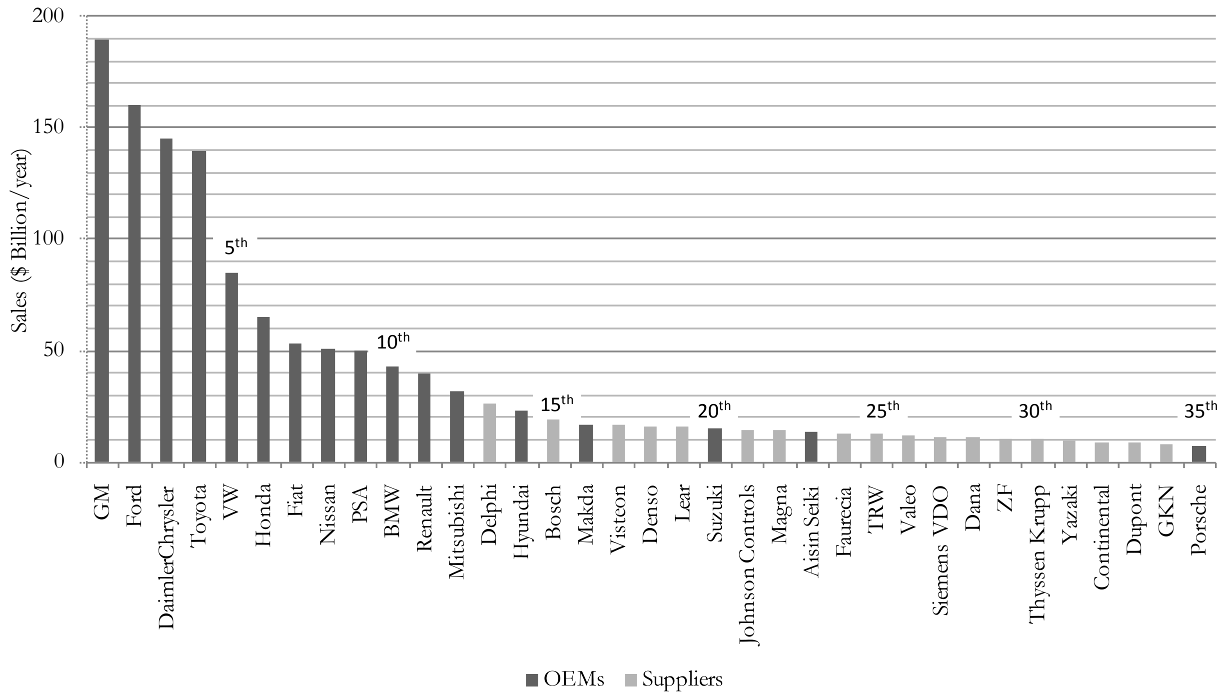


Figure 32. The relative size of OEMs and suppliers (Maxton and Wormald, 2004)

Following the description of Figure 31 (above), after components, parts, modules and systems are assembled at OEMs' plants, the car leaves the factory and enters the downstream end of business that involves buying a new car, servicing it, re-selling it (few iterations, if any), to finally retiring it. Initially, the car is commercialized through the distribution and retailing network that can account for between 20% and 40% of the final price of a new car in the market (Nieuwenhuis and Wells, 2003). Retailing systems differ among markets and differences are related to the relationship between retailers and OEMs, and number and type of dealers.

Traditionally, vehicle manufacturers have enjoyed a protected and controlled franchised dealer channel for retailing new cars. In the USA, the franchised dealership system is held in place by tough laws that ensure that cars can only get to the market through the dealers' network. In Japan, manufacturers have almost total control over their dealers, even though the great majority is independent business. In Europe, vehicle manufacturers were protected by the original Block Exemption regulation to the market competition provisions of the Treaty of Rome by which they had exclusivity of their single-brand retail networks (they decided the location and nature of shops), until the recently enacted New Block Exemption (NBE) (refer to section 3.3.2, p. 83, where we discuss legal issues related to car organ transplant). This extended to the aftermarket spare parts, also. Price Water House & Coopers consultants (2005) estimate that the NBE regulation will increase the diversity of the outlets from which consumers can buy new cars, as new retailers enter the market and gradually alter distribution from a dealer-based system to a retailer-based system that includes multi-channel formats.

Contrarily to most retailer sectors (e.g., electronics or food stores) where multiple brands compete targeting for different consumer segments, ranging from the very small shop to the 'big-discounts' megastores, car customers were usually limited to the single-brand new car dealers. This is changing. For instance, the emergence of Internet shopping that might shortcut the retailer's pathway and approximate vehicle manufacturers to customers, although this is far from competing with 'shop-floor' sales, as many websites redirect customers to street-dealers. Physical and eye contacts with the purchased object are still determinant in buying cars. With respect to Internet shopping, e-commerce might bring new sources for product differentiation through car customization, by which car's would ultimately be tailor-made according to the customer's idiosyncrasies (Helper and MacDuffie, 2000).

Another difference between markets is that in the USA the majority of dealers represent more than one brand, whereas 70% of European dealers are single-brand (Maxton and Wormald, 2004). This has somehow changed in Europe and multi-branding retailers are now beginning to arise. Another difference is the number of dealers. There are approximately 20,000 outlets in the USA against 60,000 outlets in Europe (a much more fragmented market), corresponding to an average number of plates per dealer of 2.4 in the USA versus 1.2 in Europe and greater productivity of American dealers (Maxton and Wormald, 2004). Again, the NBE regulation is expected to reduce the number of existing dealership outlets operating in the EU to as little as half of today's level by 2010 (PriceWaterHouseCoopers, 2005). In fact, the number of franchised dealers has already fallen 15% in two years (2002 to 2004).

Finally, when the car gets to the car owner and is used, it needs servicing and repairs throughout its useful life. Again, the organization of the aftermarket differs on a country basis.

However, the structure presented in Figure 31 (top-down) is likely to be generic for all situations.

The aftermarket is composed by:

- Used car traders – mainly through the franchised dealers (the same that sell new cars, through a plethora of multi-brand traditional local dealers or 'private-to-private');
- Parts and components retailers, both franchised and independent – which are supplied by both OEMs and independent companies; and
- Service and repairs activity by franchised garages, traditional and new forms of independent garages. These can provide either routine servicing that does not require qualified and specialized mechanics or technical repairs by specialists, such as electrical systems.

On top of Figure 31 are the suppliers who provide spares parts and components to the aftermarket. On the left are the Original Equipment suppliers whose market entry points are the parts and service department of the car manufacturers who operate in centralized warehouses. Here, they accumulate equipments needed to support, not only, the vehicles of their brands currently in production but also those out of production but still in operation, for up to 10 years (or longer in the case or critical components). In the middle is the traditional independent aftermarket that deals with multi-branding. They cannot afford to carry inventories of the spare parts they need for servicing and repairs other than a few oils and standardized items (e.g., lamps). The rest comes from a network of local parts stockists that have to be very local in that most parts are expected to be delivered within 20 to 60 minutes. On the right are the 'new forms' of the aftermarket that encompass fast-fits or menu services (e.g., overall check and selected refitting for used car remarketing), which concentrate on routine servicing and simple repair operations that do not need very specialized mechanics.

Car owners typically desert the over-priced franchised sector after a few years (for example, only 40% of British car owners remain with the original franchised dealer for servicing). The upshot of this is reflected in the national patterns of parts distribution in Europe (see Figure 33), where Germany remains dominated by Original Equipment suppliers and Portugal and the UK are dominated by the independent sector (Maxton and Wormald, 2004). As such, market shares of each stream of servicing and repairs depend largely on the vehicle age and the country under consideration. Among other, the following issues can explain such variability: the mistaken belief of losing the original OEM's warranty when servicing in independent garages (which is prevented by the NEB regulation, as we refer in section 3.3.2, p.83) and the idea that the residual value of used-cars remains significantly higher if serviced by the franchised sector.

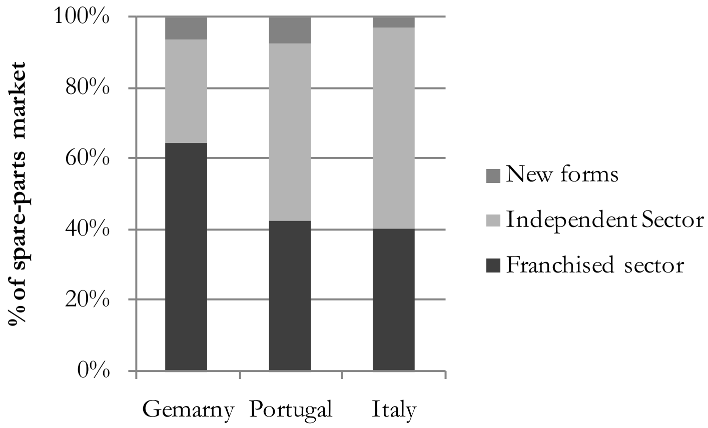


Figure 33. Segmentation of the spare parts market in three EU countries (adapted from Maxton and Wormald, 2004, p.179)

The different parts (car making, retailing and aftermarket) of the automotive world presented before are not independent. For instance, Maxton and Wormald (2004) recognize the reliance of car manufacturers on financial cross-subsidies as major structural problem of the automotive industry. As referred by the automotive industry experts, there is a 'fight for the aftermarket where the money is earned' (Maxton and Wormald, 2004). As depicted in the following figure, half of the value added of the automotive industry is for the aftermarket, including the profits for OEMs, suppliers and other players we referred to above. For instance, while dependent on the profits from new and used car sales, approximately 50% of profits of car dealers come from spare parts sales and servicing. In fact, the whole lifecycle product is being increasingly promoted by dealers (mainly by the single-branded franchised dealership). They supply the new vehicle, offer complete set of services to support the car during its operation, and the bundle is set up to take the car back in part exchange for a new one (usually the down payment for financing the next car).

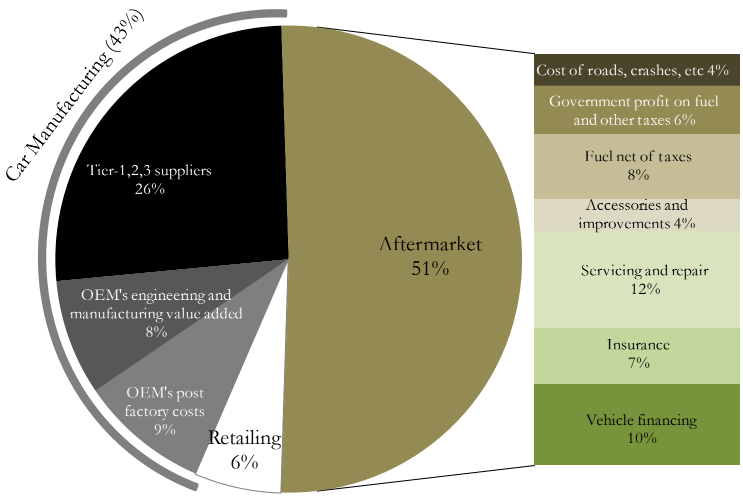
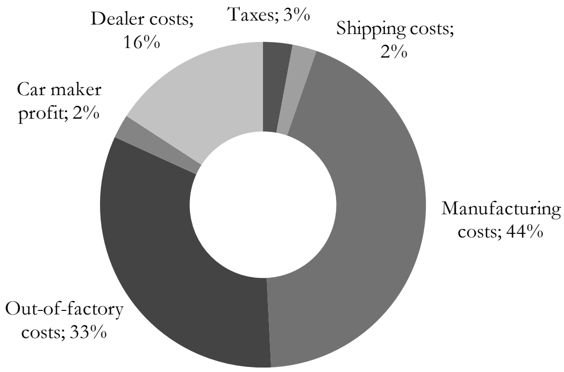


Figure 34. Breakdown of automotive industry value added (adapted from Maxton and Wormald, 2004, p.165)

A striking aspect is the meager profit margins from selling one car for the car manufacturers and retailer dealership. According to Nieuwenhuis and Wells (2003), profit margins for the car makers corresponds to 1% of the total automotive profits pool, as a percentage of profits generated over 10 years. Delucchi *et al.* (2000) estimate that Ford's corporate true profits of the 2000 Ford Taurus correspond to 2% of total manufacturing costs, including retailing, shipping and taxes. Finally, as referred in a report by the Mercer Management Consultant (2003), the current (2002) profit margin in the retailing industry round 0.5% in Germany and is expected to increase to 2-4% after the expected effects of the NBE regulation come about.



Note: Out-of-factory costs include: division costs (engineers, testing, and advertising); corporate costs (executives, capital, R&D) and corporate cost of money.

Figure 35. Manufacturing costs breakdown of a 2000 Ford Taurus (based on Delucchi *et al.*, 2000, p.238)

In short, there is a great pressure on the car manufacturers to cut costs down (which they have been partially doing by transferring that pressure on their suppliers) but, also, to maintain or increase market share for which they have to find new ways of car production to meet customer expectations. In this respect, one important goal of the Foresight Vehicle Program for the UK automotive industry is to "*(…) produce more vehicle variants*" and, apparently, Sloan's motto continues to determine current market trends, i.e. "*a car for every purse and purpose*" (Womack *et al.*, 2007). As illustrated by Figure 36, in an almost static market in volume terms, the total number of variants on offer in the UK car market more than doubled, from 1303 in 1994 to 3155 in 2005, while the number of models increased 40% and body styles increased approximately 25% (Orsato and Wells, 2007).

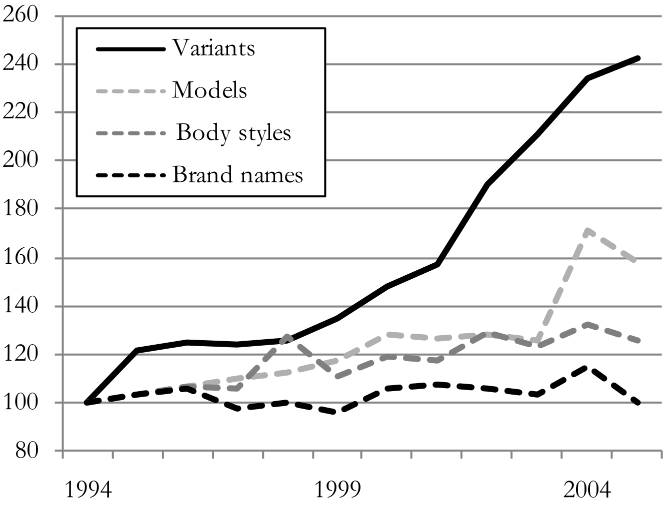


Figure 36. Brand names, models, body styles and variants in the UK market, 1994 to 2005 (adapted from Orsato and Wells, 2007)

To be precise, a car model is a particular vehicle type sold under a brand name (e.g., Volvo) and is usually defined and/or constrained by the use of a particular platform configuration[18]. The same model can have engineering derivatives, giving rise to variants characterized by different mechanical contents or body styles. For example, Volvo offered the S80 and four additional models, back in 1998, based on a new product platform. Associated to these five models, customer could choose among 14 colors, 9 engines, 5 transmission alternatives, left and right-hand steering, giving a total of 6,300 variants. Many other options were available, such as 22 types of interior trim and 9 wheel variants. All in all, Volvo could offer more than one million car variants and, thus, making it possible to customizing each car to individual buyers specifications with a flexible, well-organized activity structure. The important feature that made this venture possible was that these models were designed according to modular principles (Fredriksson and Gadde, 2005).

Intuitively, we argue that aiming for more product variants would counter the objective for ease and cost effectiveness of car organ transplant since a wider variety of transplanting kits would be required and, as such, would make it harder to be accepted by car owners. However, we have seen that achieving customization of cars according to customer preferences requires a different, more modular, approach to building cars than that which is mainstream at present. In this sense, the same Foresight Vehicle program we mentioned above confirms that "*vehicles that can be reconfigured, either for fashion or functionality, will need appropriate new design and manufacturing systems*" (SMMT, 2004). Again, the emphasis is put on the adaptability of future vehicles and the corresponding manufacturing system as new challenges are faced and the path towards more customization, standardization and modularity is likely to appear as an appropriate response to such challenges. From an engineering perspective, a modularization generally has three purposes: 1) to make complexity manageable, 2) to enable parallel work, and 3) to accommodate future uncertainty (Baldwin *et al.*, 2006). These authors continue saying that "*modularity accommodates uncertainty because the particular elements of a modular design may be changed after the fact and in unforeseen ways as long as the design rules are obeyed*". Interestingly, Graedel and Allenby (1997) had already suggested that "*a next step in modular design is the creation of systems that permit graceful upgrade of individual modules while the rest of the automobile remains the same*". Finally, Baldwin and Clark (2002) mention that "*modular designs offer alternatives that non-modular ("interdependent') designs do not provide. Specifically, in the hidden modules* (meaning that design decisions in those modules do not affect decisions in other modules)*, designers may replace early, inferior solutions with later, superior solutions*". All authors above and others (Sako and Murray, 1999, Camuffo, 2000, Nieuwenhuis and Wells, 2003, Seidel *et al.*, 2005) reinforce the idea that with increasing modularity, the automotive industry should potentially experience easier upgrading of the currently fast changing technological components without substituting the entire vehicle.

[18] As defined by Nieuwenhuis and Wells (2003), the platform corresponds to the basic elements of a monocoque which carry all the key powertrain elements. The meaning of the term has been extended to include the basic set of parts that can be shared by a number of models made by a car maker (or even several car makers).

With respect to standardization and modularization, Helper *et al.* (1999) mention that there are important debates about whether, “once again, auto manufacturing will strike off in a new direction, commonly described as ‘modular assembly, after three distinct automotive industrial revolutions: Henry Ford’s mass production, Alfred Sloan’s customized mass-production and Toyota's lean production. Figure 37 illustrates the three past automotive revolutions and the fourth revolution foreseen by Maxton and Wormald (2004) as the unbundling of car makers and increased out-sourcing and modularity in design and production.

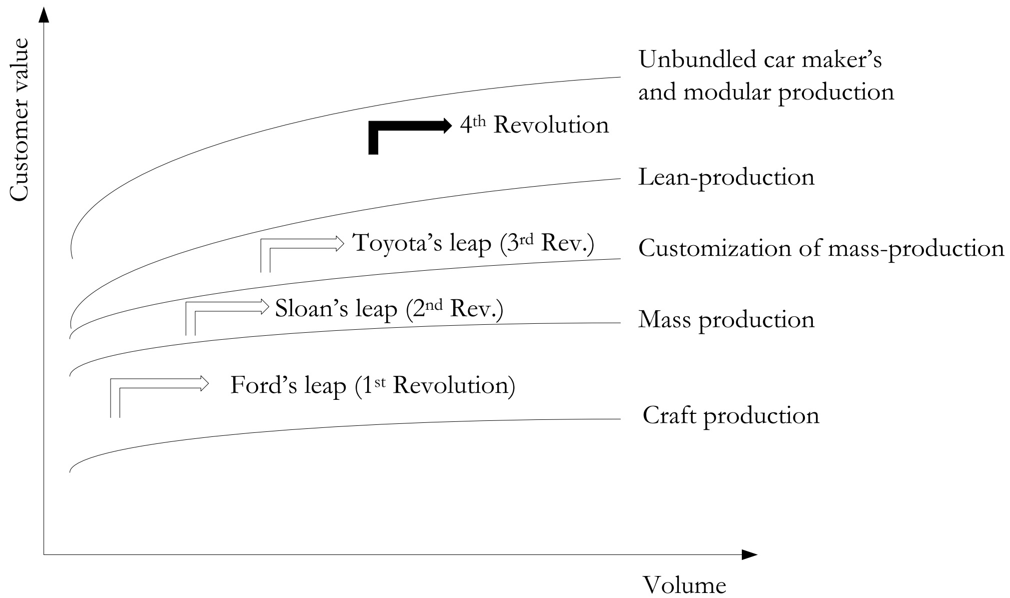


Figure 37. Three automotive revolutions and foreseeing the fourth (Maxton and Wormald, 2004, p.258)

For a comprehensive review of the three main production systems of the automotive industry refer to the IMVP conducted by James Womack, Daniel T. Jones and Daniel Roos (Womack *et al.*, 2007). Associated to each manufacturing systems, Maxton and Wormald (2004) refer to the first, second and third automotive revolutions (refer to Figure 37, above). We note that concept of ‘revolution’ used here should not be confused with the ‘industrial revolution’ associated to the Kondratieff cycles we mentioned before, although the advent of the automobile, the ICE and oil, triggers the fourth industrial revolution (Freeman and Louçã, 2002).

Henry Ford engineered the progress from craft to mass production and made it possible by inventing the continuous assembly line and, more importantly, by making parts completely and consistently interchangeable to allow for simplicity of attaching them to each other, for the concept of spare parts and for cutting down the overall production costs. The limit to mass-production as envisioned by Ford (i.e., single, static model at an ever decreasing unit price) was full-standardization from components to the final vehicles and workers’ tasks. Alfred Sloan managed to accommodate this conflict between standardization and the model diversity needed to satisfy the large range of consumer demand (as mentioned before, ‘a car for every purse and purpose’). He standardized many mechanical items (e.g., pumps) while introducing customization by changing more frequently the external appearance of the vehicles and adding many ‘hang on’ features (e.g., automatic transmission, air conditioning, etc.). Then Toyota leap-frogged over customized mass production through lean production. While centering the concept of the elimination of wasteful resources in all production processes (and thus the term 'lean'), lean production employs teams of multi-skilled workers at all levels of the organization and uses highly flexible, increasingly automated machines to produce volumes of products in great variety. Modularity in production and increased outsourcing (Helper *et al.*, 1999) could follow together with the unbundling of the bigger car manufacturers. According to Maxton and Wormald (2004), car makers will have to reconstitute themselves and achieve a balance between scale (which favors cost reduction) and diversity (which favors market penetration). Current automotive industry path towards extensive outsourcing can provoke drastic changes in the value chain and car makers should reposition themselves accordingly.

Baldwin *et al.* (Baldwin *et al.*, 2000) define modularity as: (1) a functional partitioning into discrete scalable, reusable modules consisting of isolated, self-contained functional elements; (2) rigorous use of well-defined modular interfaces, including object-oriented descriptions of module functionality; (3) ease of change to achieve technology transparency and, to the extent possible, make use of industry standards for key interfaces. Takeishi and Fujimoto (2001) analyzed the concept of modularization in the auto industry and extended the definition of modularization by identifying three facets of the phenomenon:

- <u>Modularity in design</u> implies that a complex system can be split up and distributed across separate modules. It allows one-to-one correspondence between the subsystems and their functions and enables, for example, the designer to focus solely on the subsystems functionality, becoming a "module with self-contained function".
- Modularity in production aims to achieving 'structurally cohesive modules' (while 'modularity in design' strives for 'functional cohesiveness') which become easy to manage in terms of material handling and quality control.
- <u>Modularity in inter-firm</u> systems focuses on the division of labor in production processes by which car makers draw the boundaries for out-sourcing of large cohesive modules produced by outside suppliers ("assemblers-suppliers" cohesiveness).

Although referring to the computer industry, Baldwin *et al.* (2006) defines a fourth facet of modularization which is 'modularity in use':

- A system of goods is modular-in-use if consumers can mix and match elements to come up with a final product that suits their taste and needs ("customization").

For example, consumers often buy bed frames, mattresses, pillows, linens, and covers made by different manufacturers and distributed through different retailers. The parts all fit together because different manufacturers make the goods in standard sizes. These standard dimensions constitute design rules that are binding on manufacturers, wholesalers, retailers, and users. Modularity-in-use thus supports customization of the system to suit the needs and tastes of the end-user. Car tuning and styling are existing practice of modularity-in-use in the automotive industry that involves specialty equipments producers showing important and growing turnover (OTE, 2008, SEMA, 2008). Organ transplant in cars would benefit from modularity in use enabled through modularity in design, although not directly performed by car owners.

As surveyed by Helper et al. (1999) among major auto-makers, modularity in production has a major potential, namely “the value of parts integration during design with advantages in weight reduction, simpler assembly process, quality improvement, and ease of recycling”. Interestingly, Sako and Warburton (1999) found also that modularity “has been partially permitted by, and probably even stimulated by, the spread of lean production”. In this respect, Womack *et al.* (2007) documented the fact that under the Japanese system, suppliers held more responsibility, had longer term relations and, through the use of ‘black-box’ design (or hidden modules of modularity in design), possessed certain areas of greater technical expertise.

The are several definitions of what a module is in the automotive industry. While Sako and Warburton (1999) contend that a ‘standard module’ should be able to fit into standard interfaces on different OEM’s products, OEMs themselves regard a module as “a group of components which are physically close to each other, that are assembled and tested outside OEMs’ facilities and which can be assembled very simply onto the car” (we presented a similar definition in section 3.2.1, p.60, when referring to the concept of car organ transplant). With regards to increased standardization, the authors found that a number of factors may increase the possibility of increasing standardization of parts across car makers:

- the devolution of responsibility for design and assembly to suppliers (i.e., modularity in inter-firm);
- suppliers’ growing financial strength and ability to fund investment (including R&D);
- suppliers’ accelerating technical expertise;
- reducing asset specificity of suppliers’ investment; and
- OEMs persuading suppliers to pay for tooling, which may encourage suppliers to seek scale economies through commonality.

Transplanting kits are a collection of ‘best available technologies’ (BAT) composed by components, modules and systems that are to be transplanted in used cars and by which the cars’ energy and environmental efficiencies are expected to be increased. Following the discussion above, transplanting kits should benefit from the new paradigm of vehicle manufacturing foreseen by industry experts. Accordingly, car organ transplant would involve new conceptions of car <u>design</u>, <u>production</u>, <u>ownership</u> and <u>serviceability</u>.

With respect to car <u>design</u>, standardization and modularity is essential for organ transplant in order to enable intra and intergenerational interchangeability of components, parts and systems. Full compatibility between the main building blocks of the transplanting kit and the recipient vehicle must be ensured through clearly defined standardized interfaces. In addition, <u>car owner</u> should be more aware of and give greater credit to the lifecycle ownership costs and possibly be more prone to extend their cars service time. With respect to <u>serviceability</u>, Gershenson and

Ishii (1993) defined it as the ease at which a system can be serviced[19]; how often the system needs servicing; how easy it is to service; how long the service takes; and how much it costs. The authors point out that the possible enhancement in reliability associated to increased modularity (better design and performance of each module) could be negated by the increased costs of each repair, because of large modules being (possibly) hardly accessible and handled. This is why the authors argue that serviceability should be incorporated in the design of product. We add that design should also include the corresponding changes in the aftermarket infrastructure. Car organ transplant would make part of car servicing and, as such, it should acknowledge these issues also: ease, duration and costs of operations.

After identifying how car organ transplant might fit in the automotive industry and possibly benefit from foreseen changes in design and manufacturing systems, we present an insight into the possible mechanical hurdles that may arise when performing such transplants. Furthermore, we analyze the legal framework for organ transplant in cars. As mentioned earlier, it is not a primary objective of the present thesis to analyze these issues in detail.

3.3. Insights to possible 'complications of surgery'

3.3.1 Limits to organ transplant

Although our research does not aim to explaining the mechanical complexity of car technological transplant, the present section presents some limits and difficulties of its application, namely the intergenerational technological compatibility of components, parts and systems when time lags between model years are too long, i.e. the possibility to change a component from model year t with a newer component from model year $t+x$, where x is a non-zero and positive integer. Complications of surgery may arise in car organ transplant.

First of all and the simplest issue would be to bolt in the new modules for which available space is needed under the hood and throughout the platform. On one hand, the purpose of transplanting vehicles is not to increase the powertrain capacity or power, but instead to increase its fuel economy and environmental performance. On the other, new technologies tend to reduce volume and weight of power equivalent equipments. For example, with the advances in thin-wall casting techniques for blocks and heads, engines weight and size are decreasing with time (Nieuwenhuis and Wells, 2003, Maxton and Wormald, 2004). This means that the probability of the total weight of the transplanting kit being lighter increases with time (refer to the introduction of lighter materials, for example aluminum - Automotive Aluminum, 2007),

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[19] Service includes diagnosis, maintenance, repair, and anything else that affects the activity needed to keep the system functioning properly. Importantly, serviceability and reliability are complementary in that one decreases while the other prevails, and vice-versa. For example, today's cars would require major servicing every 20,000 kilometers (or more) due to increasing reliability of components only, while in the 80s they would be serviced every 10,000 kilometers (or less).

which promotes better handling, performance and economy, and less components reworking is necessary. For instance, reworking the front suspension to compensate for any extra weight on the front end compared to the original vehicle is typically obligatory in classic powertrain swaps when car tuners aim to increasing the power of their car and, as such, require bigger engines. All in all, space should not be a problem for organ transplant in cars. Still, design should consider this aspect.

Likewise, components should fit together electrical and mechanical interfaces should be possible between different model years. Although not necessarily, 'all-in-the-family' swaps usually fit when main components (engine, transmission and chassis) are all the same make (Clarke, 1990). This corresponds to the definition of modularity from OEMs and to the standardized modules across OEMs as contended by Sako and Warburton (1999). As referred by Clarke (1990), automotive engineers often have to take the future into consideration when vehicles are designed, making possible future accommodations for new engines since older counterpart may not be available for that model in a few years. Although no references were found disagreeing with Clarke's statement, there seems to be no real evidence that current automotive industry brings about this aspect when designing new vehicles. Issues like style, energy and safety are foremost important in the extremely competitive car market than the future eventual engine swap, although this is what we are contending in the present dissertation and that is foreseen for the future car industry by some authors we quoted in the previous section.

While in our discussion, we have been taking for granted the mechanical freedom to design interchangeable modules, it might be a tougher problem as physical phenomena intervene and in many cases can result in impossibility to subdivide some car systems into smaller interchangeable modules. As stated by Whitney (2003), modularity in design has been evolving in VLSI[20] systems where modules can be given standard interfaces, permitting plug-and-play design by which whole industries have opened up to competition and innovation. However, while VLSI are signal processors (involving few watts of power), cars (which the author refers to as CEMO[21]) involve both signal and power processing (involving much more power by several orders of magnitude). Whitney's (2003) arguments to limit modularity in cars (and CEMOs in general) are summarized in the following table. In short, the author argues that mechanical modules do not have the same versatility than VLSI due to the power they have to handle and also due to the interdependence (often in sequence) between two modules. He argues that the backload power can be easily avoided in signal processing using logic controls and electronic devises. Conversely, backload in mechanical power transmission cannot be shut-down and as such must be avoided during the design stages of the vehicles requiring in that sense pair wise and system testing. Accordingly, the author foresees that cars and airplanes will achieve only limited modularity in practice.

[20] "Very Large Scale Integration" systems (e.g., microprocessor with 3 million elements).
[21] "Complex Electro-Mechanical-optical" systems.

Table 6. Differences between VLSI and mechanical systems (Whitney, 2003)

Issue	VLSI	Cars (or CEMO in general)
Component Design and Verification	- Model-driven single function design based on single function components. - Design based on rules once huge effort to verify single elements is done. - Few component types needed.	- Multi-function design with weak or single-function models. - Components verified individually, repeatedly, exhaustively; many component types needed.
Component Behavior	- Behavior is the same in systems as individually. - Dominated by logic, described by mathematics. - Design errors do not destroy the system.	- Behavior is different in systems and in isolation in that after assembly the systems are tested and fine tuned. - Dominated by power, approximated by mathematics, subject to system and life threatening side effects.
System Design and Verification	- Follows rules of logic in subsystems. - System design is separable from component design. - Logical implementation of main functions can be proven correct beforehand. - Simulations cover all significant behaviors. - Main system functions are accomplished by standard elements.	- Logic captures a tiny fraction of behavior. - System design is inseparable from component design. - Main function design cannot be proven correct in isolation or beforehand. - Large design effort is devoted to side effects. - Complete verification of avoidance of side effects is impossible.

These possible 'complications of surgery' should naturally be addressed during design stages of new vehicles. In addition, we would argue that before deciding on whether to *transplant a car,* there must be a compromise solution between two opposing criteria: (1) there has to be minimum time span between original car equipment and transplanting kits before technological development occurs and potentially provide energy and environmental lifecycle benefits; (2) that same time span should not be too long in order to avoid major technical differences that could hinder car transplant due to exceeding adaptation costs. This issue will be analyzed in Chapter 6 (Part B) when we compare different car ownership strategies and the best periodicity for car transplanting (under the assumptions considered in our analysis). We anticipate one major result of our research in that the environmental payback period is 6 years if a car is transplanted at the age of 5. We accept that such time interval seems reasonable regarding the criteria presented above.

3.3.2 Legal issues and organ transplant in cars

We shall consider the case of the European Union, only (although different in structure and form, regulation in other countries should be close in substance). The directive 2007/46/EC of the European Parliament and of the Council (September 5th, 2007) establishes a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles. Among other relevant issues, the directive highlights the necessity for:

- The technical requirements applicable to systems, components, separate technical units and vehicles should be harmonized and specified in regulatory acts, for all Member States. Those regulatory acts should primarily seek to ensure a high level of road safety, health protection, environmental protection, energy efficiency and protection against unauthorized use.
- It is important to lay down measures enabling vehicles to be approved on an individual basis, in order to allow sufficient flexibility in the multi-stage approval system.
- The main objective of the legislation on the approval of vehicles – i.e., ensuring high level of safety and environmental protection – should not be impaired by the fitting of certain parts or equipment after vehicles have been placed on the market or have entered service. Thus, appropriate measures should be taken in order to make sure that parts or equipment which can be fitted to vehicles and which are capable of significantly impairing the functioning of systems that are essential in terms of safety or environmental protection, are subject to a prior control by an approval authority before they are offered for sale. These measures should consist of technical provisions concerning the requirements that those parts or equipment have to comply with.

To our understanding of the directive's text, we infer that organ transplant activities are encompassed by these three introductory principles of the directive. In short, it aims to (1) ensure high level of environmental protection and energy efficiency that is one central objective of the concept proposed in this research, (2) to establish a multi-stage approval system (not only vehicles getting out of the assembly line) by which measures enabling vehicles to be approved on an individual basis are considered (refer to Article 2 of the directive that defines the scope of vehicles and equipment encompassed), and (3) define appropriate measures to make sure that separate technical units (including specialty equipments or transplanting kits) would be subject to a prior control by an approval authority before they are offered for sale.

Importantly, the directive also presents the definition of key concepts of which we selected the following:

- Firstly, related to the type of approval:
    - 'individual approval' means the procedure whereby a Member State certifies that a particular vehicle, whether unique or not, satisfies the relevant administrative provisions and technical requirements;
- Secondly, related to the equipments to be transplanted in recipient vehicles:
    - 'system' means an assembly of devices combined to perform one or more specific functions in a vehicle (e.g., engine) and which is subject to the requirements of any of the regulatory acts;
    - 'component' means a device subject to the requirements of a regulatory act and intended to be part of a vehicle, which may be type-approved independently of a vehicle where the regulatory act makes express provisions for so doing;
    - 'separate technical unit' means a device subject to the requirements of a regulatory act and intended to be part of a vehicle, which may be type-approved separately, but only

in relation to one or more specified types of vehicle where the regulatory act makes express provisions for so doing.

Our conception of transplanting kits would correspond to the composition of several systems, components and separate technical units.

Interestingly, article 10 of the directive ("Specific provisions concerning systems, components or separate technical units") refers that "where a component or separate technical unit fulfils its function or offers a specific feature only in conjunction with other parts of the vehicle, thereby making it possible to verify compliance with the requirements only when the component or separate technical unit is operating in conjunction with those other vehicle parts, the scope of the EC type-approval of the component or the separate technical unit shall be restricted accordingly. In such cases, the EC type-approval certificate shall specify any restriction on its use and shall indicate the special conditions for its mounting". Accordingly, we argue that the current directive includes the cases where individual equipment included in transplanting kits are approved by specific regulations, but the overall system is only approved when it is installed in the recipient vehicle and under normal operating conditions. The same article also refers that if such systems are planned to be fitted by the car manufacturer, compliance with any applicable restrictions on use or conditions for mounting should be verified at the time when the vehicle is approved.

One possible outcome for car makers would be to designing devices to be fitted after the car leaves the assembly line, provided that intergenerational compatibility is ensured. In a new paradigm where car makers would shift from car providers to car mobility service providers, designing parts and components for intergenerational compatibility, and planning/designing cars accordingly, could bring lifecycle benefits for car makers as mentioned previously (refer to section 3.1 where we debate the car organ transplant and industrial ecology principles). In such paradigm, car makers would hold car property from 'cradle-to-grave' (as such, following the 'Extended Producer Responsibility' principle) while selling automobility services to their customers. This is similar to car renting solutions provided today by finance companies (mostly). However, the difference is that after the contract comes to an end, the finance company gets rid of the vehicle whereas the automobility provider would transplant the car (if necessary) and use it for new contracts, possibly aiming to different market segments than customers looking for new cars. Importantly, the corresponding business model suggested here would be encouraged if (and when) car owners would have to pay for their GHG and pollutant emissions, in the sense that they would be running in fine tuned cars equipped with cleaner technologies.

Finally, Article 31 of the directive addresses specifically the "sale and entry into service of parts or equipment which are capable of posing a significant risk to the correct functioning of essential systems". Again, transplanting kits that are not provided by car makers and, as such, are not system-type approved together with the vehicle's approval, are handled by this article. In short, it ensures that the manufacturer of parts or equipment shall submit to the approval authority a test report drafted by a designated technical service which certifies that the parts or equipment for which authorization is sought comply with the requirements including prescriptions for safety, environmental protection and, where needed, for testing standards (Paragraph 5 of article 31 of the directive).

Importantly, the new rules of Block Exemption Regulation (BER) targeting the automotive industry should also hold for car organ transplant (likewise the overall automotive aftermarket). The cars BER is the European Commission Regulation No.1400/2002 (formerly Regulation No 1475/95) which exempts from competition rules arrangements in the EU for the distribution of new cars and their subsequent servicing. As such, it allowed car manufacturers to create networks of selective and exclusive dealerships by which they controlled the sale and servicing of cars, light commercial vehicles, trucks, buses and coaches. The new rules of BER (since 1st October 2003) were planned to "put consumers in the driving seat", by giving dealers greater independence from carmakers, promoting inter-brand competition, liberalizing the aftermarket and encouraging the harmonization of prices across the region. The new rules imply that (London Economics, 2006):

- Manufacturers' warranties issued in one Member State must be valid under the same conditions in all other Member States;
- Warranty book filled out by a dealer in another Member State should not have to wait for that warranty to be honored in his home country;
- Dealers are able to market their services and reach customers in different areas or countries;
- Dealers are able to sell more than one brand of car at the same site (multi-franchising) with fewer restrictions;
- In the case of automotive service and repair, the new BER addresses a number of restrictions that create entry barriers to gaining the status of an authorized repairer. Namely, repairers' access to the authorized network is to be based on qualitative (as against quantitative) selection criteria (article 3(1)) and any a priori exclusion of stand-alone repairers is prohibited (article 4(1)(h)).

With respect to independent repairers, the new BER seeks to create a level playing field vis-à-vis the authorized repairer networks. This objective is rooted in the granting of access to technical information (article 4(2)) and to original parts (article 4(1) (i) and (j)).

The provisions will expectably increase competition in the domestic and continental car markets, which will give consumers more choice and better value for money including a reduction in car prices. The aftermarket will be opened up, with a change to the rules linking new car sales and servicing. Dealers will still have to ensure that customers' cars are serviced and repaired to manufacturer approved standards, but they will no longer have to do it themselves; and, independent garages and roadside assistance organizations will have much greater access to technical information, including diagnostic equipment and software (PriceWaterHouseCoopers, 2005).

This said, we argue that organ transplant in cars is currently possible since the existing legal framework apparently embraces the basic requirements for such operations, such as for car tuning performed today. Still, specific regulation should be worked out to explicitly include the technical terms; to possibly define limits to organ transplant (for example, which model years are allowable for transplantation); and, insurance companies should be closely involved in the process.

3.4. Similar examples and approaches

We finish the present chapter by presenting some similar examples and approaches to organ transplant in cars. We referred over the previous sections some concepts that are somehow related to the one explored here, among which retrofitting and car tuning are the most prominent (refer to section 3.2.1 for details on these concepts).

The first example is the concept of ‘kit car’. The kit car industry exists at the margins of the mainstream of the automotive industry. A kit car is an automobile that is available in a completely-knock-down (CKD) form, which means that the independent car maker buys a complete set of systems, parts and components that he needs to assemble into the final car. The concept of the customer building his own kit car should not be entirely dismissed and again we find the parallel in the computer industry. Usually many major mechanical parts such as the engine and transmission are taken from one or more donor vehicles. Kits vary in completeness from as little as a book of plans to a complete set of all the components required. ‘Kit car’ companies broadly follow the principles of lean production. Some of them are able to break even at 20 or 30 cars a year with their cheap tooling while for firms such as Lotus or TVR the per-model breakeven volume is probably in the range of 3,000-5,000 a year (Nieuwenhuis and Wells, 2003). We refer this case since it illustrates the interchangeability of standardized parts and components underlying the kit car concept.

Another example is the life extension of classic cars. With this respect, the Morris Minor Centre in Bath has shown that extending the life expectancy of classic car is cheap and viable, especially if it is updated in the process. Charles Ware (the founder of the centre) argues in his booklet (Ware, 1982) that car depreciation wastes consumer’s money and leads to premature scrapping of materials since the low residual value of the car renders repair uneconomical. The main underlying reason is the oversupply created by the current automotive industry system that is based in pushing for new cars consumption and rapid stock turnover. Conversely, he contends that, like houses, cars should be regarded as a long-term investment, rather than a shorter-term consumer ‘durable’. We complete this concept by saying that ‘product stewardship’ should be used at the owner’s and manufacturer’s advantage, when (and if) the car making paradigm changes. The concept explored in our research is pretty much in line with Charles Ware vision.

There are also examples of government lead strategies to enhance vehicle stock energy and environmental performance that include approaches like repowering and retrofitting. For instance, the Carl Moyer program[22] (CARB, 2004, 2006) funds the incremental cost of cleaner-than-required engines, equipment, and emission reduction technologies, to encourage the voluntary purchase of BAT. While regulations continue to be the primary means to reduce air pollution emissions, the Carl Moyer Program plays a complementary role to California's regulatory program by funding emission reductions that are surplus, i.e., early and/or in excess of what is required by regulation. The Carl Moyer Program accelerates the turnover of old highly polluting engines, reduces the costs to the regulated community, speeds the commercialization of advanced emission controls, and reduces air pollution impacts on environmental justice communities. The core principle is that emission reductions must be real, surplus, quantifiable, and enforceable in order to meet the underlying statutory provisions. Typical candidate projects are: engine repowering (i.e., replacement of an existing engine with a new, emission certified engine); retrofitting (i.e., installation of a verified emission control system on an existing engine – e.g., diesel particulate filters); new purchases of vehicles or equipment certified to optional, lower emission standards; fleet modernization (or equipment replacement) where old vehicle/equipment is scrapped; and vehicle retirement. Initially, the program aimed mostly at off-road equipments (e.g., water well pumps) and vehicles (e.g., agriculture) and later to heavy-duty vehicles. The striking feature of the Carl Moyer program is the vision of providing incentives to go beyond the existing regulation by exploring all possibilities for incremental efficiency gains, including the swapping of older engines in cars.

Similar programs are undergoing in other places in the USA, such as the "Heavy-Duty Engine Incentive Program Projects" promoted by the San Joaquin Valley Air Pollution Control District (2006). Another example of large scale retrofitting program was undertaken by a Consortium of national (e.g., Center for Sustainable Transport of Mexico City) and foreign institutions (e.g., U.S. Environmental Protection Agency) in the Mexico city by which very old heavy duty vehicles are retired and replaced and not-so-older vehicles are retrofitted with particle filters and catalytic converters (EMBARQ, 2007). Several European countries (e.g., Sweden, Germany, Switzerland and Denmark) have also entailed a large scale initiative to retrofit diesel ICE as from late 90s though regulation (e.g., environmental zones), agreements with vehicle manufacturers (e.g., all light duty vehicles sold in Germany after 2004 were equipped or retrofitted with particle filters) and financial incentives (e.g., German authorities gave incentives of 600€/retrofit for 80% reduction on particulate emissions).

Similar experiences are common in other sectors. As mentioned earlier, modularity has been most important in the technological development of the computer industry (Baldwin *et al.*, 2000) and, accordingly, computer owners can update their hardware since the intergenerational compatibility of components and parts is insured by standardization. Differently, in the context

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[22] This program is named in honor of the late Dr. Carl Moyer who originally created and masterminded this program.

of the military industry, the US Department of Defense grounds the equipment acquisition system on the lifecycle cost and total ownership cost approaches (US Department of Defense, 2003, 2004). The feature that relates most with the concept explored in our dissertation is the mandatory "evolutionary acquisition strategy" when planning for future investment in military equipment (US Department of Defense, 2003): 1) first phase - defining, developing, producing and deploying an initial, militarily useful capability based on proven technology, demonstrated manufacturing capabilities, and time-phased capabilities needs; and 2) second phase (and beyond) – planning for subsequent development, production and deployment of technological increments beyond the initial capability over time. The interesting point here is that the investment is planned for several generations of the same artifact in an evolutionary way. In biology, 'evolution' is driven by two major mechanisms: natural selection and genetic drift. Here, we are interested in the former by which individuals with advantageous traits are more likely to reproduce, so that more individuals in the next generation inherit these traits. Over many generations, adaptations occur through a combination of successive, small, random changes in traits, and natural selection of those variants best-fitted for their environment (Britannica Online Encyclopedia, 2008). In short, evolution implicitly involves betterment. The 'Manager's guide to technology transition in an evolutionary acquisition environment' by the US Department of Defense (2003) may bring to light useful suggestions to be explored by car makers for a new 'evolutionary car selling' concept by which they would provide their customers the possibility of planned organ transplant over an extendable service time bundled to the car they sell or alternatively the mobility service associated to the vehicle they 'rent' or 'lease'.

The examples and approaches presented are not an exhaustive list of similar concepts to organ transplant in cars. They rather illustrate that the concept presented in our research has been used (or came near) in other situations and sectors of the economy.

3.5. Summary and conclusions

This chapter aimed mostly to presenting the concept of organ transplant in cars and how it could be integrated in the automotive industry. Beforehand, we explained how it is inherently related to the principles of industrial ecology. Together with other similar practices (e.g., retrofitting, remanufacturing, refitting, reconditioning, recycling and reusing – not to mention all), organ transplant in cars may potentially refrain the voracious automotive industrial metabolism in that the service time of cars is potentially extended (unless abrupt interruption occurs – e.g., car crash), while keeping the car technologically updated and more performing. Consequently, virgin materials are potentially saved (or at the least, their extraction is delayed) and waste materials minimized (including dissipative pollution).

We then present a detailed description of our conception of car organ transplant which we recall '*corresponds to replacing any parts, modules and systems of the car that are technologically outdated, downgraded or malfunctioning while keeping the remaining components and parts that are state-of-the-art and fully operative, in order to improve the overall system's energy and environmental efficiency and possibly reach 'like new' standards, during the car's service life*'. With this respect, we discuss thoroughly the appropriateness of the term we choose (i.e., transplanting) by comparing it with similar concepts such as retrofitting or 'eco tuning'. Afterwards, we present the composition of the transplanting kit that we use to model lifecycle options in the forthcoming chapters. In this sense, we explain our options for inclusion of components, parts and systems in the set of organs of the transplanting kit. Importantly, we highlight that one fundamental and unavoidable feature of the organs to be transplanted is the inter-generational interchangeability between models (and desirably between brands) that is not automatically ensured by car makers today, while intra-generational compatibility is naturally required and planned when designing cars for the sake of spare parts interchangeability.

We follow the analysis of the concept by exploring its potential integration in the overall automotive system. In this sense, we begin with a short presentation of the structure, players and production systems of the automotive industry. One prominent aspect of today's extremely competitive automotive industry is the pressure for cutting down costs and diversification of supply by widening the range of variants to satisfy an increasingly eclectic demand. In this sense, some industry experts foresee radical changes in the manufacturing system and industry structure (they called it the fourth automotive industrial revolution) by which increased customization in supply is required with further leaning production while guarantying mass production to benefit from economies of scale. Standardization and modularization (in design and in production) are regarded as promising approaches to enable such changes together with the increased outsourcing of larger and more complex pre-assembled modules. These changes are expected to have profound consequences in the value chain of the automotive industry in that suppliers will continue to gain increasing shares in the original value added of the final vehicle together with importance in the technological development of the modules they supply, turning OEMs into assemblers rather than full chain manufacturers (as they originally were). Several authors refer that, in the future, the automotive industry should create systems that permit graceful upgrade of individual modules while the rest of the automobile remains the same – what we named intergenerational interchangeability or compatibility. We concluded that organ transplant in cars could make part and benefit from all the new concepts and changes anticipated for the future of the automotive industry. Accordingly, we concluded also that car organ transplant would involve new conceptions of car ownership and serviceability in that owners would have greater awareness and give greater credit to lifecycle ownership costs and the aftermarket should be prepared to ensure easy, fast and cheap organ transplants.

We also analyzed the legal framework for organ transplant in cars and we generically concluded that it should be feasible today since the existing regulation apparently embraces the basic requirements for such operations, likewise for car tuning operations. With this respect, the new block exemption regulation gives aftermarket dealership and servicing garages greater independence from carmakers, promoting inter-brand competition, liberalizing the aftermarket and encouraging the harmonization of prices across regions. To our understanding, the new EU directive (2007/46/EC – September 5th, 2007) opens up new opportunities including organ transplant in cars.

Among other features we analyzed in section 3.3.2, this regulation establishes a framework for the approval of motor vehicles by detailing specific regulations for car systems, components and separate technical units, whether these are mounted by authorized or independent repairers. In addition, it provides specific regulation allowing for future intergenerational interchangeable original equipments without necessary testing if the original design of the vehicles anticipates such possibility (Article 31 of the directive). Still, specific regulation should be worked out to include specifically the technical terms; to possibly define limits to organ transplant (for example, which model years are allowable for transplantation); and, insurance companies should be closely involved in the process. Although we regarded the European context only, we assume that similar regulation should be available in other regions, particularly in the US and Japan where car tuning is so widely performed.

Finally, we analyze some potential drawbacks for organ transplant in cars related to mechanical limitations of such operations. Although 'all-in-the-family' transplants should not bring greater issues, car design (both for modularity and serviceability) will have to ensure intergenerational interchangeability between modules where the design of standardized and consolidated (particularly in time) interfaces between modules is prominent (particularly, as the difference between model years gets larger). On the other hand, full interchangeability between OEMs might conflict with other important targets of the automotive industry. For instance, increased standardization associated to modularization in design might reduce the range of possibilities for car customization that is vital for the future of car makers, as we mentioned earlier. Other complications may arise that are related to physical restrictions to modularity. While modularity in electronic system has boosted related industries (e.g., computers) and problems have been gracefully solved, modularity in large electro-mechanical systems may face problems, mostly because the latter handle high power transmission between modules (several orders of magnitude more than signal processing) by which backload problems might generate system or human dangerous side effects and electro-mechanical module's functionality is system-dependent, i.e. they perform differently in isolation or after being integrated in the system. Again, these aspects are complex challenges for car designers to conceptualize standardized interfaces.

We ended this chapter by presenting similar examples and approaches inside and outside the road transport system. These examples illustrate that the concept we explore here might have good expectations of applicability as similar cases were already undertaken. The most striking input from this section is the contribution from the US Department of Defense and their 'evolutionary military acquisition system' in that it may bring to light useful suggestions to be explored by car makers for a new 'evolutionary car selling' concept by which they would provide their customers the possibility of planned organ transplant over an extendable service time bundled to the car they sell or alternatively the mobility service associated to the vehicle they 'rent' or 'lease'.

Part A of the dissertation ends now giving room to part B where we analyze the potential impacts from organ transplants on the car ownership of one individual (or household) over 20 years, including all vehicle and fuel life cycle stages.

B. Car ownership strategies and lifecycle burdens

We mentioned that the slow turnover of fleets holds back the efficiency gains striving from technological improvements, especially when markets are nearly saturated and diffusion rates decelerate. As referred in the previous part, the concept of *organ transplant* arises in this context. In short, it corresponds to installing in older cars *transplanting kits* composed of 'best available technologies' (BAT) by which the car's energy and environmental efficiencies are increased. Not only it would make cars more efficient during their useful lifetime[23], but it would also possibly contribute to a partial dematerialization of the automotive industry. Importantly, a transplanting kit weights as much as 20% of a conventional car and costs about 25% a new car (attending to our definition of transplanting kit). Apparently, it is a potentially attractive alternative to common car ownership, i.e. buying, using and maintaining new or remarketed cars. Still, we have to evaluate the environmental implications and final balance of technological transplants, i.e., if the additional energy and environmental burdens associated to the production of transplanting kits and scrappage of replaced equipments are outweighed by the car's performance expected gains. Likewise, we must analyze to what extent it is attractive from the car owner's perspective (in economic terms) by analyzing, for example, what are the payback periods of the transplant investment.

Furthermore, as technological change is systemic, it should not be treated as a discrete and isolated event that concerns only the car (Grübler and Gritsevskyi, 2002). In this sense, car organ transplant inherently involves not only a whole host of other technologies during car use and maintenance, but also in the up and downstream stages of the car's lifecycle, i.e. technologies used for materials production, manufacturing of the car or vehicle dismantling before final scrappage. Additionally, we could also address the psycho-sociological dimension of new technological artifact. If technological transplant is to become successful, consumers have to understand what it is and be aware of costs, advantages and risks involved – if any of the latter exist or are significant. We will return to this point in chapter 9 (Part C) when we explain how this issue is incorporated in our discrete choice model of remarketed cars. All in all, we are referring to a new technological artifact that builds on existing socio-technological systems of production, use and end-of-life management. These are briefly the reasons for approaching our research problem through system and life-cycle thinking.

In view of the fact that this problem is inherently complex, we begin with a simpler analysis of the potential impacts from technological transplants on the car ownership of one individual (or household) over 20 years, including all life cycle stages of the vehicle and fuel use. The present part of the dissertation analyses different ownership scenarios (including car technological transplant) and discusses the arguments sustaining why car organ transplant might be of interest for car owners and might increase the overall environmental performance of car ownership. In this sense, we divided our analysis into three chapters.

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[23] The useful life (referred to service lifetime, also) of an asset is an estimate of how long the asset will be used (as opposed to how long the asset will last until its residual value or salvage value is zero).

Chapter 4 and Chapter 5 are mostly methodological and describe the development of two models for exploring the concept of car organ transplant, while Chapter 6 is predominantly analytical where we estimate and interpret the results from the models presented in previous chapters. Chapter 4 presents a lifecycle energy and environmental inventory (LCI) model. The modeling of the LCI involves the identification of the functional unit (here, the 20-years car ownership), definition of the relevant system boundaries (sections 4.1 and 4.2) such as the lifecycle stages of the product system (section 4.3) and respective parameterization (section 4.4). Our LCI results (section 4.5) provide information about all inputs – here, energy and raw materials consumed – and outputs – emissions and solid waste – in the form of elementary flows to and from the environment from all the processes involved in the study for all phases considered.

Chapter 5 describes the total car ownership costs (TOC) model. After a brief review on the costing methodologies (section 5.1), we list all car ownership costs considered in our model (section 5.2) and describe how we analyzed the costs of car organ transplant (section 5.3). Both chapters include analytical formulas and assumptions (when required, the reference country is Portugal) and the corresponding models result in the car ownership economic profile over 20 years (section 5.4).

Chapter 6 is predominantly analytical. After presenting some specifications on the methodology (section 6.1) we used to analyze the possible advantages of car organ transplant (either by buying transplanted cars or by transplanting own cars) compared to conventional car ownership approaches (keeping a car over 20 years, buying new cars or buying remarketed cars, over the same period), results are discussed in section 6.2. As LC modeling relies strongly on assumptions, Chapter 6 includes a sensitivity analysis (section 6.3) to selected parameters in order to survey the robustness of our conclusions and trustworthiness of the respective implications.

Chapter 4. Life-cycle energy and environmental inventory of car ownership

Todd and Curran (1999) defined the concept of life-cycle as the "c*onsecutive and interlinked stage of a product system, from raw material acquisition or generation of natural resources to the final disposal*". Using the *life cycle* concept through what is known as "*life cycle thinking*" is the way to address problems (namely environmental impacts) from a holistic perspective. Why using a life cycle perspective in our case? Embracing the whole lifecycle of a product or activity ensures that no environmental burdens are shifted to other phases, i.e. it is avoided that improvements in one part of the life cycle – e.g. product manufacturing – lead to even higher impacts in other parts of the same life cycle – e.g. product use (European Commission, 2006a). Therefore, we will address the potential benefits of car organ transplant using lifecycle analysis methodologies in the case of energy and environmental impacts and total lifecycle costing techniques in the case of the economic survey (Chapter 5).

4.1. Background of system thinking and lifecycle analysis

Lifecycle analysis (LCA) has its roots in the 1960s when concerns about the rapid depletion of fossil fuels and the effects of the world's changing population on the demand for finite raw materials and energy resource supplies arose (for example, refer to Meadows *et al.*, 1972). The predictions of rapid depletion of fossil fuels and resulting climate changes sparked interest in performing more detailed energy calculations on industrial processes. For instance, the Midwest Research Institute (and later, Franklin Associates) initiated, in 1969, a study for the Coca Cola Company (cited in Jensen *et al.*, 1997) to determine which type of container had the lowest releases to the environment and required the smallest amount of raw materials and energy. This methodology was refined and generated the Resource and Environmental Profile Analysis – REPA (Hunt *et al.*, 1992). After the oil crisis of 1973 and seeking to trim down energy consumption, approximately 15 REPAs were performed between 1970 and 1975. Meanwhile, in Europe, a similar inventory approach was being developed, later known as the 'Ecobalance'. In the UK, Ian Boustead calculated the total energy used in the production of various types of beverage containers (1972). He consolidated his methodology to make it applicable to a variety of materials and, in 1979, published the "Handbook of Industrial Energy Analysis" (cited in Jensen *et al.*, 1997). It was not until the mid 1980s and early 1990s that a real wave of interest in LCA swept over a much broader range of domains and applications. By the 1992 UN Earth Summit, LCA methodologies were among the most promising new tools for a wide range of environmental management tasks (Jensen *et al.*, 1997).

However, LCA was mostly used by environmental consultants and, eventually, it became clear that different LCAs carried through by different consultants resulted in different and sometimes conflicting conclusions. This could be explained, in part, by different methodological choices (Russell *et al.*, 2005). An effort to reach consensus on a broad, international level was initiated within the Society of Environmental Toxicology and Chemistry (SETAC) in 1990 and the harmonization process soon resulted in the so-called SETAC Code of Practice (Consoli *et al.*, 1993). In addition, a standardization process started within the framework of the International Organization for Standardization (ISO). The international standards that were developed and accepted in the late 1990s (ISO 14040, 1997, revised in 2006) present recommendations or requirements for several methodological issues that were not covered in the SETAC Code of Practice. Nevertheless, some problems remained unsolved and the academic world started a new field of research that conducted to the creation of the International Journal of Life Cycle Assessment. Some important milestones were extended from the basis of www.ecobilan.com and are resumed in the following box.

Box 1. Historical milestones in the development of LCA methodologies

1969: Coca Cola survey by Midwest Research Institute (and later, Franklin Associates)

1984: Publication of the "Ecological report of packaging material" by EMPA (a Swiss research institution of materials science and technology – http://www.empa.ch)

1980-90: Society of Environmental Toxicology and Chemistry (SETAC) starts its first LCA studies (http://www.setac.org).

1992: First European scheme on Eco-labels that was revised by the new Regulation (EC) Nº 1980/2000 (http://ec.europa.eu/environment/ecolabel/index_en.htm)

1992: Creation of SPOLD by an association of industries that, after 1995, published a Directory of life-cycle inventory data sources (a comprehensive survey of potentially useful basic data) and developed the SPOLD format, both to facilitate LCI data exchange and the choice of relevant data sets (http://lca-net.com/spold/whatis.html).

1993: SETAC publishes the Code of Practice (Consoli *et al.*, 1993) that describes a procedural framework for LCA.

1996: NF X30-300 is the first standard published in France for Life Cycle Assessment.

1996: Creation of the International Journal of Life Cycle Assessment specifically dedicated to LCA research (http://www.scientificjournals.com/sj/lca/ausgaben).

1997-2000: the International Organization for Standardization creates the ISO 14040-44 international series of standards to define the concepts, principles, different stages and requirements of the LCA methodology (ISO 14040, 1997, revised in 2006).

1998-2001: ISO 14020, 25, 48, 49, series of standard and technical documents concerning communication, environmental declaration directions and working methods.

There are several definitions of life cycle assessment among which we highlight the one proposed initially by the SETAC (Consoli *et al.*, 1993):

"LCA is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life-cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal."

A LCA is a large and complex effort that comprises four main stages: *goal and scope definition, inventory analysis, impact analysis* and *interpretation*. These are illustrated in the following figure.

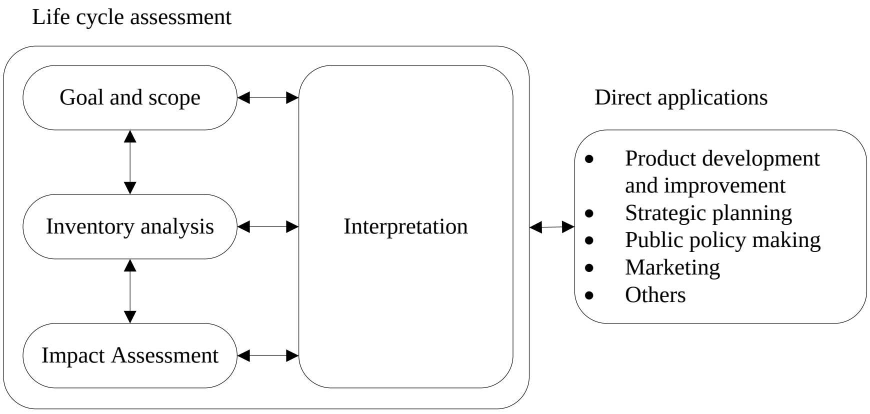


Figure 38. Stages in life cycle assessment (Consoli *et al.*, 1993, ISO 14040, 2006)

The first step is probably the most critical in the LCA process since decisions have to be made on what materials, processes or products are to be considered (defined as the *functional unit* for which the LCA is applied) and how broadly will alternatives be defined.

The second component, *life cycle inventory* modeling *(LCI)* uses quantitative data to establish the levels and types of energy and materials input to an industrial system and the product output and environmental releases. Based on an inventory flow diagram, all inputs and outputs of materials and energy are listed for most or all life cycle stages. The principal task here is to collect large amounts of data depending on the level of disaggregation of the life-cycle defined in the scoping process.

The third stage, *life cycle impact analysis (LCIA)* involves relating the outputs of the system to the impacts on the external world into which those outputs flow, or at least, to the burdens being placed on the external world. In this stage, impact assessment seeks to measure the magnitude and significance of potential environmental impacts of the defined product system.

There are several methodologies used for LCIA (refer to Jensen *et al.*, 1997, for a review of several methodologies) and they broadly contain the following main issues: environmental impact category definition, classification, valuation and normalization/weighting. Typically, the '*impact categories*' considered are: abiotic resources, biotic resources, land use, global warming, stratospheric ozone depletion, ecotoxicological impacts, human toxicological impacts, photochemical oxidant formation, acidification, eutrophication and work environment (for a detailed description of each category refer to Jensen *et al.*, 1997).

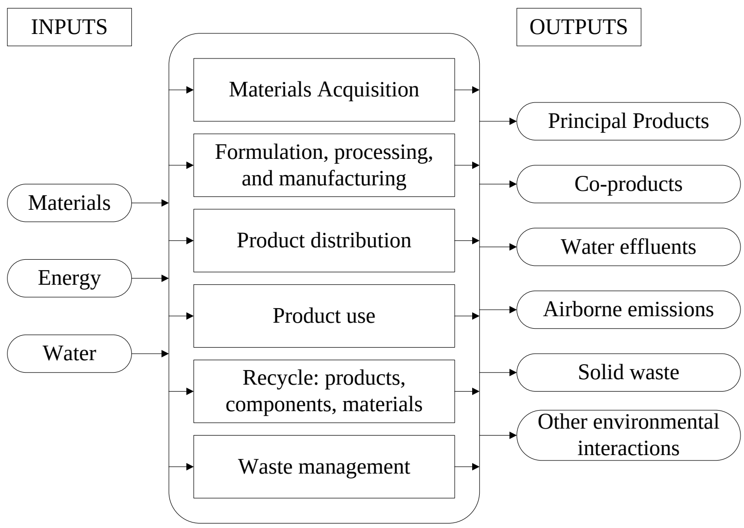


Figure 39. The elements of a life-cycle inventory analysis (Graedel, 1998)

After defining which environmental categories are considered, '*classification*' aims to assign inventory input and output data to those categories that is a qualitative step based on scientific analysis of relevant environmental processes. Some outputs contribute to different impact categories and therefore, they have to be mentioned twice and double counting issues are to be addressed with caution.

After their classification, impacts enter the stages of '*valuation, normalization and weighting*' into one overall indicator. Weighting methods have been developed by different institutions based on different principles: proxy approach, technology abatement approach, monetarisation, authorized goals or standards ("distance to target") and authoritative panels (refer to Jensen *et al.*, 1997, for a review of the several approaches). The Eco-indicator 99 (Goedkoop and Spriensma, 2001) is a state-of-the-art method developed under the authority of the Dutch Ministry of Housing, Spatial Planning and the Environment for the RIVM (National Institute of Public Health and Environmental Protection of the Netherlands). In this method, damage categories are weighted based on the "distance to target" principle after a normalization procedure – by which each effect calculated for the life cycle of a product is benchmarked against the known total effect for this class, e.g. the EU averages. Here, it is assumed that the severity of '*damage to human health*', '*ecosystem quality*' or '*resources depletion*' can be assessed by the difference between its current level and the maximum value. These are three broad categories used in the Ecoindicator 99 that group a more extensive list of detailed categories as those presented above. In this sense, environmental standards and quality targets are predetermined. For example, to create a weighting set for the Eco-indicator 99, 365 questionnaires were sent out to a Swiss LCA interest group. 82 were returned; 45 of these could be used as basis for the weighting factors. The panel members were asked to rank and weigh the three damage categories referred above (Goedkoop and Spriensma, 2001).

Finally, interpretation is the phase where the results of the LCI and LCIA are interpreted according to the goal of the study and where sensitivity and uncertainty analysis are performed to qualify the results and the conclusions. The output from LCA activity is often the clarification of needs and opportunities for reducing environmental impacts as a result of industrial activities being performed or contemplated.

The approach of the present research is inspired in the LCA concept, by which environmental burdens are measured for all life cycle stages of vehicles and fuels. As referred previously, during the LC inventory, various data categories are measured, including air and waterborne emissions, material and energy consumption, and waste generation. We emphasize that we do not intended to perform a full LCA of a car, but instead to compare several scenarios of car ownership based on the LCI analysis.

Most detailed LCA studies of complete cars (Kaniut *et al.*, 1997, Schukert *et al.*, 1997, Heather and Lave and Lester, 1998, Kobayashi *et al.*, 1998, Sullivan *et al.*, 1998, not to mention all, Sullivan and Cobas-Flores, 2001) were performed in the 1990s and proved to be massive tasks to accomplish. The most complete study is considered to be the US Automotive Materials Partnership (USAMP) survey of a generic gasoline sedan (Sullivan *et al.*, 1998), by which LC energy use, material inflows, air and waterborne emissions and waste outflows were quantified. The 1995 mid-sized generic vehicle is a hypothetical synthesis of the Dodge Intrepid, the Chevrolet Lumina and the Ford Taurus. More recently, Delucchi (2003) suggested a comprehensive life cycle emission model to compare not only different vehicle technologies (existing and future) but also different transportation fuels. Many additional surveys were performed to compare also different alternatives of vehicles or fuels (Weiss et al., 2000, Hackney and de Neufville, 2001, Wang et al., 2001, Arthur D. Little, 2002, Delucchi, 2004, among others). To detail one of these surveys, the Energy laboratory at MIT (Weiss *et al.*, 2000) conducted a LCA study of new automotive solutions in the future where they estimated life cycle energy consumption, CO_2 emissions, and costs associated with various technologies in 2020 including current internal combustion engine vehicle (ICEV), electric drive vehicles (EDV), whether full electric, hybrid or fuel cell. For a comprehensive review of LCA surveys of complete cars or comparison of different types of automotive technologies, refer to the paper written by MacLean and Lave for the Journal of Progress in Energy and Combustion Science (2003).

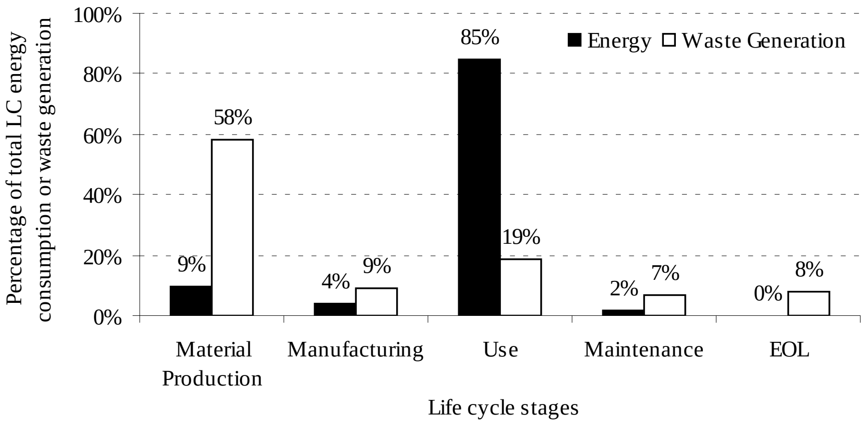
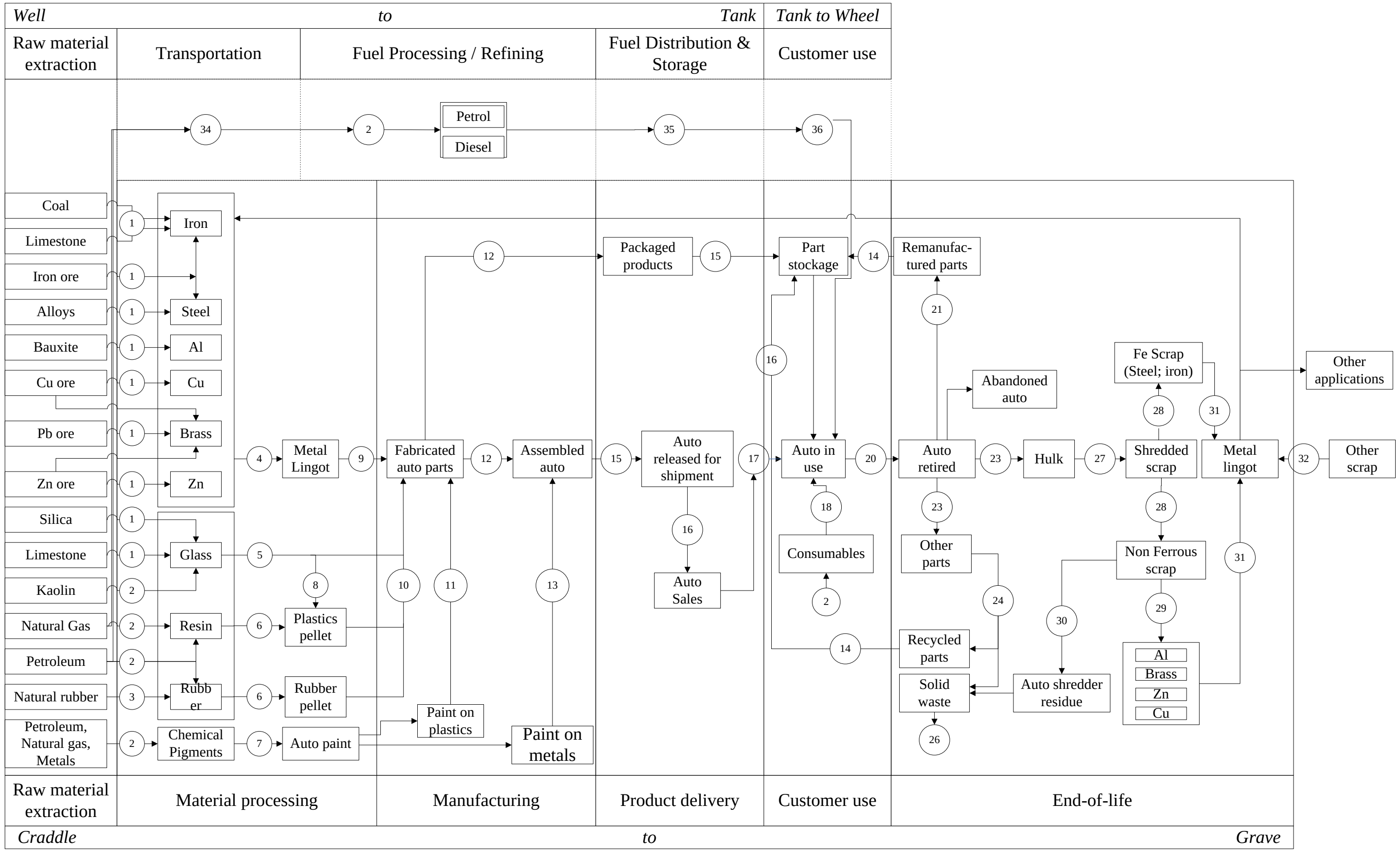


Figure 40. Life cycle energy consumption and waste generation of a generic midsized car based on 192,000 km lifetime service (based on Sullivan *et al.*, 1998)



(1) Mining, refining, ore processing
(2) Drilling, distilling, processing
(3) Latex gathering, processing
(4) Melting, casting
(5) Melting, refining, processing
(6) Molding
(7) Paint manufacturing
(8) Compounding
(9) Casting, extrusion, stamping, machining, joining
(10) Blow molding, injection molding
(11) Spraying, in-mould coloring
(12) Auto assembly
(13) Spraying
(14) Packaging
(15) Preparing auto for shipment
(16) Delivery to dealers
(17) Delivery to customer
(18) Use of consumables
(19) Parts sale
(20) Sale of auto junk
(21) Reuse/remanufacture
(22) Sale of remanufactured parts
(23) Dismantling
(24) Recycling
(25) Landfill disposal
(26) Shredding
(27) Magnetic separation
(28) Separation of non-ferrous metals
(29) Air separation
(30) Processing of scrap materials
(31) Mixing of other scrap
(32) Manufacturing of other products
(33) Transport of primary resource
(34) Transport of finished product
(35) Pumping of liquid fuels, and compression or liquefaction of gaseous fuels.
(36) Dispensing fuels to the final customer.

Figure 41. Life-cycle of a passenger car use: '*Well-to-Wheel*' and '*Cradle-to-Grave*' (adapted from Graedel and Allenby, 1997, Delucchi, 2003)

The life cycle stages included in our study are: material processing (or production), manufacturing and assembly of the vehicle and transplanting kit (hereafter referred to manufacturing), use, maintenance and repair (hereafter referred to as maintenance), and end-of-life. As patent in the USAMP study (Sullivan *et al.*, 1998, not to mention all), the distribution over the vehicle's life cycle stages varies with the environmental burdens under scrutiny. According to the results of that study, 85% LC energy consumption is allocated to car use. Differently, 58% of solid waste is generated during the materials production and 19% during the use of the vehicle (refer to Figure 40).

Our methodological approach includes also the fuel's life cycle inventory. Figure 41 (above) presents a life cycle diagram of a car from "cradle-to-grave"[24] combined with the fuel LC from "well-to-wheel"[25] (adapted from Graedel and Allenby, 1997, Delucchi, 2003). This LC diagram does not comprise the use of LPG (which corresponds to a smaller fraction of fuel used by passenger cars) and biofuels, natural gas based or H_2 fuels that we do not include in our study.

Furthermore, we recognize that we do not include here the life cycle of the road infrastructure (roads, parking lots, lighting, and other components necessary to allow vehicles to perform their functions under a wide array of conditions), since transplanted cars are not expected to impact their LC differently than conventional vehicles. Still, we point out that road infrastructure accounts for 15% of energy consumption or greenhouse gas emissions of a sedan's LC (see Table 7, below), as analyzed by Chester and Horvath (2007) for the US road infrastructures. Importantly, it contributes twice as much as fuel production to the LC environmental burdens. Furthermore, as recognized by Graedel and Allenby (1997), the most significant processes (90% of LC energy consumption) of the road infrastructure interacting with the environment are those related with the manufacture of road materials: minerals (largest component by weight), asphalt pavement, cement, metals and concrete pavement.

As mentioned by Kim (2003), LCA studies of vehicles referred previously have mostly focused on measuring the static environmental performance of a specific model year based on its average characteristics. Here, the meaning of *static* refers to the analytical approach of LCA of cars: analysis of one model produced in a specific year, considering all life cycle stages. As we will describe later, our functional unit is '*car ownership and mobility over 20 years*' and hence we cannot limit the LCI to one single model. In fact, it may easily cover several model years over the time period considered. We have to build our analysis on a dynamic LCI model that allows for the calculation of inputs and outputs for cars produced in different years. For instance, if one consumer buys a car in 1990 that is replaced in 2000, the environmental burdens of the newer vehicle are expected to be lower (provided that the latter is of an equivalent size to the former car type).

[24] All stages of the car since raw materials (e.g., iron ore) are extracted (*cradle*) until the vehicle is dismantled, recycled and final waste is disposed, eventually (*grave*).

[25] All stages of fuels since they are extracted (*well*) until they are consumed for motive power (*wheel*).

Table 7. LC inventory results of car use including infrastructure life cycle (Chester and Horvath, 2007)

		Energy (GJ)	GHG (ton)
Vehicle [a)]	Manufacture	3 (0.3%)	0 (0.2%)
	Operation	890 (77.9%)	69 (80.3%)
	Maintenance & repairs	2 (0.2%)	3 (3.3%)
	EOL	0 (0.0%)	0 (0.0%)
	Sub-total	895 (78%)	72 (84%)
Fuel [b)]	Refining	85.0 (8%)	0.0 (0%)
Infrastructure [c)]	Roadway construction and maintenance	148 (12.9%)	12 (13.4%)
	Roadway lighting	12 (1.1%)	3 (2.9%)
	Herbicides and Salting [d)]	2 (0.2%)	0 (0.0%)
	Sub-total	162 (14%)	14 (16%)
Total		1,142	86

[a)] the vehicle is a 2005 sedan (for a lifetime service of 190,000 miles); [b)] Includes petroleum refining and subsequent supply chain; [c)] Infrastructures include parking lots, different road hierarchy from local streets to interstate highways, for a 10-year lifetime service; [d)] Herbicides are routinely used for vegetation management along roadways and salt for de-icing.

By dynamic LCI modeling we mean that energy consumption, CO_2, CO, NMVOC, NO_X, PM emissions, materials consumption and waste generation are calculated as functions of the vehicle age and model year, for each life cycle stage, and they all evolve over time. The dynamic characteristic of the model aims to incorporate the technology improvements (emissions control, powertrain, and other vehicle designs that affect efficiency), the regulatory and socio-economic requirements (demography, regulation and macro-economic changes) and aging and wear of the car (driving and maintenance behavior), that evolve over time.

Figure 42 illustrates how these factors (regulatory and socio-economic requirements, technology improvement and aging and wear of equipments) influence the energy and environmental efficiency of a vehicle, over time, acting on different parameters of the efficiency equation, at different life-cycle stages of the car.

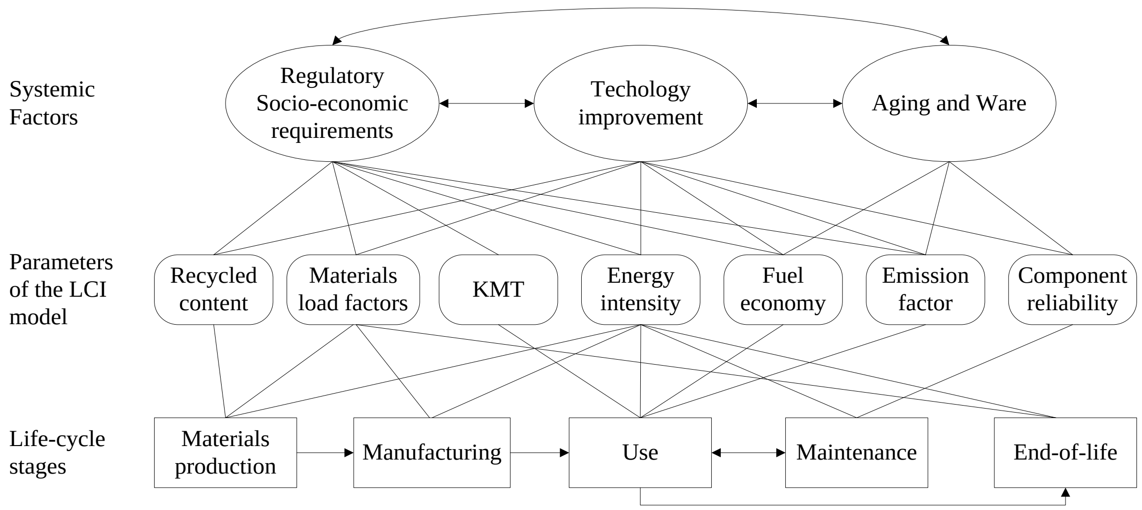


Figure 42. Factors, parameters and life-cycle stages illustrating the dynamic LCI for a generic vehicle (adapted from Kim, 2003)

In the hypothesis of our study, aging and wear of the car are affected by technology improvements since we aim to transplant improved powertrains (or other outdated or malfunctioning equipments) with higher fuel economy and lower environmental intensity. This interaction between systemic factors is reflected in the environmental performance at the bottom of Figure 42 for different life cycle stages. The environmental performance is determined by the parameters of our LCI model (middle row of Figure 42). For example, car technological transplant involves: new equipment production (and thus material use), recycling and scrappage of replaced equipment, new energy intensity of production factors (assuming that industrial procedures and energy sources change), increased fuel economy of the new powertrain, reduced emission factors, and higher reliability (since the equipment is new and more advanced).

Moreover, there are indirect effects motivated by these immediate impacts. For example, if reliability of the new components is higher, then we would expect that the conventional car lifetime is extended by a few years. In this sense, the scrappage of the car and its replacement by a new one are delayed. Down the road, there would be less materials consumption and waste generation (assuming that the remaining variables of the system remain unchanged). These systemic interactions are analyzed in the Part C of this dissertation.

The LCI modeling of the car and transplanting kit (and respective functions and parameter details) are described in section 4.4 (p.118). The overall dynamic modeling approach follows the methodology proposed by Kim (2003). We describe now the functional unit and boundaries of the lifecycle study.

4.2. Functional unit and boundaries of the life cycle study

After reviewing the concepts of LCA, the following sections characterize the objects we are analyzing in this dissertation (i.e., automobile and transplanting kit), describe the functional unit and define the system's boundaries of our analysis.

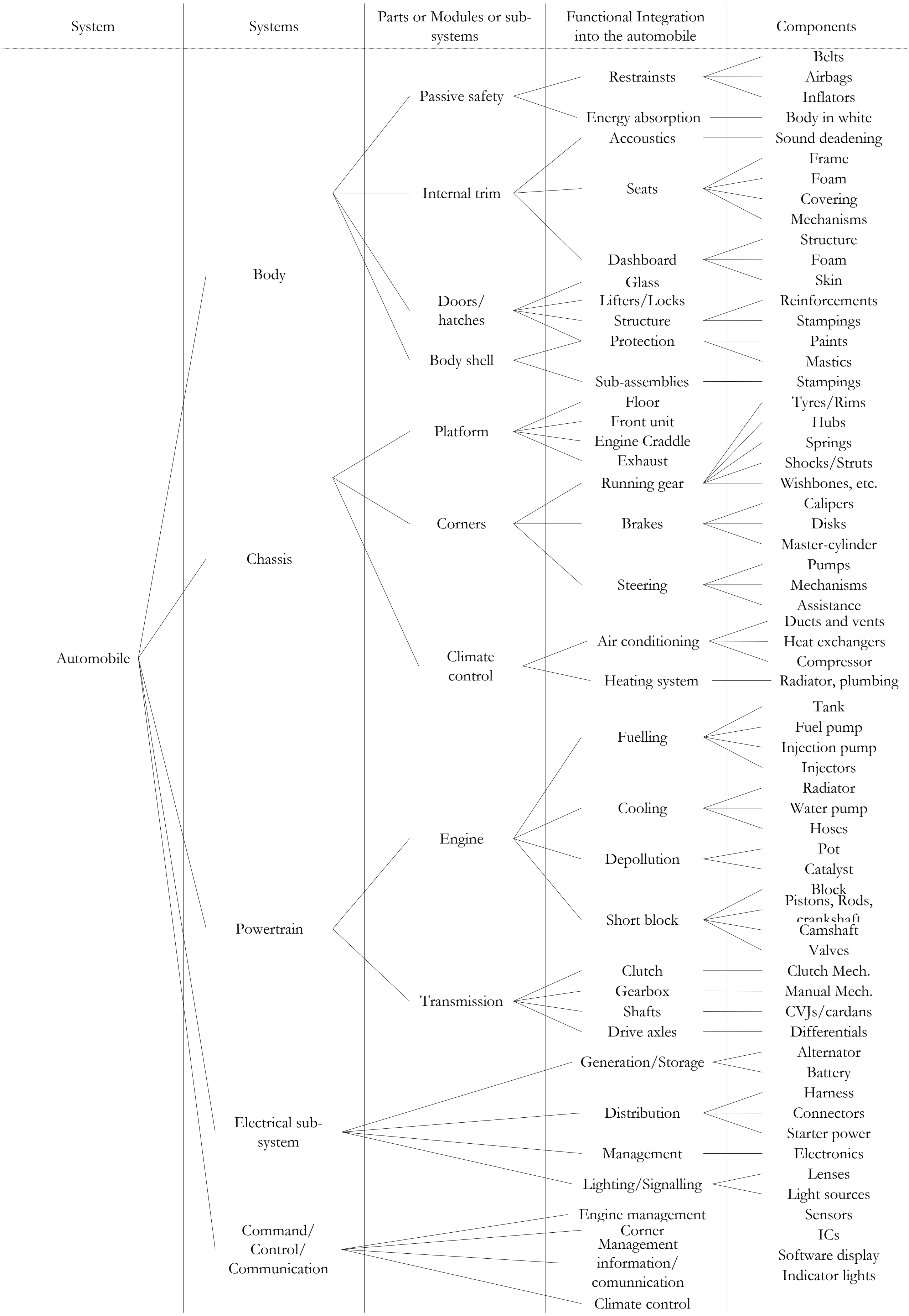


Figure 43. System structure of a generic automobile (Delucchi *et al.*, 2000, Maxton and Wormald, 2004)

Private car and transplanting kits are the centerpieces of our research. Therefore, we briefly describe the generic constitution of an automobile and recall the composition of the transplanting kit we described in Chapter 3.

Automobiles are increasingly multiple compounded systems that are complex to design and develop, given that their sub-systems, parts and components must function together as perfectly and reliably as possible. The major sub-systems of cars are commonly referred to as the body, the chassis, the drivetrain (or powertrain – refer to footnote 1, p.1), the electrical power and the command, control and communication subsystem. Each sub-system divides into parts that have specific functions to which different components respond. Figure 43 (p.106) presents the diagram that illustrates the structure of a generic automobile – adapted from Maxton and Wormald (2004) and Bosch (2004).

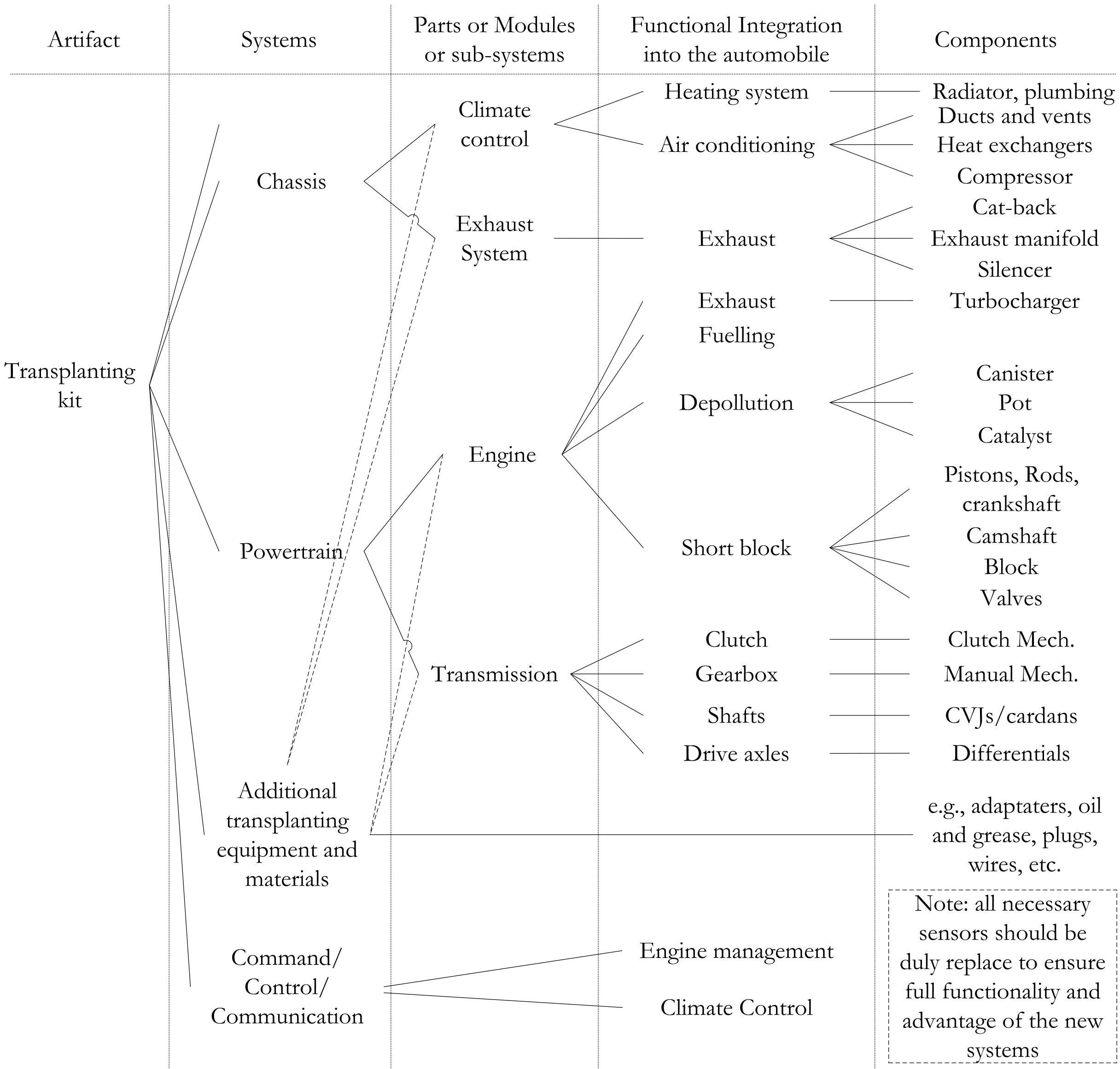


Figure 44. Parts and components of a transplanting kit (source: author based on the classification by Delucchi *et al.*, 2000, Maxton and Wormald, 2004)

We recall in Figure 44, the transplanting kit's composition that depicts our understanding of the parts and components that significantly affect the energy efficiency and emissions of an automobile and that are prone to being transplantable into older vehicles. Again, we refer that we do not rule out other transplanting kit compositions with fewer or more parts and/or components – for example, transplanting the engine only. As mentioned in section 3.2.2 (p.66), for our analysis we decided to consider a more complete set of parts and components that would affect the overall efficiency of the car. Therefore, our results are potentially conservative in the sense that the transplanting kit is more expensive and, hence, less attractive than other cheaper solutions (for example, conventional remarketed cars).

Finally, amid the hundreds of car makes and models available in the market, we had to determine categories of generic cars for simplification purposes. In this sense, our classification is the one used by the TREMOVE project (Ceuster *et al.*, 2007a) and also in the assessment of the economic costs of the voluntary agreement between the European Commission and the major carmakers (Brink *et al.*, 2005), by which associates of ACEA, KAMA and JAMA committed to drastic reductions of CO_2 emissions until 2012. The authors grouped the makes and models according to typical auto industry categories. They also checked for correlation with engine capacities (as used in our study) and their exercise showed that the vast majority of the vehicles fall into the same categories in both cases.

Hence, the *car taxonomy* adopted here is determined by the methodologies used to calculate energy consumption and emissions, i.e. EMEP/CORINAIR guidelines (EEA, 2002). However, this classification is quite different from those used by the automotive industry. We could not find a unique classification system since different sector of activity use different systems. Furthermore, each country produces its own regulations; many vehicles fall into multiple categories or do not fit well into any; not are all car types common in all countries; and names for the same vehicle can differ by region.

The directive 2007/46/EC of the European Parliament and of the Council (September 5th, 2007) establishes a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles. The directive includes the definition of vehicle categories and vehicle types (Annex II of the directive) as follows:

- Category M: Motor vehicles with at least four wheels designed and constructed for the carriage of passengers.
- Category M1: Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat.
- Category M2: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tones.
- Category M3: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tones.

Table 8. Car taxonomy used in the automotive industry and by major rental companies

Example	British English	EuroNCAP	ACRISS code (class and type)	Conventional European size classes in the automotive industry		Our segmentation
Smart Fortwo	Microcar, Bubble car	-	MC	A	Mini	Small (Gasoline or Diesel)
Renault Twingo	City car	Supermini	ED			
Renault Clio	Supermini		ED	B	Small	
Ford Focus	Small family car	Small family car	CD	C	Lower Medium	Medium (Gasoline or Diesel)
Volkswagen Passat	Large family car	Large family car	SD	D/F	Medium	
Audi A4	Compact executive car		SD	E/F	Upper Medium	Big (Gasoline or Diesel)
BMW 5 Series	Executive car	Executive car	FD	H		
BMW 7 Series	Luxury car	-	PD	-	Luxury	
Porsche 911	Sports car	-	XS	-	Sport	
Jaguar XK	Grand tourer	-	PX	-	-	-
Ferrari F50	Supercar	-	XX	-	-	-
Volkswagen Eos	Convertible	-	XX	-	-	-
BMW Z4	Roadster	Roadster Sports	FT	-	-	-
Citroën C4 Picasso	Leisure activity vehicle	Small MPV	CW	M	MPV	Big (Gasoline or Diesel)
Opel Meriva	Mini MPV		CC			
Ford Focus C-MAX	Compact MPV		IW			
Ford Galaxy	Large MPV	Large MPV	IM			
Suzuki SX4	Mini 4x4	Small Off-Roader	CD	-	-	-
Honda CR-V	Compact 4x4		XF	-	-	-
BMW X5	Large 4x4	Large Off-Roader	XF	-	-	-
Jeep Grand Cherokee	Off-roader		XF	-	-	-

Within the Category M1, the directive defines the following vehicle types, according to the bodywork type: saloon, hatchback, station wagon, coupé, convertible and multi-purpose vehicle. However, this classification is not suitable for other purposes, since it is too aggregate. In a different way, major car rental companies use the letter segmentation and/or the ACRISS classification code (http://www.acriss.org), while the European New Car Assessment Program has their own EuroNCAP code (http://www.euroncap.com).

The ACRISS Car Classification Code (http://www.acriss.org) is a code used by many car rental companies, including Avis, Hertz, Alamo, Europcar and National, for classifying the category of vehicles. It has four letters:

- 1st letter determines the car class: M = Mini; E = Economy; C = Compact; I = Intermediate; S = Standard; F = Full Size; P = Premium; L = Luxury; X = Special);
- 2nd letter determines the car type (B = 2 Doors; C = 2/4 Doors; D = 4 Doors; W = Wagon/Estate; V = Van (over 6 passengers); L = Limousine; S = Sport; T = Convertible; F

= 4-Wheel Drive; P = Pick Up; J = All Terrain; K = Van (cargo); X = Special; R = Recreational);

- 3rd letter determines the car transmission: A = Automatic; M = Manual; and
- 4th letter determines the presence of Air Conditioning: R = Yes; N = No.

The Euro NCAP (http://www.euroncap.com) is a European car safety performance assessment program founded in 1997 by the Transport Research Laboratory for the UK Department for Transport. The organization is now backed by the European Commission, the governments of France, Germany, Sweden, The Netherlands and Spain, as well as motoring and consumer organizations in every EU country. Euro NCAP publishes safety reports on new cars, and awards 'star ratings' based on the performance of the vehicles in a variety of crash tests, including front, side and pole impacts, and impacts with pedestrians.

The latter classifications are more detailed than the categorization included in the EU directive. The previous table is an illustration of common classifications of car types.

Analysis in Part C (Chapters 7, 8 and 9) include all car types presented in the last column of Table 8. In the present part of the dissertation, we address medium gasoline-fuelled cars only, according to five scenarios of car ownership used to compare the impacts of technological transplant.

The functional unit for this study, i.e. what will be analyzed and compared, is defined as the 'ownership and mobility of a generic car over a period of 20 years or 300,000 km service'. The functional unit includes the complete service lifetime for one (or several) generic mid-sized gasoline-fuelled vehicles depending on the car ownership choices of the individual (or household) over the 20 years period. Average personal annual motorized kilometrage does not differ greatly amongst industrialized countries, ranging from 10,000 to 15,000 kilometers per car per annum (Eurostat, 2003b, Davis and Diegel, 2006). Therefore, the service lifetime can also be defined as 200,000 km to 300,000 km. We opted in this chapter for a lifetime service of 300,000 km.

Finally, the size of parts and components, the technology and the material composition of vehicles and transplanting kits vary from one car type to another. However, these differences are not accounted for in the analysis of the present chapter. The results of the study are expected to be representative of the achievable results of any gasoline-fuelled midsized automobile regardless of material or design differences. A sensitivity analysis is performed later in this chapter to assess the robustness of our conclusions.

4.3. LCI model

The analysis of the lifecycle of a car (or parts and components of the car) is based on dynamic modeling approach that includes the following energy and environmental burdens: energy consumption (expressed in gigajoules), CO_2, CO, NMVOC, NO_X, and PM emissions (all pollutants expressed in kilograms), material consumption and waste generation (both expressed in kilograms). We note that material consumption striving from maintenance (e.g., oil, filters, spark plugs, wiper blades, disc brakes, battery, etc.) and repairs (e.g., water pump, fuel pump, bumper, alternator, suspension, etc.) are a smaller fraction of the overall lifecycle (4% on a weight-basis, according to the USAMP study, not considering petroleum and the water used) and therefore is not addressed in the use and maintenance sections, below. Similarly, waste produced during use and maintenance of cars is also a smaller share of the lifecycle materials burden (4% on a weight-basis) and therefore it was not considered in those lifecycle stages.

In this study, the lifecycle inventory (LCI) analysis of a car and transplanting kit (referred to as TK) builds on the LCI results from the USAMP survey and other complementary studies (Schweimer and Levin, 2000, among others, Finkbeiner *et al.*, 2006). The dynamic modeling of LCI follows the methodology proposed by Kim (2003). The basis of the methodology is to calculate environmental burden intensities (i.e., energy intensity, emissions factors and material load factors) for each model year (*y*) and age (*k*), in calendar year (*t*) – whether it is a car or a TK. The following generic equation is used to calculate environmental burdens over the 20-years horizon of analysis:

$$E(p,y,k,t)=\sum_{p=1}^{20/f}\sum_{t=1}^{t+f}e(p,y,k,t)\times M(E,y,k,t) \qquad 4\text{-}1$$

where,

E denotes the total environmental burden under scrutiny (as mentioned in the introductory paragraph);

e denotes the environmental burden intensity (e.g., fuel economy in grams/km) – coefficient of the previous equation;

M(E,y,k,t) refers to the multiplicand (or factor) of the equation that might be annual kilometers travelled, if the environmental burdens E under analysis is energy consumption or emissions, or curb weight, if E refers to material consumption or waste generation; and

f indicates the periodicity of car swap or transplant (for simulation purposes, f is constant over the time period of analysis) and *p* is the corresponding number of car owners over 20 years – *p=20/f*, where *p* is conceptually an integer and if otherwise resulting from this quotient the decimal fraction indicates that that the last owner has had the car for a shorter period than f.

The dynamic characteristic of our LCI model is taken into account since the environmental burden intensity (*e*) varies with the model year (*y*) and age (*k*), over time (*t*). We emphasize that the formula of the coefficients *e* varies according to the life cycle stage. The detailed modeling processes we used to calculate environmental burden for each life cycle stage is described in the following sections.

4.3.1 Materials production

According to the surveys we reviewed, materials production makes the second largest contribution to the total environmental burdens of a vehicle life cycle, accounting for 9-11% of energy consumption (and 6-8% of CO_2 emissions). The largest is the use phase (including fuel production and maintenance), responsible for more than 80% of both life cycle burdens (i.e., energy consumption and emissions). Materials production is by far the largest consuming stage of raw materials (e.g., 99.8% of iron and 78% of water used, according to Sullivan *et al.*, 1998). This stage includes raw material acquisition, transportation and processing, prior to the parts and components manufacturing and assembling of vehicles (which is the manufacturing phase of the vehicle).

Energy consumed and pollutants emitted during materials production depend primarily on the production and processing efficiency parameters of the iron, steel and plastics industries, since these materials corresponds to more than 85% of the car's curb weight (refer to section 4.1). These parameters are expressed in GJ/kg_{material} or g/kg_{material} for energy intensity and emissions, respectively. Other materials include non-ferrous metals, such as aluminum, copper, etc., and other non-metallic materials, such as glass and other miscellaneous materials. The car-equivalent composite energy intensity and emission factors are obtained by calculating the weighted average factors on the basis of the cars' material weight composition. Refer to section 4.4 for details on the estimation of these parameters.

With respect to raw materials consumption and waste generation, the coefficient e is based on the materials flows presented in section 4.4.5 and is calculated on the percent-material fraction (m) of the car and the corresponding load factor (l), (see Eq.4-2). The load factor is an indexed value to the curb weight of a finished car (where, index = 1).

$$e(m, lc, y) = m(y) \times l(lc) = m(y) \times \frac{m^*(lc)}{m^*(car)} \qquad 4\text{-}2$$

where y refers to the model year of the car, or TK, lc refers to life cycle stage under analysis, $m^*(lc)$ is the reference material fraction used in the life cycle lc (as presented in Ginley, 1994, cited in Graedel and Allenby, 1998, and Sullivan *et al.*, 1998) and $m^*(car)$ is the reference material fraction of the car used by the same authors. Although the automotive industry is constantly evolving over time (and getting more efficient, supposedly), we consider the load factors to be constant over time.

Referring to Eq.4-1, the multiplicand (M) refers (in this case) to the curb weight of the car that varies with the model year, since the industry is introducing lighter materials (e.g., aluminum) in the car composition in response to government's expectations of increased fuel economy. Still, crash requirements, manufacturing costs and consumer preferences for additional car equipments and functions can result in increased vehicle weight. On the whole, the weight evolution of a generic car is not necessarily in the downward trend. We comment on this issue in forthcoming sections, when we describe the car weight evolution we used in our research.

4.3.2 Car manufacturing

This stage corresponds to the manufacturing of parts and components and assembling of the final car. Parts manufacturing represents the primary transformation of engineered materials including stamping, casting, forging, molding, etc... Discrete parts often require many other processing steps, such as machining, cleaning, trimming, etc. Components manufacturing involves further processing and assembly of parts into higher-level components. Final vehicle assembly integrates all parts, components, and fluids into the final vehicle for final test and rectification before entering the distribution and retailing circuits. Refer to Figure 45 for an illustration of the major steps in producing an automobile, including the materials production also.

Environmental burdens are also calculated on a weight basis and the coefficients are expressed in (GJ/kg $_{vehicle}$ or TK) or (kg $_{pollutant}$/kg $_{vehicle}$ or TK) for energy consumption and emissions, respectively. Refer to section 4.4 for details on the estimation of these parameters.

4.3.3 Use ('Well-to-wheel')

As presented in Figure 41 (p.102), the use phase of the car belongs to both vehicle and fuel life cycles and environmental burdens associated to this phase can be classified into the pre-combustion ('well-to-tank') and combustion ('tank-to-wheel') burdens. Combustion environmental burdens are functions of VKT (vehicle kilometers travelled) over the vehicle's life cycle and the vehicles' fuel economy and emission factors. Hence, in the equation 4-1, the factor *M* corresponds to the kilometers travelled yearly.

Energy consumption and emissions for the pre-combustion phase (i.e., 'well-to-tank') include resource extraction, initial conversion of petroleum, transport of petroleum, fuel production and distribution and marketing of gasoline and diesel. The following graphs (Figure 46 to Figure 49) present the fuel's life cycle energy efficiency and carbon intensities (greenhouse gases – GHG) as calculated in a collection of studies reviewed by MacLaen and Lave (2003), to which we added the USAMP results. Energy intensity was calculated from the number of MJ of fuel delivered to consumer divided by the number of MJ of primary energy input. Greenhouse gases are reported in the studies in grams of CO_2 equivalent[26] emitted to produce 1 MJ of fuel. Information regarding the remaining pollutants was taken from other complementary sources (Wang, 1999, Edwards *et al.*, 2006).

[26] CO2 equivalent includes CO2, CH4, and N2O that are weighted by their Global Warming Potential (GWP), where the GWP is the 100-year International Panel on Climate Change (IPCC) values of 21 for CH4 and 310 for N2O (Watson and the Core Writing Team, 2001, p.47). Globally, CO2 emissions account for more than 99% of the fuels CO2 eq. emissions (refer for example to APA, 2007).

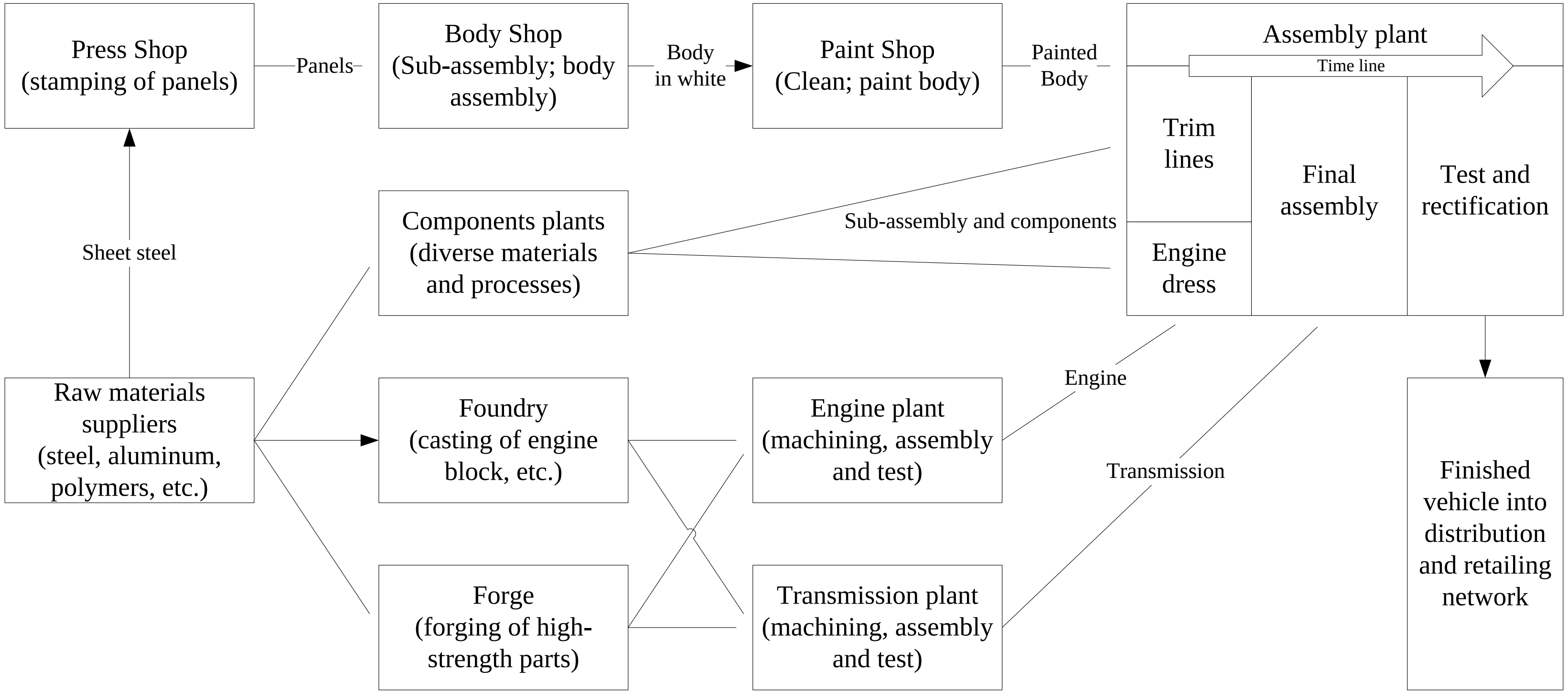


Figure 45. Major steps in producing an automobile (Maxton and Wormald, 2004, p.143)

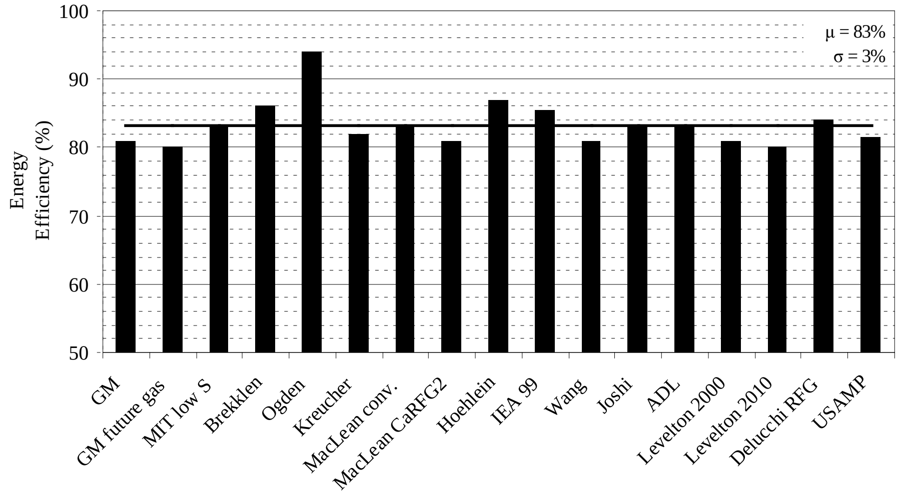


Figure 46. Gasoline fuel cycle ('well-to-tank') efficiencies reported in life cycle studies (Wang, 1999, Edwards *et al.*, 2006)

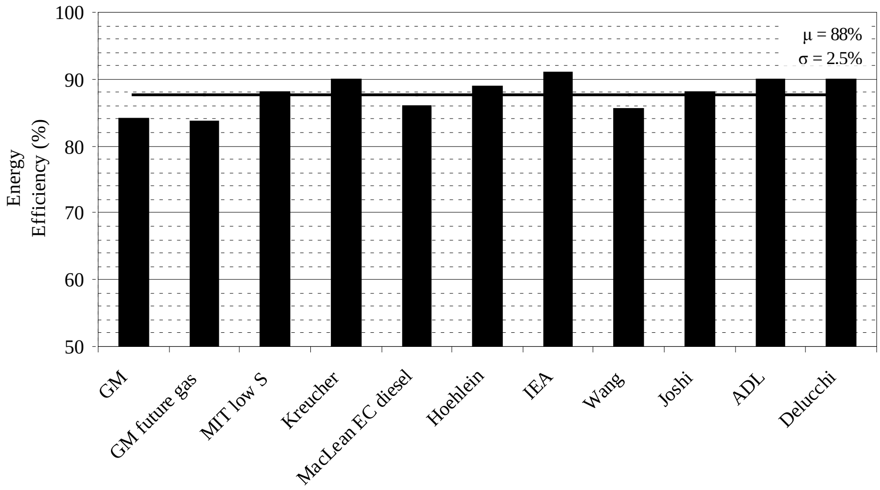


Figure 47. Diesel fuel cycle ('well-to-tank') efficiencies reported in life cycle studies (Wang, 1999, Edwards *et al.*, 2006)

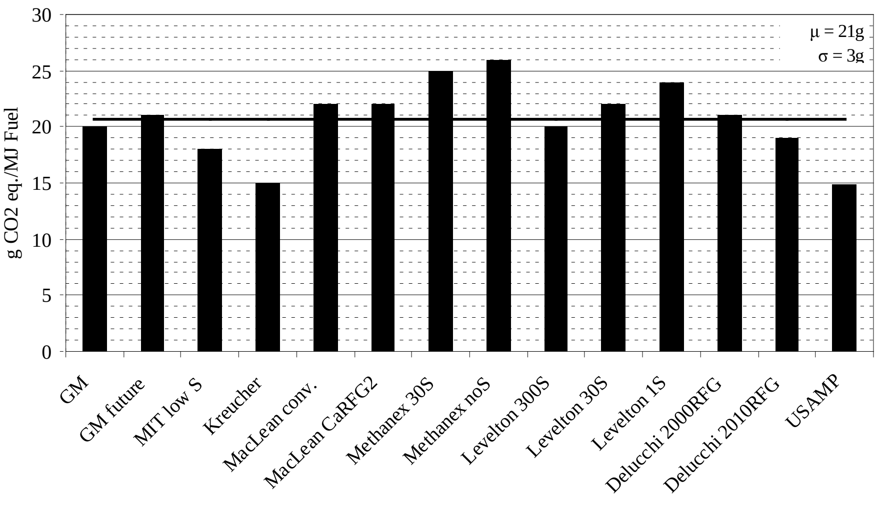


Figure 48. Gasoline fuel cycle (well-to-tank) GHG emissions reported in life cycle studies (Wang, 1999, Edwards *et al.*, 2006)

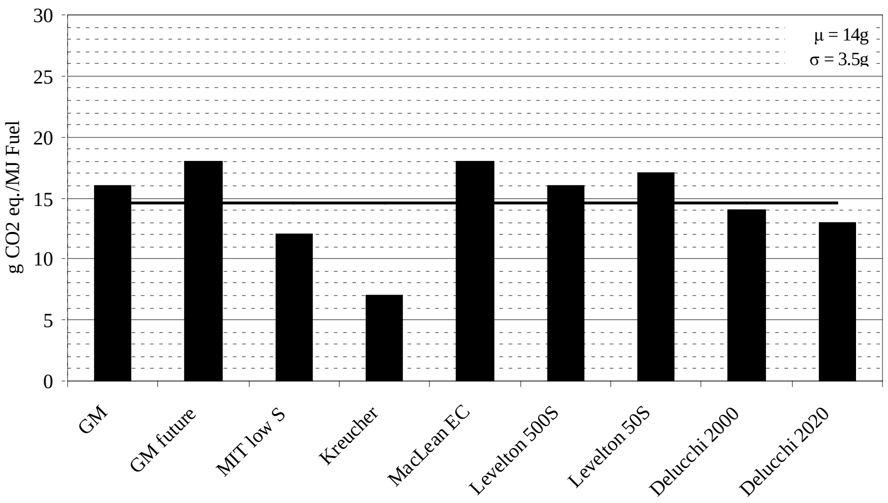


Figure 49. Diesel fuel cycle (well-to-tank) GHG emissions reported in life cycle studies (Wang, 1999, Edwards *et al.*, 2006)

The pre-combustion environmental burdens of the use phase are calculated with the following equations.

$$E(fu,p,y,k,t)=\begin{cases}\sum_{fu=1}^{2}\sum_{p=1}^{20/f}\sum_{t=1}^{t+f}\frac{VKT(t)\times FE(fu,p,y,k)}{e(fu)}, & (for\,energy)\\ \sum_{fu=1}^{2}\sum_{p=1}^{20/f}\sum_{t=1}^{t+f}VKT(t)\times e(fu), & (for\,GHG)\\ \sum_{fu=1}^{2}\sum_{p=1}^{20/f}\sum_{t=1}^{t+f}(VKT(t)\times FE(fu,p,y,k))\times e(fu), & (for\,other\,emissions)\end{cases} \quad 4\text{-}3$$

where *FE(fu,y,k)* is the fuel economy (expressed in g/km) of the model year (*y*) and age (*k*), powered with the fuel (*fu*), and *VKT* is the vehicle kilometers travelled.

We note that the LCI analysis of fuels is not dynamic, i.e., we use static aggregate emission factors, in opposition to the approach to the vehicle's analysis. Implicitly, we accept that the refining industry (and remaining fuel's LC stages) does not vary its overall performance – or at least that variation is not significant for the purpose of our analysis, effectively being categorized as a second-order effect. Although the description of the LCI parameters will be made later, Table 9 shows the 'well-to-tank' LCI parameters, as currently adopted.

Table 9. 'Well-to-tank' environmental burden parameters

Fuel	Energy Efficiency [a] (MJ Final Fuel/MJ Input Energy)	CO_2 eq. [a] (g/MJ)	CO [b] (g/vkm)	NMVOC [b] (g/vkm)	NOx [b] (g/vkm)	PM [c] (g/vkm)
Gasoline	0.83	20.5	0.087	0.060	0.124	0.012
Diesel	0.88	14.7	0.057	0.024	0.074	0.007

Sources: [a] MacLaen and Lave (2003) and Edwards *et al* (2006); [b] Wang (1999); [c] Sullivan *et al* (1998)

4.3.4 Maintenance and repairs

The maintenance and repairs phase accounts for the material production and manufacturing burdens of replacement parts. This phase includes both scheduled maintenance and unscheduled repairs. Unscheduled repairs are often associated with component failures while scheduled maintenance refers to preventive part replacements as prescribed by the vehicle manufacturer. The logic behind the calculation of the environmental burdens here is that the more the car travels the more there will be maintenance and repair operations and, hence, they depend mostly on the vehicle kilometers travelled (VKT). Likewise the combustion use phase, maintenance environmental burdens are functions of the VKT yearly, in the case of energy consumption and emissions. Refer to section 5.2.5 (p.156) for details on the frequency and description of the items replaced or repaired over the vehicle's lifetime.

The environmental burden intensities were taken from Kim (2003) estimated for the USA context, which might bias our estimates for the Portuguese situation. Still, we find it acceptable for our simulation purposes since maintenance accounts for less than 2% of the life cycle energy consumption and emissions. We note that the occurrence of unscheduled repairs is extremely variable and depends, among other aspects, on the overall VKT (as already mentioned) and on the car owner behavior (e.g., driving style, adequate maintenance procedures, etc.). For the purpose of life cycle ownership costing (Chapter 5), we analyze this issue in more detail. Regarding the environmental LCI, it is assumed by Kim (2003) that unscheduled repairs occur after 10 years (i.e., approximately 150,000 km of VKT). Additionally, we assumed that the environmental burden does not depend on the car type, i.e. energy consumption and emissions do not vary greatly with the car size.

4.3.5 End-of-life

The end-of-life (EOL) phase influences only marginally the car's LC energy consumption (0.2%) and emissions (e.g., 0.04% of CO emissions). The EOL environmental burdens depend on the car material composition and energy intensity parameters of EOL processes. These consist of four components: transportation of the used car to a dismantling facility; dismantling; shredding; and disposal of the shredder residues, where the transportation of retired vehicles or substituted parts and components represent 66% of the total energy consumed during this phase (Sullivan *et al.*, 1998). It is assumed that the EOL environmental burden is proportional to the vehicle's curb weight. Again, the calculation of environmental burdens is based on the unit mass (kg) of cars and the coefficient e is expressed in $(GJ/kg_{vehicle\ \text{or}\ TK})$ or $(kg_{pollutant}/kg_{vehicle\ or\ TK})$, regarding energy consumption and emissions, respectively. As with the material production and manufacturing phases, we estimate the coefficient e based on the results provided by Kim (2003). Again, we implicitly accept that Kim's evolution of the vehicle's material composition is embedded in the coefficients we calculate.

With regards to waste generation, we used the same procedure as the material production and vehicle manufacturing phases (refer to section 4.3.1 and Eq.4-2, p.112). Material consumption is not significant during the EOL stage (less than 0.6% according to the USAMP survey).

4.4. LCI parameters

The following sections provide the parameters and major assumptions of generic gasoline-powered car LCI model, including energy intensity, emission and material load factors. As referred in chapter 2, the technosystem of a car includes a whole cluster of upstream and downstream technologies regarding materials and fuel production, car assembly, dismantling, reuse, recycling and waste final disposal. They all evolve over time and, thus, the energy intensities and emission factors presented here include their historical trends and forecasts. For the use phase, we dedicate two specific sections for the fuel economy and emissions, respectively, where we present more detailed calculation methodologies.

We used information mainly from the following studies: the USAMP survey (Sullivan *et al.*, 1998), a survey on a VW Golf (Schweimer and Levin, 2000), a survey on a Mercedes-Benz S-class (Finkbeiner *et al.*, 2006), the study on dynamic LCI by Kim (2003), the life cycle emission model developed by Delucchi (2003) and the study on the life cycle performance of remanufactured engines by Smith and Keoliean (2004).

Regarding the use phase, fuel economy of cars is calculated based on a logarithmic regression of data presented in several studies (EEA, 2002, ACEA, 2003, Worrell and Biermans, 2004, Brink *et al.*, 2005b, Ceuster *et al.*, 2007b). These studies include estimates of average fuel economy (past and forecasted) for different car types. Likewise, we estimated emission factors during the operation of cars following the EMEP/CORINAIR guidelines (EEA, 2002). We recall that parameters for the LCI analysis of fuels ("well-to-tank") were presented in Table 9 (p.116).

Table 10 presents the LCI aggregate results (and estimated emission factors) from the generic midsize sedan analyzed by the USAMP, from the gasoline VW Golf surveyed by Schweimer and Levin (2000) and from the Mercedes-Benz S-Class survey by Finkbeiner et al. (2006).

Importantly, we underline some differences between these studies: life cycle stages considered are different; vehicles are from different model years (1995, in the case of the USAMP survey, 2000 in the case of the VW Golf, and 2005 for the Mercedes-Benz analysis); the Mercedes Benz is heavier and its engine is bigger than the vehicles analyzed by the USAMP, which in turn are all heavier than the VW Golf; and finally, the service mileages are also different (refer to the table's notes for details). For comparison purposes, we calculated the energy intensity and emission factors for equivalent LC stages of all surveys.

Table 10. LCI results of the USAMP generic car, of a VW Golf and a Mercedes-Benz S-Class

Totals (GJ or kg)	USAMP (1995) [a]						VW Golf (2000) [b]					Mercedes-Benz (2005) [c]				
	Vehicle	Mat. & Man.		Operation		EOL	Vehicle	Mat. & Man.		Operation		Vehicle	Mat. & Man. [j]	Operation		EOL [k]
		Mat.[d]	Man.[e]	Operat.[f]	Maint.[g]			Mat.	Man.	Fuel [h]	Operat.[i]			Fuel	Operat.	
Energy Cons.	973	94	39	821	17	2	445	48	37.6	34	325	1,359	190	166	1,000	2
CO_2	59,091	4,440	2,562	51,331	615	143	29,732	1,890	2,512	1,991	23,339	94,600	10,406	11,352	72,700	142
CO	1,943	64	6	1,833	39	1	n.a.	n.a.	n.a.	n.a.	n.a.	115	35	16	63	1
NMVOC	257	13	7	235	2	0	107.7	4.8	1.6	94.3	7	198	11	179	8	0
NO_X	254	13	8	229	3	1	23.9	4.2	5.2	11.5	3	74	19	49	4	2
PM	53	26	8	17	2	0	10.09	7.77	7.19	1.85	0.59	n.a.	n.a.	n.a.	n.a.	n.a.
Energy consumption and emission factors [l]																
Energy Intensity	n.a.	87.26		4.36		1.41	n.a.	80.83		2.39		n.a.	105.48	3.89		1.13
CO_2	n.a.	4,571		270		93.52	n.a.	4,157		169		n.a.	5,765	280		78.61
CO	n.a.	45.51		9.75		0.45	n.a.	n.a.		n.a.		n.a.	19.26	0.26		0.32
NMVOC	n.a.	13.04		1.23		0.11	n.a.	6.04		0.68		n.a.	6.06	0.62		0.11
NO_X	n.a.	13.82		1.21		0.53	n.a.	8.88		0.10		n.a.	10.27	0.18		1.01
PM	n.a.	22.65		0.1		0.16	n.a.	7.22		0.02		n.a.	n.a.	n.a.		n.a.

[a] Sullivan et al. (1998) (midsize gas. sedan; 1,532 kg; 120,000 miles service or 192,000 km); [b] Schweimer and Levin (2000) (gas. VW Golf; 1,058 kg; 150,000 km service, 10 years);

[c] Finkbeiner et al. (2006) (Mercedes-Benz S-Class gas. car; 1,805 kg; 300,000 km service);

[d] Materials production (including raw material extraction, transportation and processing);

[e] Vehicle Manufacturing (including parts and components manufacturing and assembling of vehicles);

[f] Operation includes fuel production also;

[g] Maintenance and repairs; [h] Fuel production; [i] Differently, this survey groups the operation, maintenance and EOL environmental burdens;

[j] Groups LC phases described in [d] and [e]; [k] In the survey this stages is referred as "recycling" and we assumed it includes all the EOL processing;

[l] Energy intensity (and emission factors) is expressed in MJ $_{\text{Input}}$/kg $_{\text{Vehicle or TK}}$ (and g/ kg $_{\text{Vehicle or TK}}$) in the case of materials production, manufacturing and EOL; or, in MJ Input/vkm (and g/vkm) in the case of operation, fuel production and maintenance.

From Table 10, we conclude that generically the LCI of the German models are quite similar. Differently, the USAMP survey presents some discrepancies. Energy intensities and emissions factors are, in general, of the same order of magnitude, except in the case of CO, NOx and PM emissions during car use, where USAMP vehicles emit more by factors of 37, 9 and 6, respectively. The fact is that the USAMP vehicles are older and, meanwhile, environmental control equipments were introduced to comply with the much more stringent regulation progressively enforced since then. Similarly, the Mercedes Benz is more energy and carbon intensive than the Golf, during the operation stage, since it has a larger engine. Similarly, energy intensity and emission factors presented by USAMP for materials production and manufacturing stages double those estimated for the German models. This relates to the intrinsic characteristics of the materials and automotive industries. We will come back to the transferability of LCI analyses later. Finally, materials consumption and waste generation load factors were taken from the USAMP survey (Sullivan *et al.*, 1998), from the VW Golf survey (Schweimer and Levin, 2000), and from Gidley's material flow analysis for the transport industry (1994, cited in Graedel and Allenby, 1998).

4.4.1 Annual vehicle kilometers

A number of factors have a significant impact on the annual vehicle kilometers of cars: vehicle type and technology (which depend on the price and taxation level), running costs (which depend on the fuel type and air emissions), vehicle age and a set of other parameters such as the range of the vehicle, marital and professional status of car owners, 1st or 2nd car of the household, etc. According to the 1994 figures presented by André et al. in the MEET project (Andre *et al.*, 1999), the average annual kilometers travelled per household vehicle varies greatly amid the EU member states: from 10,000 km (Spain) to 19,000 km (Finland), and the average reaches approximately 15,000 km/year. Among the factors presented above, the fuel type strongly influences car use: the 1st year mileage of gasoline-powered cars is 12,000 km, on average, while for diesel-powered it is more than 21,000 km. Moreover, statistical evidence suggests that car usage decreases also with age, due to the shifting of the primary to secondary car usage, among other issues. In a detailed analysis of a Swiss survey on the use of passenger cars (cited in Andre *et al.*, 1999), a primary vehicle of a three-car household was driven, on average, 14,418 km per year while secondary and tertiary vehicles were driven 8,478 and 5,117 km, respectively. Finally, according to a French survey (also cited in André et al., 1999), the annual mileage of cars varies also with the environment where the vehicle is driven. For example, cars circulating in large cities are driven on average 13,000 km while in rural areas cars are driven on average 14,500 km (here, differences are not so meaningful).

As referred in section 9.4.1 (p.284), there are no statistics available for the Portuguese situation. Therefore, after the calibration procedure described in that chapter, we estimated the following 1st year mileage for gasoline and diesel cars in Portugal.

Table 11. First year mileage by car type

Fuel Type	Gasoline			Diesel		
Engine Size (c.c.)	<1,400	1,400-2,000	>2,000	<1,400	1,400-2,000	>2,000
First year mileage	8,800	9,200	9,400	22,500	24,000	24,500

Regarding annual kilometrage variation during the car lifetime service, we assumed the same decreasing factors for all car types (refer to the next equation and Figure 50 that shows the indexed mileage curve we used), as presented by Samaras et al. (2002) and used in the TREMOVE project (Ceuster *et al.*, 2007b).

$$KM_{i,k} = KM_{i,k=0} \times \left[-0.2056 \times ln(k) + 1.1413\right] \qquad 4\text{-}4$$

, where *i* refers to the car type and *k* corresponds to the car age.

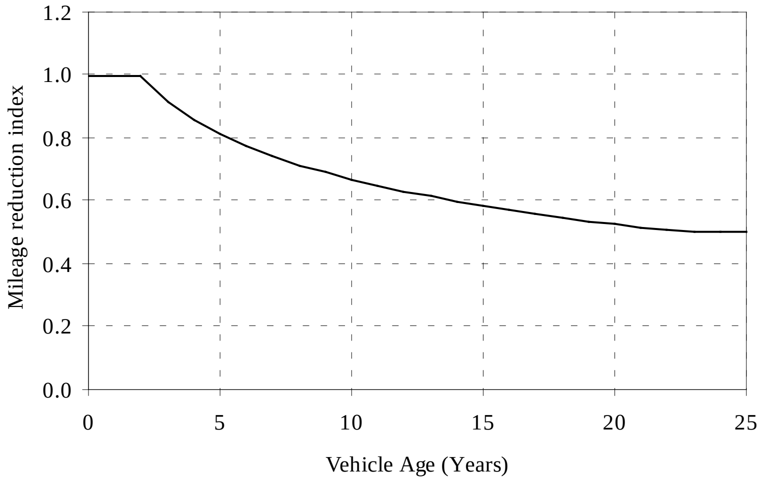


Figure 50. Variation of car usage with age (Samaras *et al.*, 2002)

In the present chapter, we address the case of a midsize gasoline-powered car and therefore the 1st year mileage is 9,200 km and the usage factor decreases according to the curve of Eq.4-4. The details regarding the effects of this curve on LC emissions are described and discussed in Chapter 9, where we perform a sensitivity analysis to the shape and parameters of this curve.

4.4.2 Energy intensity and emissions for up and downstream phases to car use

As mentioned earlier, we use the static LCI analyses resumed in annex A.4 (p.363), as reference values for the base year 2000. We referred also that LC inputs and outputs vary with time as material and production technologies or dismantling and recycling technologies evolve and become more efficient, eventually. In this sense, it is assumed that environmental burdens vary proportionately with the energy intensity of the materials and automotive industries or EOL facilities – as suggested by Kim (2003). We note that 'end-of-pipe' techniques can reduce emissions from industrial activities without involving improvements on the energy intensity of those industries[27]. That is, emission reductions can be greater than those achieved through

[27] For instance, the EU BREF's (Best Available Technology References) on the production of iron and steel give some examples of BATs that can further improve the environmental performance of this industry (IPPC, 2001a).

increased energy efficiency and therefore our estimates based on variation of the energy intensity are conservative, eventually.

Regarding the variation of energy intensity coefficients, Kim (2003) used the historical trends reported by the US Department of Energy and from American industry associations (such as the Aluminum Association), whereas forecasts were taken from the Annual Energy Outlook by the US Energy Information Administration (EIA). Prudently, we verified to what extent these estimates are transferable to the EU context, considering that our research focuses mostly vehicles from the European market: 90% of cars sold in Portugal (in 2006) were manufactured by ACEA members, 7% by the JAMA and KAMA members and less than 1% by the American Big Three[28] (ACAP/AUTO INFORMA, 2007). In this sense, we compared the evolution of the US industries (as used by Kim) with European industries (see Table 12). From this table, we confirm that the historical trends of the iron and steel and aluminum industries from the USA and the EU are consistent. Therefore, we use the environmental burden coefficient for the materials production stage, estimated from Kim (2003).

Table 12. Energy intensity (MJ/kg) for the iron, steel and aluminum production

Industry	USA	EU	2020 Forecast [e)]	Theoretical Minimum [f)]
Steel and Iron †	32; 27; 25 [a)]	24;21;19 [c)]	15	7
Aluminum ‡	90;63;55;50 [b)]	76;61;54;50 [d)]	40	32

† Steel production energy intensity from iron ore to crude steel;

‡ Aluminum production energy intensity from bauxite ore to primary aluminum;

a) Values refer to 1980, 1990 and 1998 (Worrell *et al.*, 1997, Kim, 2003);

b) Values refer to 1950, 1990, 1998 (Choate and Green, 2003) and today (Kim, 2003);

c) Values refer to 1980 (Worrell *et al.*, 1997), 1990 (idem) and 2000 (IPPC, 2001a);

d) Values refer to 1950 (Moors, 2006), 1980 (IPPC, 2001b), 1998 (idem), and today (Moors, 2006);

e) According to the forecasts by the Annual Energy Outlook from the Energy Information Administration;

f) We found several thermodynamic minimum energy requirements, in the literature, although with small variations (among others, Utigard, 2005, Moors, 2006).

Regarding the manufacturing life cycle phase, we previously said that coefficients depend on the automotive industry energy and environmental performances. After comparing the manufacturing energy intensity presented by USAMP survey (and used by Kim), 61MJ/kg in 1995, and the value presented by Schweimer and Levin (2000), 48MJ/kg in 1998, we observed that the German carmaker consumes less 20%. With respect to energy consumption and CO_2 emissions, values are equivalent. Despite the differences between car making industries, we calculated environmental burden coefficients based on data from Kim (2003). We recall that the car manufacturing stage accounts for less than 3-4% of the LC energy consumption and emissions and, hence, our assumptions do not decisively influence the overall LC analysis.

[28] The Big Three are General Motors, Ford and Chrysler.

Regarding EOL, environmental burdens are associated with dismantling, shredding and transportation of retired vehicles or substituted parts and components. In addition, nearly 66% of the EOL-related energy is consumed during their transportation. Therefore, the variation of environmental burden coefficients (compared to the base LCI by the USAMP, on a weight basis) would be mostly influenced by the variation of fuel efficiency of heavy duty vehicles (assuming that distances of transportation would remain constant). Since the EOL phase represent only a small fraction of the LC burdens (from 0.2% to 2.9%), we assume for simplification purposes that the variation of environmental burdens are only determined by the expected decrease of the average vehicle's curb weight (i.e., coefficients are constant over time).

The environmental burden coefficients used here are calculated on a weight basis (GJ/kg or tones of pollutant/kg) and are presented in Table 58 to Table 60, in annex A.4 (p. 363-364). We used the same coefficients for the manufacturing of transplanting kits and EOL treatment of replaced equipments. According to our coefficients, 12 GJ would be consumed to produce a new engine of 150 kg (8 GK for material production and 4 GJ for machining and assembly). Smith and Keolian (2004) estimated similar results and the total energy consumption would reach 11,6 GJ. Volkswagen (VW AG, 2005) reports that in 2004 the average energy consumption per vehicle production is 11 GJ, while, in 2006, BMW Group reports 10 GJ/unit (BMW Group, 2008). Meanwhile, PSA Peugeot commitment is to reach 7.5 GJ/unit by 2010 (PSA Peugeot, 2007). Finally, we highlight that Toyota Motor Manufacturing (situated in France) began, in 1997, its program of "Green, Clean and Lean Factory" (Toyota Europe, 2001). Their high-efficiency performances in the machining and assembly of vehicles and engines reached, by 2000, 6.7 GJ/vehicle (which is half of our estimates presented above) and 0.5 GJ/engine (12.5% of our estimates), respectively. Again, we observe that our calculations are conservative in the sense that, possibly, we overestimate the environmental burdens associated to technological transplants, and therefore underestimate the respective potential benefits.

4.4.3 Fuel economy of cars

Fuel economy (or fuel consumption factor) is the amount of fuel required to move the automobile over a given distance and is expressed herein (liters/100 km). The following table presents the density and low heating values[29] of gasoline and diesel fuels.

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[29] Heating values express how much energy is released on combustion of a given quantity of fuel (e.g., J/kg). If the water vapor created in the combustion reaction is condensed, the heat of transformation (condensation) can be recovered and the energy obtained from the combustion process is increased. These conditions yield the "High Heating Value" of the fuel. Otherwise, the 'Low Heating Value' is yielded as the heat of transformation of the vapor is lost to the atmosphere. In our case, it is appropriate to use the low heating value of a fuel, such as gasoline and diesel (http://www.princeton.edu, access date: 21st of March 2008);

Table 13. Density and low heating values of fuels

	Fuel Density [a] (kg/liter)	Low heating value [a] (MJ/Kg)
Gasoline	0.748	44.77 (32 - 48) [b] [33.5] [d]
Diesel	0.82	43.31 (32 - 40) [b] [35.5] [c]

a) Values used were taken from the Portuguese energy authorities (Direcção Geral de Energia e Geologia-DGEG, http://www.dgge.pt);

b) Figures presented in brackets are the range of values found in other sources;

c) Values in square brackets are the equivalent LH values expressed in (MJ/liter).

Fuel economy of cars is determined in laboratory tests as required by the European Union regulation (NEDC, 93/116/EEC). Tests are performed in a combined chassis dynamometer using the New European Driving Cycle (NEDC) that is composed by:

- Four similarly weighted ECE Urban Driving Cycles (UDC) that simulate city driving during 195 seconds, and
- One Extra Urban Driving Cycle (EUDC), which simulates highway driving conditions during 400 seconds.

The following figure illustrates both driving cycles, where the x-axis represents the time line of a standard trip (~1,200s or ~20 min) and the y-axis represents the vehicle speed variation over that period.

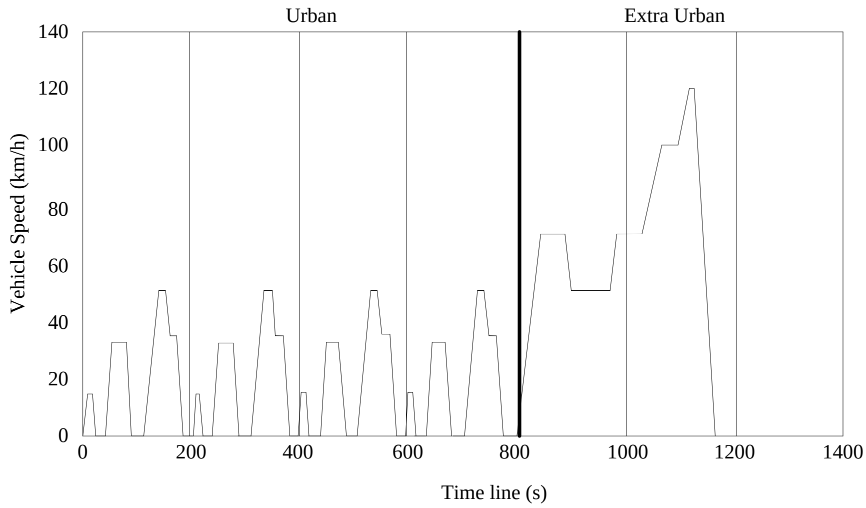


Figure 51. New European Driving Cycle (NEDC) (European Union Directive 93/116/EEC)

The first segment in the NEDC represents an urban cycle with a 'stop-and-go' pattern; the second segment represents an extra-urban cycle at up to 120 km/h (the test's average speed is 32.5km/hr over 11 km). Each vehicle is measured from a cold-crank with all devices that consume energy turned off, e.g. radio and air conditioning. Then the NEDC is run again with a warm engine and the air condition on to take into account one important energy user in a vehicle. As disputed by André et al. (2006), the use of one unique set of driving cycles to test all cars can be seen as a weak point of emission estimation, as vehicles could conceivably be tested differently depending on their performance levels and usage characteristics. The same applies to fuel consumption that is strongly influenced by driving behavior whether in urban or extra-urban environment and other use and maintenance-related factors, such as deflation of tires.

Engine specific fuel consumption — Rolling resistance — Aerodynamic drag — Acceleration resistance — Climbing resistance — Braking resistance

$$FE = \frac{\int fe.\dfrac{1}{\eta_{tr}}.\left[\left(m.f.g.\cos\alpha + \dfrac{Q}{2}.c_d.A.v^2\right) + m.(a + g.\sin\alpha) + B_r\right].v.dt}{\int v.dt} \qquad \text{4-5}$$

Consumption per unit of distance — Distance — Vehicle Speed

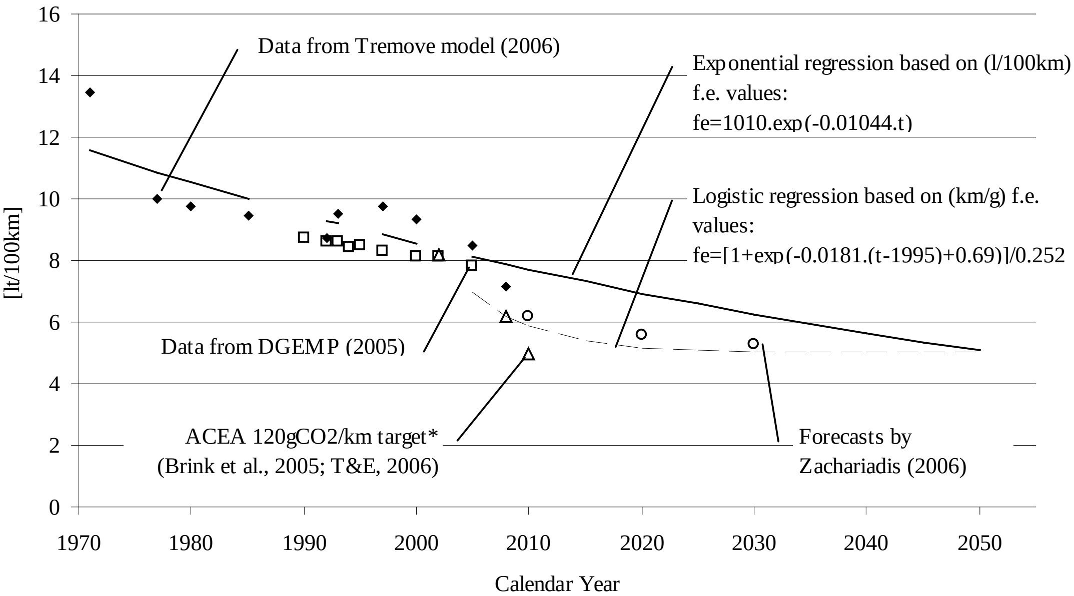
As proposed in the Automotive Handbook by Bosch (2004), fuel economy (FE in Eq.4-5) can be calculated with the following expression that distinguishes four distinct groups of factors: engine efficiency, transmission efficiency, external resistance and behavioral factors.

Table 14. Variables, parameters and possible external impacts on fuel economy of cars

Symbol	Variable and parameter	Unit	Effects of external factors
FE	Consumption per unit of distance	g/km	Cumulative effect of all factors combined
fe	Engine specific fuel consumption	g/kWh	☺ - Technological improvements (refer to chapter 2) ☹ - Deterioration due to cumulative mileage and/or defective maintenance
η_{tr}	Transmission efficiency	-	☺ - Technological improvements (refer to chapter 2) and driving behavior ☹ - Deterioration due to cumulative mileage, defective maintenance and driving behavior
m	Vehicle mass	kg	☺ - Vehicle design: downsizing of vehicles; introduction of lighter materials (e.g., aluminum) ☹ - Curb weight increase due to additional auxiliary equipment
f	Coefficient of rolling resistance	-	☺ - Technological improvements in the design and materials of tire ☹ - Defective maintenance, namely deflation of tires
g	Gravitational acceleration	m/s2	External resistance
α	Angle of ascent	º	Idem
Q	Air density	Kg/m3	Idem
c_d	Drag coefficient†	-	☺/☹ - Vehicle design
A	Frontal area	m2	Idem
v	Vehicle speed	m/s	☺/☹ - Driving behavior
A	Acceleration	m/s2	Idem
B_r	Braking resistance	N	☺/☹ - Driving behavior
T	Time	s	n.a.

Notes: † Air drag is important because the energy per kilometer needed to overcome it varies with the square of speed – air drag at 70km/h is $(70/35)^2$, or four times, what it is at 35km/h; ☺ - Positive effect on fuel economy; ☹ - Negative effect on fuel economy.

Table 14 presents the units of the parameters and variables used in the equation above such as some of the major external factors that can determine the overall fuel economy of cars (based on the equation suggested by Bosch, 2004). This formulation was presented to discriminate the factors that determine the fuel economy of cars. Some of the parameters are model-specific, i.e., engine and transmission efficiencies, weight, aerodynamic drag, etc... As referred in section 4.2, our segmentation of car types refers to small, medium and big cars, whether gasoline or diesel-powered. Still, fuel economy varies extensively depending on the specific characteristics of each model within each car segment considered here. Thus, average fuel consumption historic trends (and forecasts as well) have been calculated.



Note: (*) In this case, fuel consumption corresponds to ACEA's target for gasoline-fuelled vehicles, assuming past emissions shares between gasoline and diesel.

Figure 52. Evolution of fuel economy of an average midsized gasoline-fuelled car (based on Xu, 2000, ACEA, 2003, Brink *et al.*, 2005b, DGEMP, 2005, ACEA, 2006, T&E, 2006, Zachariadis, 2006, Ceuster *et al.*, 2007b)

Figure 52 shows the evolution of the fuel economy of a midsized gasoline car estimated by several studies (Ntziachristos and Samaras, 2000, ACEA, 2003, Brink *et al.*, 2005b, DGEMP, 2005, ACEA, 2006, Ceuster *et al.*, 2006a, Zachariadis, 2006). The exponential and logistic curves were estimated through a regression analysis based on the fuel consumption figures (past and forecasted) of the TREMOVE model (Ceuster *et al.*, 2006a) and estimates by Zachariadis (2006). The former presents some refinements to the original values of fuel economy provided by the COPERT III methodology (Ntziachristos and Samaras, 2000), which are differentiation of fuel consumption factors according to engine size of diesel vehicles, improved fuel efficiency deriving from technological improvements, and differences between test cycles and real world (Ceuster *et al.*, 2006a). Regarding the forecasts of fuel consumption, we considered also the monitoring reports of the ACEA voluntary agreement and the respective CO2 emission targets (ACEA, 2003, 2006) and the targets determined in the British SMMT's foresight vehicle technology roadmap (SMMT, 2002, 2004) that determines a fuel economy improvement of 55% and 40% for conventional diesel and gasoline powertrains, respectively (since 2000 until 2025). With respect to the real world values compared with test cycle figures, the TREMOVE model assumes a 15% increase in real world consumption factors. Their assumption is based, among other scientific work, on the work in the framework of the ARTEMIS project and on the CO_2 Monitoring Database for 2002 cars (ACEA, 2003).

Fuel consumption (l/100km) by cars is calculated with the following equation:

$$fe_{c,y,k} = \begin{cases} \dfrac{\left[1+e^{(a.y+b)}\right]}{K_c} & (\ for\ k \le 3\ ) \\ \dfrac{\left[1+e^{(a.y+b)}\right]}{K_c} \times \left(1-d_f\right)^{-k} & (\ for\ 12 \le k < 3\ ) \\ \dfrac{\left[1+e^{(a.y+b)}\right]}{K_c} \times \left(1-d_f\right)^{-12} & (\ for\ k > 12\ ) \end{cases} \qquad 4\text{-}6$$

where,

$fe_{c,y,k}$ is the fuel economy of a vehicle of type *c*, model year *y* and age *k*,

K_c corresponds to the achievable lowest fuel economy of the ICE car types considered in our study, and

d_f is the deterioration factor due to cumulative mileage.

Whereas there is extensive literature (Stedman et al., 1994, Ross et al., 1998, Samaras et al., 1998, Austin and Ross, 2001, Pokharel et al., 2001, Slott, 2007, just to mention a few) regarding the decline of emission factor of regulated pollutants, we could not find much information addressing the decline of fuel economy. As referred by Spitzley et al. (2005), fuel economy can decline with age due to defective maintenance and/or powertrain deterioration, particularly under severe urban driving conditions. However, other research suggests that this result is not relevant to the vehicle population in general (Austin and Ross, 2001). Still, we (arbitrarily) considered an overall decline of 15% over 12 years (for example, 7 liter/100km becomes 8ltr/100km after 12 years of constant annual mileage). This assumption has an impact on the overall conclusions of our study and hence it is surveyed in our sensitivity analysis, later.

Although our functional unit refers to midsize gasoline-powered cars, in the present chapter, equivalent regression curves have been calibrated for other car segments that are considered in chapters 4 and 5 (refer to the following table).

Table 15. Fuel economy regression curve (source: author)

Vehicle type	Fuel	Engine size	K a)	a	b	r^2
		c.c.	100km/liter			
PCGS	Gasoline	<1,400	0.25 (4)	-0.14	0.49	0.62
PCGM	Gasoline	1,400 – 2,000	0.20 (5)	-0.1621	0.688	0.61
PCGB	Gasoline	> 2,000	0.17 (6)	-0.12	0.31	0.29
PCDS	Diesel	<1,400	0.35 (3.5)	-0.06	0.02	1.00
PCDM	Diesel	1,400 – 2,000	0.24 (4)	-0.10	0.14	0.46
PCDB	Diesel	> 2,000	0.18 (5.5)	-0.10	0.17	0.48

a) Values in brackets correspond to the equivalent fuel economy expressed in liters/100km.

Finally, we compared our fuel economy function of PCGM with the expected efficiency improvements considered by Edwards *et al.* (2006) for equivalent engines and conclude that between 2002 and 2010 we estimate a 7% reduction (~1%/year) while they anticipate a 15% reduction (~2%/year). In addition, Plotkin (2008) refers in his analysis of fuel economy and carbon standards for light vehicles that engines have improved dramatically over the past 2 decades, and they will continue to improve according to recent presentations by a number of automakers and suppliers at the 2007 Society of Automotive Engineers World Congress. According to Plotkin (2008), overall efficiency gains of about 25% (>5%/year) should be possible from engine improvements alone, until 2020. Therefore, our estimates of fuel economy are conservative compared to theirs.

4.4.4 Exhaust emissions factors

As previously mentioned, the environmental burden coefficient for the use phase of cars is calculated with the EMEP/CORINAIR methodologies (EEA, 2002) that we briefly describe in the following paragraphs. The methodology used here covers regulated exhaust emissions of carbon monoxide (CO), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOC), diesel exhaust particulates (PM), and carbon dioxide (CO_2). According to the detail of information available for the Portuguese car fleet and the approach adopted by the methodology to calculate emissions, the above mentioned pollutants can be categorized into two groups:

- Group 1: Pollutants, for which a detailed methodology exists, based on specific emission factors (expressed in grams/km) and covering different traffic situations and engine conditions. These are CO, NOx, NMVOC and PM.
- Group 2: Emissions dependent on fuel consumption, such as CO_2, for which emissions are produced as a fraction of fuel consumption based on the chemical mass balance.

Total emissions are calculated by summing emissions from three different sources, namely: 1) the thermally stabilized engine operation (hereafter, referred to as hot emissions – e_{HOT}); 2) the warming-up phase (hereafter, referred to as cold-start emissions – e_{COLD}); and 3) evaporative emissions (e_{EVAP}). The latter occur in significant quantities for gasoline vehicles in the form of NMVOC emissions, contrary to what happens with diesel-fuelled vehicles. Hence, in chapter 4 and 5, evaporative emissions are calculated for gasoline car types, only. Concentrations of most pollutants during the warming-up period are many times higher than during hot operation and a different methodological approach is required to estimate (over-) emissions during this period.

This said CO_2 emissions (2nd group) are estimated on the basis of fuel consumption only, assuming that the carbon content of the fuel is fully oxidized into CO_2 (referred to as global CO_2). If "end-of-pipe" CO_2 emissions were to be calculated, then other emissions of carbon atoms in the form of CO, VOC and PM emissions (nearly 5% of global CO_2 emissions) would have to be discounted from global CO_2 – refer to EEA (2002) for mathematical details. The following formula is used to estimate global CO_2 emissions:

$$e(f,y,t,k) = 44.011 \times \frac{FE(f,y,t,k)}{12.011 + 1.008 \times r_{H:C,m}}$$

$$\text{or} \begin{cases} e(y,t,k) = 3.1856 \times FE(y,t,k) & (for\ gasoline) \\ e(y,t,k) = 3.1375 \times FE(y,t,k) & (for\ diesel) \end{cases} \qquad 4\text{-}7$$

where,

$e(c,f,y,t,k)$ is the emission factor (expressed in g $_{CO2}$/g $_{fuel}$) of the model year y, powertrain technology t, and age k, powered with fuel f;

$FE(f,y,t,k)$ is the fuel economy of the car (expressed in g $_{fuel}$/km); and

$r_{H:C,m}$ denotes the ratio of hydrogen to carbon atoms in the fuel (~1.8 for gasoline and ~2.0 for diesel).

With respects to Group 1 pollutants, total emissions are calculated with the following equation:

$$e(c,f,y,t,k) = \begin{cases} e_{HOT} + e_{COLD} & (for\ CO, NO_x\ and\ PM) \\ e_{HOT} + e_{COLD} + e_{EVAP} & (for\ NMVOC) \end{cases} \qquad 4\text{-}8$$

In addition, e_{HOT} emissions are heavily dependent on the engine operation conditions. Different driving situations impose different engine operation conditions and therefore a distinct emission performance. In that respect a distinction is made between urban, rural and highway driving to account for variations in driving behavior. Vehicle speed is used as a proxy indicator (we assumed 25, 60 and 100 km/h as urban, rural and highway driving speeds, respectively, for the Portuguese context). e_{HOT} is estimated for each driving mode as follows:

$$e_{HOT} = 20\%.e_{HOT,Highway} + 30\%.e_{HOT,Rural} + 50\%.e_{HOT,Urban} \qquad 4\text{-}9$$

where percentages are the annual mileage fractions assumed for each driving condition (these are consistent with those presented in APA, 2007).

e_{COLD} are calculated as an extra emission over the emissions that would be expected if all vehicles were only operated with hot engines and warmed-up catalysts (see Eq.4-10). The ratio of cold over hot emissions is used and applied to the fraction of kilometers driven with cold engines. This factor varies from country to country: driving behavior (i.e., varying trip lengths) and climate conditions affect the time required to warm up the engine and/or the catalyst. The fraction of a trip driven with cold engine is usually attributed to urban driving because the assumption is made that the large majority of vehicles starts any trip in urban areas.

Exhaust emissions ($E_{EXHAUST}$) are calculated with the following equation:

$$e_{EXHAUST} = e_{HOT} + e_{COLD} = \frac{\sum_{m=1}^{12} \left\{ e^{HOT}_{(c,f,y,t,k,d)} \times \left[1 + \beta_m \times \left(cf^{cold/hot}_{(c,f,y,t,k,d)} - 1 \right) \right] \right\}}{12} \qquad \text{4-10}$$

where

$e_{EXHAUST}$ denotes the annual average exhaust emissions from car type *c*, model year *y* and age *k*, powered by fuel *f*, under driving conditions *d*;

$e_{HOT}(c,f,y,t,k,d)$ denotes the hot emissions factor[30];

βm denotes the average monthly value for the fraction of mileage driven with cold engines or catalyst operated below the light-off temperature[31] (*m* are months from Jnauray to December);

$cf_{cold/hot}$ is the ratio of cold-extra emission over hot emissions (expressed in grams/grams)[32].

As cars deteriorate with age and cumulative mileage, exhaust emissions increase (as mentioned in the previous section, this is supported by evidence from many surveys of on-road emissions). This was modeled in the EMEP/CORINAIR methodology as follows (refer to tables 8-38 and 8-39 for parameter values):

$$MC_{C,i} = A^M \times M_{Mean} + B^M \qquad \text{4-11}$$

where

$MC_{C,i}$ is the correction coefficient for a given kilometrage, pollutant *i* and a specific driving cycle that depend on the driving speed, i.e. (UDC) or (EUDC);

M_{MEAN} is the mean fleet mileage of vehicles for which correction is applied; and

A^M, B^M are coefficients to be selected from tables 8-38 and 8-39 of the EMEP/CORINAIR guidelines.

[30] eHOT equations were calibrated for each car size (based on engine size), technology t and fuel type f. Emission factors depend on the vehicle speed (as a proxy of driving condition d). To calculate CO, VOC and NOx emissions by gasoline-fuelled cars, refer to tables 8-3 to 8-5 (for $t < 1992$) and table 8-10 (for $t \geq 1992$), of the EMEP/CORINAIR guidelines (EEA, 2002). NMVOC is given as the remainder of VOC minus methane (CH4) emissions. With regards to diesel-fuelled cars, refer to tables 8-12 and 8-13, for pre and post-Euro 1 technology, respectively. CH4 emission equations and parameters are listed in table 8-32 of the same methodological guidelines.

[31] βm is calculated from average monthly temperature (annual average is nearly 16°C) and aver age trip length (10 km/trip) – refer to Table 8.8, p. B710-46 of EMEP/CORINAIR guidelines (EEA, 2002).

[32] Like for the previous footnotes, refer to tables 8-7 and 8-14 to calculate cf cold/hot coefficients of gasoline and diesel-fuelled cars, respectively.

It was found that sample emissions tend to stabilize at the higher mileage region (above ~120.000 km). Therefore, it is assumed that emissions do not further degrade above this limit and a constant degradation value is applied on the base emission factor to calculate the emission level of older vehicles.

e_{EVAP} are calculated with the following equation:

$$e_{EVAP} = 365 \times \left[\left(a_c \times e^d \right) + s^c + s^{fi} \right] + R$$

with
$$\begin{cases} s^c = (1-q)\left(\mathrm{p} \times \mathrm{x} \times \mathrm{e}^{\mathrm{s,hot}} + \mathrm{w} \times \mathrm{x} \times \mathrm{e}^{\mathrm{s,warm}}\right) \\ s^{fi} = q \times e^{fi} \times x \\ R = mj \times \left(\mathrm{p} \times \mathrm{e}^{\mathrm{r,hot}} + \mathrm{w} \times \mathrm{e}^{\mathrm{r,warm}}\right) \end{cases} \tag{4-12}$$

where

e_{EVAP} are evaporative emissions in year y (expressed in g $_{NMVOC}$/year);

a_c denotes the number of gasoline-fuelled car types c (in the present chapter, ac = 1);

e_d refers to the mean emission factor for diurnal losses of gasoline powered vehicles equipped with metal tanks, depending on average monthly ambient temperature, temperature variation and fuel volatility (RVP) (expressed in grams/day);

s^c denotes the hot and warm soak emission of gasoline powered vehicles equipped with carburetor (expressed in grams/day);

s^{fi} denotes the hot and warm soak emission of gasoline powered vehicles equipped with fuel injection (expressed in grams/day);

R refers to the hot and warm running losses (expressed in grams/day);

q denotes the fraction of gasoline powered vehicles equipped with fuel injection;

p denotes the fraction of trips finished with hot engine (dependent on the average monthly ambient temperature);

w is the fraction of trips finished with cold or warm engine (shorter trips) or with catalyst below its light-off temperature;

x refers to the mean number of trips of a vehicle per day, averaged over the year;

$e_{s,hot}$ is the mean emission factor for hot soak emissions (which is dependent on fuel volatility RVP – Reid Vapor Pressure);

$e_{s,warm}$ is the mean emission factor for cold and warm soak emissions (which is dependent on fuel volatility RVP and average monthly ambient temperature);

e^{fi} is the mean emission factor for hot and warm soak emissions of gasoline powered vehicles equipped with fuel injection;

$e_{r,hot}$ is the average emission factor for hot running losses of gasoline powered vehicles (which is dependent on fuel volatility RVP and average monthly ambient temperature);

$e_{r,warm}$ is the average emission factor for warm running losses of gasoline powered vehicles (which is dependent on fuel volatility RVP and average monthly ambient temperature); and

m_j is the total annual kilometers travelled by gasoline powered vehicles of car type *c*.

All e_{EVAP} parameters are characterized in the EMEP/CORINAIR guidelines. Since there is no reliable statistical information concerning vehicles equipped with canister[33], in Portugal – as mentioned in the Portuguese national inventory report from 2007 (APA, 2007, p.131), it was assumed that all post-Euro 1 vehicles are equipped with canisters (i.e., parameter 1-q=0), for chapters 4 and 5. Furthermore, it was considered that all post-Euro 1 vehicles are equipped with fuel injection (i.e., parameter q=1).

The following table summarizes the factors we used in the present chapter to estimate emissions from a midsize gasoline-powered car, using the methodology presented before. Emissions vary with the age (or equivalent cumulative kilometers) of the car. Refer to annex A.5 (p. 368) for the emission factors of all vehicle types considered in this dissertation.

In the next section, we present the load factors used to estimate the material flows involved in the life cycle of a car, since the extraction of raw materials until their end-of-life treatment, whether it is through reuse, recycling or final disposal.

[33] A canister is the filter which absorbs gasoline vapour in a car tank.

Table 16. Emission factors for a midsize gasoline-powered car with model year and cumulative kilometers (Source: author based on EEA, 2007b)

Pollutant	Model Year between...		Declining emission factors with age and equivalent cumulative kilometers [a)]					
	Low	High	0 (9,200)	5 (50,000)	10 (83,000)	15 (112,000)	20 (137,000)	25 (162,000)
CO	-	1971	26.26	29.19	37.59	44.80	46.67	46.67
	1972	1977	21.27	23.62	30.35	36.13	37.63	37.63
	1978	1980	15.71	17.41	22.28	26.46	27.55	27.55
	1981	1985	16.14	17.89	22.91	27.21	28.33	28.33
	1986	1992	9.87	10.89	13.80	16.30	16.95	16.95
	1993	1995	3.68	3.84	4.30	4.70	4.80	4.80
	1996	1999	2.84	2.82	2.94	3.05	3.07	3.07
	2000	2004	2.86	2.84	2.97	3.08	3.11	3.11
	2005	2008	2.56	2.55	2.61	2.66	2.68	2.68
	2009	2013	2.56	2.55	2.61	2.66	2.68	2.68
	2014	2050	2.56	2.55	2.61	2.66	2.68	2.68
NO_X	-	1971	2.71	2.86	3.82	4.64	4.86	4.86
	1972	1977	2.71	2.86	3.82	4.64	4.86	4.86
	1978	1980	2.66	2.80	3.73	4.53	4.75	4.75
	1981	1985	2.71	2.86	3.82	4.65	4.86	4.86
	1986	1992	2.84	2.99	4.01	4.88	5.11	5.11
	1993	1995	1.18	1.19	1.27	1.34	1.35	1.35
	1996	1999	1.09	1.08	1.11	1.14	1.14	1.14
	2000	2004	1.04	1.04	1.05	1.06	1.06	1.06
	2005	2008	1.03	1.03	1.04	1.05	1.05	1.05
	2009	2013	1.03	1.03	1.03	1.04	1.04	1.04
	2014	2050	1.03	1.03	1.03	1.04	1.04	1.04
NMVOC[b)]	-	1971	3.05	3.31	4.04	4.67	4.84	4.84
	1972	1977	2.59	2.79	3.36	3.85	3.98	3.98
	1978	1980	2.52	2.71	3.26	3.72	3.85	3.85
	1981	1985	2.52	2.71	3.26	3.72	3.85	3.85
	1986	1992	2.23	2.39	2.83	3.21	3.32	3.32
	1993	1995	0.50	0.50	0.54	0.57	0.61	0.65
	1996	1999	0.19	0.21	0.29	0.40	0.55	0.75
	2000	2004	0.11	0.12	0.17	0.23	0.32	0.44
	2005	2008	0.06	0.07	0.09	0.13	0.17	0.24
	2009	2013	0.05	0.06	0.08	0.11	0.14	0.20
	2014	2050	0.05	0.06	0.08	0.11	0.14	0.20

Note: Values are expressed in (g/km); a) Equivalent cumulative kilometres are presented in brackets; b) NMVOC emissions do not include evaporative emissions.

4.4.5 Materials car composition, flows and final disposal of waste

Today's passenger car weight is much diversified ranging from 700 kg to nearly 3,000 kg (excluding driver and with an empty fuel tank). In addition, Spielmann and Althaus (2007) refer in their analysis that 26.2% diesel vehicles sold in Switzerland in 2004 weigh on an average 262 kg more than the petrol cars (i.e., approximately 20% more). Table 17 (below) presents a compilation of different car weights and material composition we collected from the literature. From the sample analyzed here – we note that, although it is a short list, some of the vehicles are considered generic vehicles and thus representative of a large number of car type – the percent-material composition remains quite constant for equivalent model years. Still, the trend is for the progressive introduction of lighter materials (such as non-ferrous materials and plastics) in more recent model years, in detriment of heavier ferrous metal (i.e., iron and steel), which to a large extent responds to governments expectations of increased fuel efficiency of new cars. The following figure illustrates the growth of aluminum contents of different parts of a light non-commercial vehicle between 2002 an 2006.

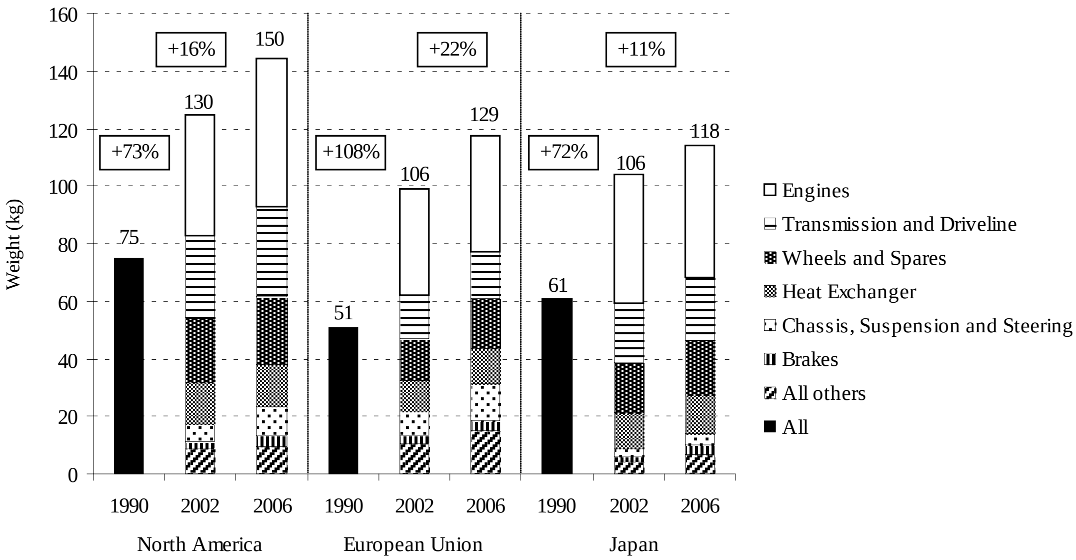


Figure 53. Use of aluminum in different parts of the vehicle (Automotive Aluminum, 2007)

Table 62 (in annex A.6, p.374) presents the average curb weight for the vehicle segments and model years (1990 to 2030) considered in our research. The data for our base year results from a compilation of makes and models representative of the car segments we used in our study. Data was retrieved mainly from the technical descriptions provided in Parker's webpage, http://www.parkers.co.uk/ (access in June 2007). Note that the present chapter addresses only midsize gasoline-fuelled cars while chapters in Part C include the remaining car types presented in Table 8.

Table 17. Weight and material composition of different passenger car types

Materials \ Source	USAMP [a]	Graedel [b]	Schweimer [c]		Spielman and Althaus [d]					Ferrão [e]		Reis [f]	Finkbeiner [g]	SMMT [h]
MY	1995	1998	1999	1999		2000	2000	2000		1985	1998	1998	2005	2006
Metals (non-ferrous)	137 (9.3%)	115 (8.0%)	71 (6.7%)	76 (6.5%)	57 (6.6%)	50 (5.0%)	225 (25.0%)	233 (31.0%)	117 (9.0%)	71 (6.8%)	105 (10.0%)	85 (5.0%)	335 (18.5%)	(8.0%)
Aluminum	96 (6.5%)	68 (4.7%)			31 (3.6%)	30 (3.0%)	198 (22.0%)	188 (25.0%)	88 (6.8%)					
Others	8.5 (0.6%)				26 (3.0%)	20 (2.0%)	27 (3.0%)	45 (6.0%)	29 (2.2%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)
Metals (ferrous)	987 (66.9%)	1000 (69.7%)	634 (59.9%)	722 (61.1%)	635 (73.2%)	700 (70.0%)	423 (47.0%)	240 (32.0%)	855 (65.8%)	745 (71.5%)	687 (65.4%)	1096 (64.0%)	950 (52.6%)	(67.0%)
Iron	155 (10.5%)	207 (14.4%)										229 (13.4%)		
Steel	830 (56.3%)	793 (55.3%)										867 (50.6%)		
Plastics	143 (9.7%)	101 (7.0%)	167 (15.8%)	182 (15.4%)		150 (15.0%)	162 (18.0%)	206 (27.5%)	174 (13.4%)	83 (8.0%)	95 (9.0%)	229 (13.4%)	338 (18.7%)	(10.0%)
Fluids	17 (1.1%)	81 (5.6%)	64 (6.0%)	72 (6.1%)	176 (20.3%)	20 (2.0%)	134 (1.5%)	8 (1.0%)	74 (5.7%)	21 (2.0%)	21 (2.0%)	128 (7.5%)	102 (5.6%)	(2.0%)
Others	192 (13.0%)	137 (9.6%)	122 (11.5%)	128 (10.9%)		80 (8.0%)	77 (8.5%)	64 (8.5%)	79 (6.1%)	82 (7.9%)	89 (8.5%)	174 (10.2%)	82 (4.5%)	(13.0%)
Total	1,475	1,434	1,059	1,181	869	1,000	900	750	1,300	1042	1050	1,712	1,805	

[a] Sullivan *et al.* (1998);

[b] Graedel and Allenby (1998);

[c] Schweimer and Levin (2000) LCI of a VW Golf 1.4ltr; 55kW Otto and a 1.9ltr; 66kW Tdi);

[d] Spielman and Althaus (2007) collated several material compositions for different generic vehicles from the literature;

[e] Ferrão and Amaral (2006) used the values referred in IPTS (2000) and APME (1999);

[f] Reis (1999) LCI of a VW Sharan (1.9 liter,100kW, gasoline);

[g] Finkbeiner et al. (2006) LCI of a Mercedes-Benz S-Class car, 180-200 kW; 300,000km service);

[h] UK's SMMT (2008) average material breakdown of a generic car.

Regarding the evolution of both weight and material composition between 1990 and 2030, we used Kim's (2003) estimates (past and forecast) presented in Table 63 (annex A.6, p. 375). The author's values do not differ much from the characteristics retrieved from existing car models, for equivalent model years. Historical trends (from 1985 to 2000) used by Kim were based on the Wards' Automotive Yearbooks. Forecasted material composition until 2020 relies on two different sources: "Delphi X" by Cole and Londal (2000), until 2009, and "On the Road in 2020" by Weis et al.(2000), until 2020. We compared these forecasts with the development targets set in the "Foresight vehicle technology roadmap" of the British Society of Motor Manufacturers and Traders (SMMT, 2002, 2004). These targets determine a 40% reduction of vehicle weight until 2025, compared to the 2005 levels. Importantly, the SMMT's target doubles the 20% weight reduction used here and, hence, the estimates we use are conservative. We assumed that cars' material composition remains constant from 2020 until 2030. Again, referring to Table 63 (p. 375), we stress that car weight increased until 2000 (according to Kim's estimates) mostly as a consequence of safety concerns. Thereafter, car weight reduces 1% per year, on average. For simplification purposes, we assumed the same percent-variation for all car types.

Regarding the transplanting kits, we used several sources to define an average material composition for the parts and components included. Table 18 (next page) presents the weight and material composition of selected parts and components obtained from different sources in the literature. These include the powertrain sub-systems and other ancillary equipments that can be replaced together with the powertrain to reduce the overall fuel consumption of cars (we recall that this corresponds to the conception of car organ transplant considered in the present research – we do not rule out other configurations of organ transplant). The following figure is an illustration of the steel flow in the production, use and final disposal a typical 1990 car (unit used is $kg_{steel}/kg_{steel\ in\ car}$), as described by Ginley (1994, cited in Graedel and Allenby, 1998).

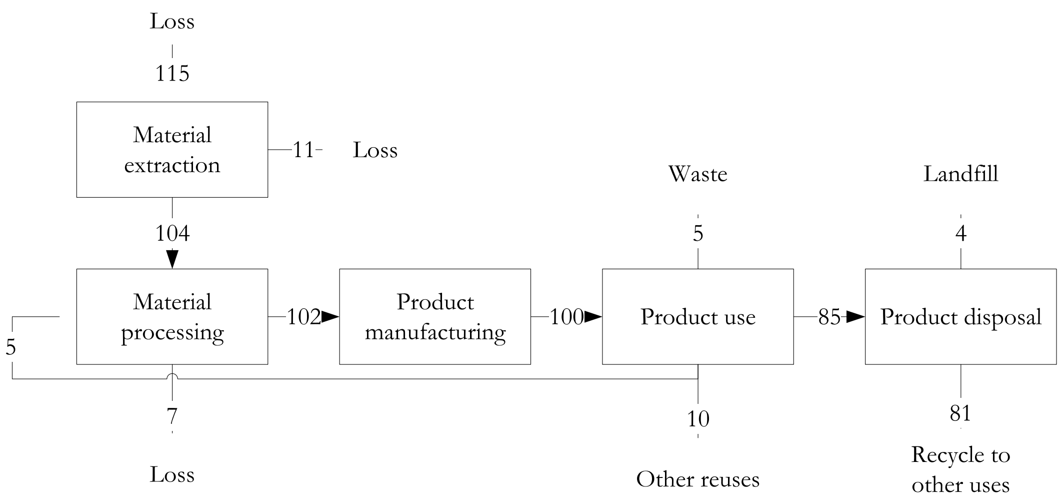


Figure 54. Example of material flow in a typical 1990 car: the case of steel (Ginley, 1994, cited in Graedel and Allenby, 1998)

Table 18 presents the final material composition matrix we used to estimate energy consumption and emissions from materials production, manufacturing and EOL stages, regarding transplanting kits. The weight values presented here refer to a midsize gasoline car. Regarding the remaining models, we assume that only the engine's weight would vary proportionately to its volume (although this represents a rough approximation since the *weight-to-*

-volume ratio does not vary linearly). The other components and materials are assumed to remain constant. Table 64 in annex A.7 (p.376) presents the average weights of transplanting kits for all car types considered here.

Table 18. Weight and material composition of selected car parts and components

Materials	Transplanting Kit	Engine [a]	Transmission [b]	Air Conditioning and heating	Catalytic Converter [d]	Exhaust System [e]	Other parts and components [f]
Metals (ferrous)	238 (72%)	114 (77%)	24 (80%)	24 (60%)	7 (55%)	23 (100%)	44 (60%)
Iron	66 (20%)	66 (44%)					
Steel	172 (52%)	48 (32%)	24 (80%)	24 (60%)	7 (55%)	23 (100%)	44 (60%)
Metals (non-ferrous)	66 (20%)	29 (20%)	5 (15%)	10 (25%)	3 (24%)		19 (25%)
Aluminum	45 (14%)	29 (19%)	5 (15%)	4 (10%)	0.2 (2%)		7 (10%)
Copper	17 (5%)			6 (15%)			11 (15%)
Other	3 (1%)	0.6 (0%)			3 (22%)		
Rubber	3 (1%)	3 (2%)					
Fluids	6 (2%)		2 (5%)	2 (4%)			3 (4%)
Plastics	14 (4%)	1.0 (1%)		4 (11%)			8 (11%)
Other	4 (1%)	1.3 (1%)			3 (21%)		
Total (% of total)	330 (100%)	149 (45%)	30 (9%)	41 (12%)	13 (4%)	23 (7%)	74 (22%)

[a] Smith and Keoleian (2004);

[b] Röder (2001)- Specific mass is 0.3Kg/KW and we used an average 100kW power delivered to the wheels;

[c] Graedel (1998);

[d] Amatayakul and Ramnas (2001);

[e] Weights were taken from Delucchi *et al.* (2000) where we assumed that the exhaust system is mainly composed by ferrous metals and the remaining equipment has the same material composition as heating system and air conditioning (miscellaneous);

[f] Includes engine electrical, engine emissions controls, oil and grease, and other components and accessories equipment.

Table 19 presents the flows of the major materials used in cars – i.e., steel (60%), aluminum (6%), other non-ferrous metals (1-2%), plastics (10%) – and an aggregate indication of the other miscellaneous materials used. Values correspond to load factors indexed to the weight of the car during its use phase. Interestingly, 15% of virgin steel (we assumed the same for iron) is lost during the extraction and processing of the material usable to finally produce the parts and components of the vehicle (5% of steel to produce a car is reused). Conversely, the quantity of virgin aluminum and copper is 10% inferior to the weight composition of a car. These materials experience a higher rate of reuse (67% and 52%, respectively, against 10% in the case of steel). Regarding the disposal of waste, the patterns vary greatly. Steel has high rates of recycling (81%) and a smaller portion is wasted (5%) during the vehicle's service or disposed in landfills (4%). Conversely, plastics and miscellaneous materials are not recycled and mostly are disposed in landfills (up to 91%). Altogether, approximately 75% of the EOL vehicle is reused (15%) or recycled (60%), on mass basis.

Table 19. Material flows of a typical 1990 automobile (based on Ginley, 1994, cited in Graedel and Allenby, 1998)

Material	Materials lifecycle stages	Inflows*		Outflows			
		Raw	Reuse	Losses & waste	Reuse	Recycling	Landfill
Steel	Material Extraction	115		12			
	Material Processing	104	5	7			
	Product fabrication	102		2			
	Product use	100		5	10		
	Product disposal	85				81	4
Aluminum	Material Extraction	90		11			
	Material Processing	79	33	10			
	Product fabrication	103		3			
	Product use	100		6	67		
	Product disposal	28				26	1
Copper	Material Extraction	90		10			
	Material Processing	81	33	14			
	Product fabrication	100		0			
	Product use	100		5	52		
	Product disposal	43				38	5
Lead and zinc	Material Extraction	70		5			
	Material Processing	65	40	5			
	Product fabrication	100		0			
	Product use	100		5	40		
	Product disposal	55				50	5
Plastics	Material Extraction	106		1			
	Material Processing	105	2	3			
	Product fabrication	104		4			
	Product use	100		5	4		
	Product disposal	91				0	91
Miscellaneous (rubber, glass, paper, etc.)	Material Extraction	101		10			
	Material Processing	90	18	5			
	Product fabrication	103		3			
	Product use	100		5	22		
	Product disposal	73				0	73

Note: In the case of material extraction, inflow materials are either raw (virgin) or reused materials.

To calculate the raw material consumption and solid waste generation we use the parameters resumed in the following table.

Table 20. Load factors of raw material consumption and waste disposal (source: author)

Materials	Material composition				Material production and manufacturing		EOL vehicle's disposal			
	Vehicle		Transplanting kit							
	(kg)	(%)	(kg)	(%)	Raw Material	Losses	Reuse	Recycle	Waste	Landfill
Steel	830	56%	149	51%	115%	20%	10%	81%	5%	4%
Iron	157	11%	66	23%	115%	20%	10%	81%	5%	4%
Aluminum	97	7%	41	14%	90%	24%	67%	26%	6%	1%
Copper	27	2%	12	4%	90%	24%	52%	43%	5%	0%
Lead and Zinc	13	1%	3	1%	70%	10%	40%	50%	5%	5%
Plastics	143	10%	9	3%	106%	8%	4%	0%	5%	91%
Miscellaneous	209	14%	11	4%	101%	19%	22%	0%	5%	73%

Note: Index 100 = Weight of material in the 'ready-to-use' vehicle.

We note that these are typical values characterized for the US automotive industry and their equivalent in Europe might be different, although to a small extent. According to Ferrão and Amaral (2006), less than 75% of an EOL vehicles is recycled today, in Portugal, and the targets defined by the EU require the removal of an increased number of plastic parts from the EOL vehicle. In particular, the removal of 14% would result in a recycling rate higher than 80% and, according to the authors' model, the task is viable in economic terms, provided that the dismantler gets a steady flow of EOL hulks, free of charge. As a matter of fact, regarding the disposal of EOL vehicles, the European Parliament has brought the principle of "extended product responsibility" to the Directive 2000/53/EC, by which the automotive industry must comply with technical requirements for car design as well as minimum reuse and recovery rates for EOL vehicles:

- Until 01/07/2003: new vehicles cannot contain lead, mercury, cadmium or hexavalent chromium (some exceptions are listed in the directive's annexes);
- Until 01/01/2006: reuse and recovery of 75% (85%) on a mass basis – of which 70% is recycled (80%) – for vehicles produced before 1980 (after);
- Until 01/01/2015: reuse and recovery of 95% – of which 90% is recycled – on a mass basis.

The concept of car organ transplant could benefit from the principles contained in this Directive, by which the increase of standardization (or modularization) in automobile production to enhance the recyclability might lead to increased intergenerational compatibility of components between model years, also.

In the previous sections, we presented the dynamic LCI model and respective parameters for a midsize gasoline-fuelled car and transplanting kits (as defined in this dissertation). Data for the remaining car types (analyzed in the 3rd Part of this study) is listed in the annexes. We present now the results we obtained for the characterization of the vehicle profile over a period of 20 years of ownership (which is our base case for comparison with alternative car ownership approaches as we will explain in Chapter 6). In the forthcoming sections, we analyze also the energy and environmental burdens associated to the production of transplanting kits and scrappage of replaced equipments.

4.5. Energy and environmental burdens of car use and organ transplant

Figure 55 presents the energy and carbon profiles of car ownership over 20-years service. Each bar in the graph displays also the equivalent lifecycle stages. Understandably, the first year includes the energy consumption and CO_2 emissions from material production and manufacturing stages. Similarly, the 20th year includes those burdens related to the scrappage of the vehicle. The remaining lifecycle stages ('well-to-wheel' and maintenance and repair) remain stable over the vehicle's service time, although energy consumption and emissions grow by 6% over the 20-years of service time (i.e., <1%/year), mainly due to car wear as it becomes older. Figure 56 shows the vehicle profile for other criteria pollutant. Again, in the 1st year more pollutants are emitted due to the production stages such as in the last year due to vehicle scrappage and, in between, emissions grow smoothly as the car wears. Importantly, PM emissions are only visible in the production stages (material production and manufacturing) since particulate emissions by gasoline-fuelled vehicles are not significant during operation stages, according to the methodology used here.

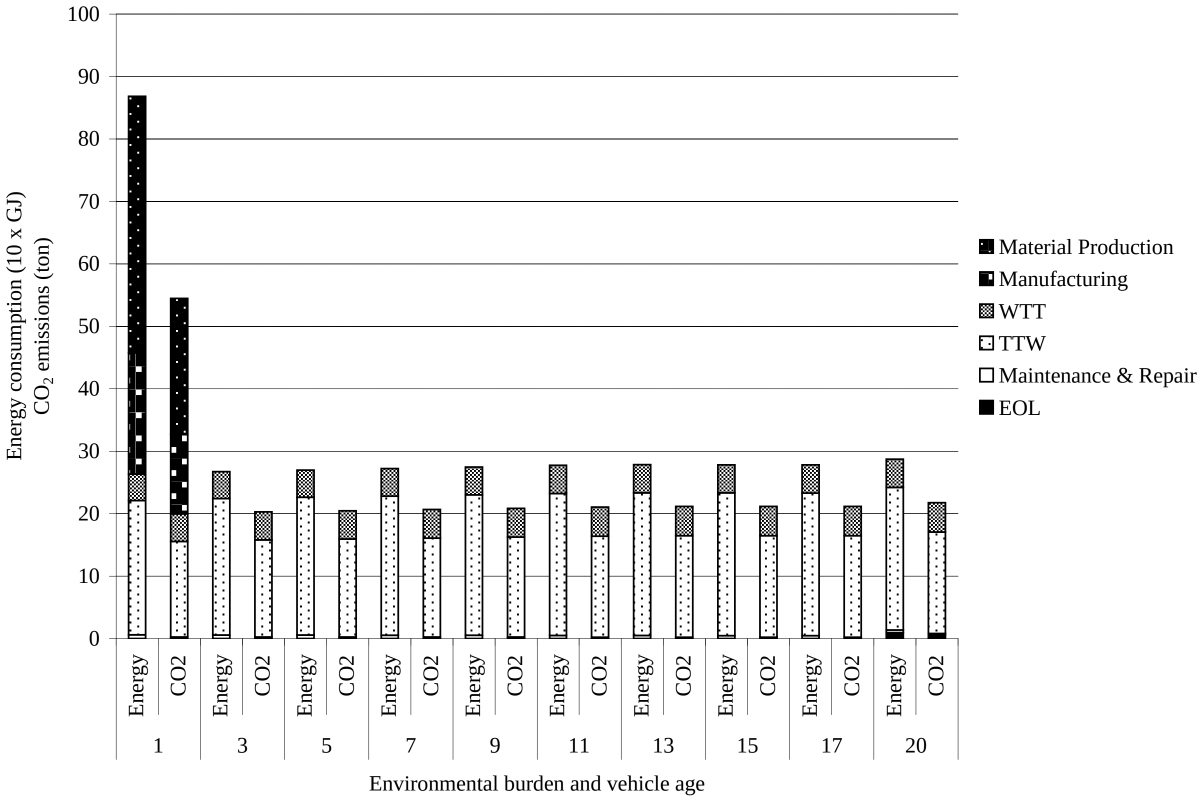


Figure 55. Lifecycle profile of energy consumption and CO_2 emissions from a midsize gasoline-fuelled car over 20 years (source: author)

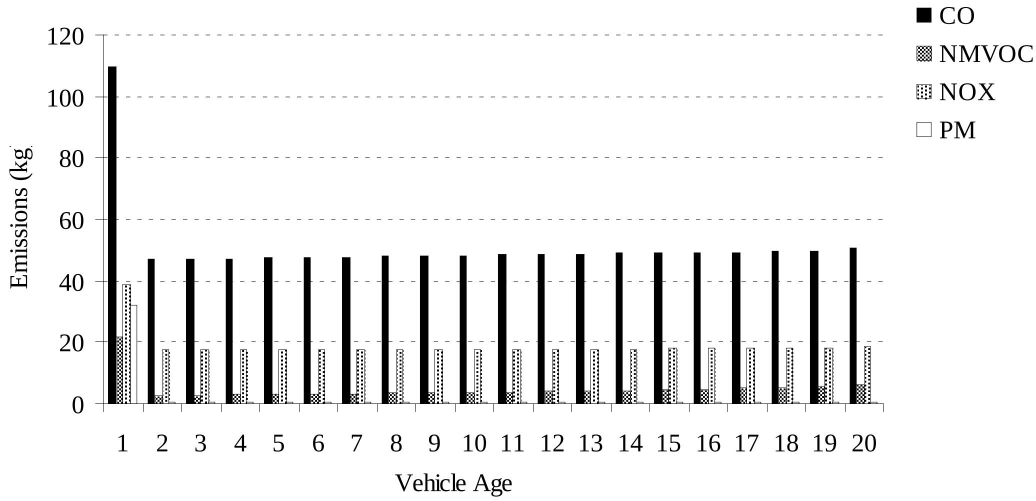


Figure 56. Lifecycle profile of criteria pollutant from a midsize gasoline-fuelled car over 20 years (source: author)

Lifecycle stages (i.e., WTT, TTW, maintenance and repair) during car use account for approximately 90% of the total service time, except in the case of PM emissions (20%) for the same reasons presented above. Material production and manufacturing make up 10% of total emissions. Again, exception is made for particulates for which lifecycle stages embody 80% of total emissions. Notably, EOL emissions are less than 1% of total lifecycle emissions, for all pollutants. Refer to Table 21 for a synthesis of these results – we note that these are consistent with those presented in (section 4.4, p.119) where data from the literature are presented.

Table 21. LC comparison of the energy and environmental burdens between a 2000 conventional car and equivalent Transplanting Kit (source: author)

Lifecycle stages	Energy (GJ)		CO (kg)		NMVOC (kg)		NO_X (kg)		PM (kg)		CO_2 (kg)		Raw Material (kg)		Solid Waste [c] (kg)	
	CC [a]	TK [a]	CC	TK	CC	TK	CC	TK	CC	TK	CC	TK	CC	TK	CC	TK
Material Production	82 (7%)	18 (2%)	57 (6%)	13 (1%)	5 (6%)	3 (3%)	13 (3%)	3 (1%)	24 (63%)	5 (39%)	4,351 *(5%)*	964 *(1%)*			279	59
Manufacturing	39 (3%)	9 (1%)	6 (1%)	1 (0%)	14 (14%)	2 (2%)	8 (2%)	2 (1%)	8 (20%)	2 (12%)	2,544 *(3%)*	564 *(1%)*	1,619	319		
Car use [b]	1,096 (90%-98%)		967 (94%-99%)		77 (80%-94%)		356 (94%-99%)		7 (17%-48%)		83,243 (92%-98%)				394	40
EOL	2.3 (0.2%)	0.5 (0.0%)	0.7 (0.1%)	0.2 (0.0%)	0.2 (0.2%)	0.2 (0.2%)	0.9 (0.2%)	0.2 (0.1%)	0.2 (0.6%)	0.1 (0.4%)	154 (0.2%)	34 (0.0%)	-	-		
Total	1,219	1,123	1,030	981	97	82	378	361	39	14	90,292	84,805	1,635	362	673	99

[a] CC – Conventional Car, TK – Transplanting Kit.

[b] Car use stages include WTT, TTW and Maintenance and repair, similarly to a conventional car of the same MY.

[c] Here, we include only losses during production stages and solid waste generated during car use and EOL stages. Reused and recycled materials account for 73% and 86% of EOL car and transplanting kit disposal, respectively (not accounting for the losses during the production stages).

The energy and environmental burdens associated to transplanting kits are lower since they are smaller in weight – approximately, a fourth of a midsize car weight – and thus less material-intensive. Consequently, related energy and raw material consumption, emissions and solid waste generation are lower, except for the operation stages where they should equal for equivalent model years. Producing a transplanting kit requires less ~1,200 kg of raw materials and ~100 GJ than a conventional midsize car. Likewise, the production of a car generates 670 kg of solid waste, almost 7 times more by mass than is generated during transplanting kits production, which produced nearly 100 kg of solid waste per kit. The material and parts production stage drives the generation of losses, for both the car and transplanting kits, with 41% and 59% of the new car and transplanting kit solid waste production, respectively. This is explained by the reuse and recycling rates of waste materials, which are mainly ferrous and non-ferrous metals – according to the material flow characterization used here. Interestingly, ~85% of the solid waste generated by a transplanting kit is reused or recycled compared to less than 75% in a conventional car. Higher rates of reuse and recycling are imposed to future car models in accordance with the European 'End-Of-Live' vehicles Directive and therefore any forecast based on these parameters leads to over-estimation of material burdens.

Previous comments are important when calculating the period required to offsetting energy consumption and emissions from car transplants. The trade-off between fixed and marginal burdens plays an important role, here. For the LCI model, the fixed burdens are created during the materials production, manufacturing, and EOL stages, while the marginal burdens are created during the use and maintenance stages.

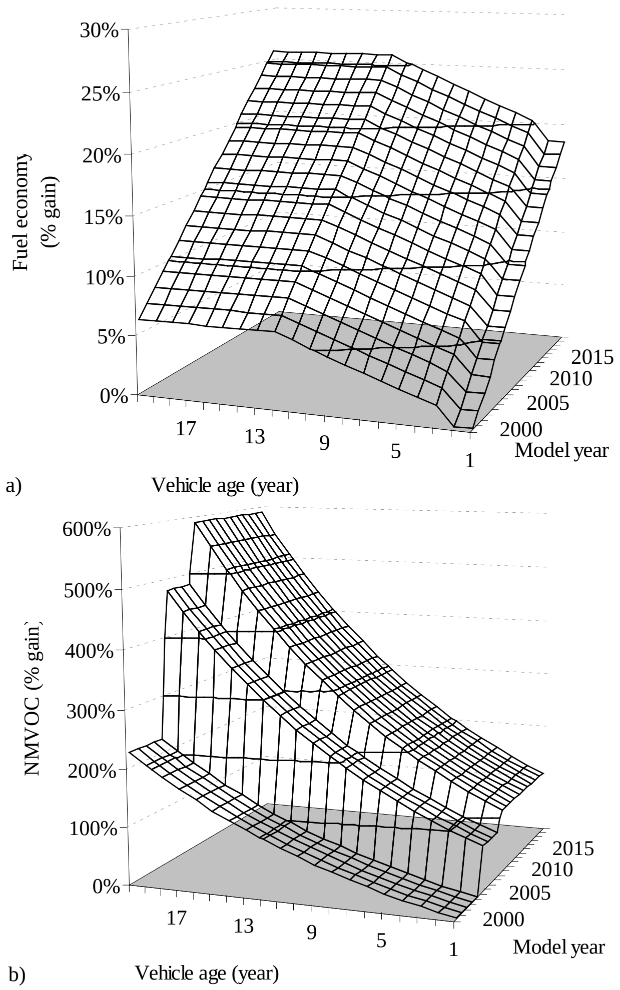
Putting it simply, the transplanting kit weighs approximately 23% (=330/1400) of a mid-size car and thus contributes with more 2.3% (=10% × 23%) of lifecycle energy consumption and emissions, where 10% corresponds to the share of lifecycle energy consumed during the production and scrappage stages of the car. Assuming an annual 0.5% gain of efficiency between model years, then the recovery period would be about 5 years (≈2.3% / (0.5% × 90%), where 90% corresponds to lifecycle share of energy consumed during the vehicle's operation. In fact, efficiency gains can be much higher since car performance deteriorates over time, while new model years become more efficient. For example, *per* km NMVOC emissions decreased 50% between EURO 3 (2000) and EURO 4 (2005) vehicles. We conclude that break-even can occur much sooner, depending on the burden under consideration and on the transplanting age of the car. For example, the break-even for NMVOC emissions is reached after 5 years if the car is transplanted at the age of 4, since efficiency gains are high (>6%/year, on average). Conversely, energy consumed (or carbon emitted) is recovered after 6 years, if the car is transplanted after 4 years of operation. Logically, compensation periods tend to be longer as the ratio of fixed-to-marginal energy or environmental burdens becomes greater. Importantly, both are expected to decrease simultaneously over time, although possibly at different rates.

Refer to Figure 57a and Figure 57b (next page) for an illustration of the efficiency gains of NMVOC emissions and fuel economy between vehicle model years while considering ageing also. As we can observe, we assumed that fuel economy and emissions deteriorate with time and these assumptions might influence decisively our results. In fact, studies indicate that both normal and high-emitter deterioration have decreased remarkably for the 1990s model years and the durability of emission controls will continue to improve with future models. We will analyze this assumption in the sensitivity analysis section, later in this chapter.

As mentioned above, the differences are explained by the efficiency gains expectable from different environmental burdens. Therefore, we analyze the compensation periods for a multi-objective function based on the economic values of emissions (except for energy, since raw energy and respective costs vary depending on the lifecycle stage considered), presented in the section 5.2.7 (Chapter 5, p.159) when we compare economic and environmental damage costs associated to each car ownership scenario.

$$U = \sum_{E} E \times u_E \tag{4-13}$$

where U corresponds to the weighted-environmental burden (in €), E stands for the environmental burdens considered (in kg), and u_E the unitary economic costs (in €/kg).



Comments: Here, we divide the coefficient of the base model year (while varying car age) by the coefficient of new model years (i.e., fixed age = 1) for varying vintages. For example, we can obtain higher gains by transplanting a 2000 MY car, aged 20, than a new car from the same MY. Gains are maximized if we transplant a 2000 MY car, aged 20, with BAT from 2015. Compatibility issues between MY may arise. NMVOC includes evaporative emissions.

Figure 57. Efficiency gains (%) of (a) NMVOC emissions and (b) fuel economy of different model years, considering car ageing (source: author)

The following table presents the number of years required to compensate the energy and emissions associated to car organ transplant.

Table 22. Break-even periods associated to car technological transplant (source: author)

Environmental Burden	Age of Transplant (years)				
	3	5	7	9	17
Energy (GJ)	16	9	7	5	3
CO_2 (kg)	9	5	4	3	1
CO (kg)	22	2	2	1	1
NMVOC (kg)	8	2	1	1	0
NO_x (kg)	98	19	17	12	8
PM (kg)	n.a.	n.a.	n.a.	n.a.	n.a.
Multi-Objective [a)] (€)	10	6	5	4	1

a) For details on the calculation of this multi-objective indicator refer to Chapter 5; n.a. - not applicable.

All environmental burden generated by the production of transplanting kit and scrappage of replaced equipments can be recovered during the remaining service time of the car, except for PM and NOx emissions. In the first case, technological transplant does not affect PM exhaust emissions from gasoline-fuelled cars. In the second case, the reduction of NOx during the operation stage is not sufficient to recover the emissions from the production stages of transplanting kits (for example, if the car is transplanted at age 5, break-even would be reached after 19 years). Importantly, the weighted-environmental burdens can be recovered after 6 years, if the car is transplanted at the age of 5.

4.6. Summary and conclusions

We used lifecycle analysis to evaluate the possible energy and environmental impacts of organ transplant in cars over a 20-year ownership of midsize gasoline-powered car. We quantified lifecycle emissions of greenhouse gases and regulated pollutants. Whereas greenhouse gases have global effects (particularly through global warming and consequently climate change), regulated pollutants have local effect on air quality (and importantly on public health). Although regulated pollution has local impacts (and therefore each lifecycle stage has a consequence in a different location), our approach bounds those lifecycle emissions of the car to the final user, i.e. the car owner. As such, we analyzed the lifecycle for five different car ownership alternatives: keep car over 20 year; buy new car periodically, over the same time period; buy remarketed cars; buy remarketed cars that were transplanted; or keep car while transplanting new and cleaner technologies periodically.

Our analysis comprised the following lifecycle stages in a LCI (lifecycle inventory) model: material production; vehicle manufacturing; fuel refining, transportation and delivery; car use; maintenance and repair; end-of-life disposal. Furthermore, whereas this lifecycle characterization refers mainly to the car *per se*, and is usually referred to 'cradle-to-grave', we included also the lifecycle burdens related to the fuel used to operate cars, which is usually referred to 'well-to-tank'. Importantly, the energy and environmental intensity of each lifecycle stage reduces over time as technological development generally makes processes more efficient, whether these relate to car production or car use. As such, the LCI model we developed is dynamic, in the sense that coefficients used decrease over time (and are determined exogenously).

Generally, the operation stage of the cars lifecycle is responsible for more than 90% of energy consumption or emissions, while the production stages are more intensive regarding material consumption, and EOL disposal is more important with respect to waste generation. EOL stage is not significant (<1%) in terms of energy consumption or emissions in the context of the vehicle's lifecycle. Importantly, burdens are more important (factor of 3) during the first year of the vehicles, since fixed burdens related to material and car productions are allocated to the first year of the vehicle service time. The second year is the less intensive in all respects and efficiency decreases smoothly as the car ages (mostly due to loss of efficiency both in energy and emissions terms). Marginal burdens (mainly, energy consumption and emissions) increase as technology loses efficiency.

The trade-off between fixed and marginal burdens plays an important role. Organ transplant in cars is to be successful only when gains obtained in marginal burdens during the operation stage offset the initial fixed burdens. Interestingly, the energy and environmental burdens associated to the production of transplanting kits correspond roughly to 20% of the vehicle's lifecycle burdens. We concluded that organ transplant in cars can generate energy and environmental benefits, depending on the age of transplant and the period the vehicle is used thereafter (according to our assumptions). The payback period of technological transplant (i.e., the time period necessary for the marginal gains in efficiency to offset the initial fixed burden) can range from 2 to 19 years, if the car is transplanted at the age of 5. The difference in payback periods is due to expected technological development with respect to fuel consumption and different pollutant emission factors. If emissions are expected to decrease significantly (e.g., NMVOC) then marginal gains are higher and, as such, the payback period is shorter. Conversely, if technology development is not expected to delivery much (e.g., NO_X), than payback periods are longer. Importantly, the estimated weighted-payback period was 6 years, for the same transplant age. Furthermore, producing a transplanting kit requires less ~1,200 kg of raw materials and less ~100 GJ than a conventional midsize car. Likewise, the production of a car generates 670 kg of solid waste, almost 7 times more by mass than is generated during transplanting kits production (i.e., ~100 kg of solid waste per kit). Consequently, we conclude also that car transplant (alone) reduces material flows when compared to a conventional car.

In the next chapter, we describe the total car ownership cost model we use to analyze the economic profile of a car over the same ownership period referred before and to compare alternative ownership approaches (Chapter 6).

Chapter 5. Total car ownership costs and organ transplant costs

When having to choose which car to buy, it doesn't matter if a car starts out cheaply (low acquisition cost) but costs more down the line (high running costs). Similarly, it is hardly preferable to choose a car that pollutes less if the start-up and operation costs are higher. We would risk saying that this is common sense judgment although it is a realistic and important reasoning to consider when analyzing our problem. Down the road, our research aims to estimate the potential fleet-wide energy and environmental benefits (including emissions and material burdens) of car organ transplant. Therefore, we will analyze the potential market acceptance of transplanted cars, in Part C of this dissertation.

Beforehand, we check if the costs of organ transplant can compete in the market place with the remaining alternatives. If not, our hypothesis would have only fragile grounds for further analysis. In fact, we could hardly conceive that a significant share of consumers would opt for transplanted cars if they are not competitive when compared to conventional alternatives, despite the potential efficiency improvements and corresponding operation cost reductions.

Effectively, consumers hardly (not to say *rarely*) consider environmental criteria when deciding which car to buy. Instead, they give priority to other attributes such as price, styling, reliability and safety. Interestingly, the Portuguese authorities reviewed the passenger-car taxation both for acquisition (Tax on Passenger Cars[34]) and circulation (Circulation Tax[35]) that now are partly levied on the carbon efficiency of the vehicle. These transformations were meant to bring car consumer choices closer to what would be the best choices in the society's perspective (i.e., minimize negative external costs of car use by choosing more efficient technologies).

After reviewing many surveys on car type discrete choice modeling, Train (1986) found a surprising consistency in the attributes considered by households when choosing cars: price, operating costs (or fuel efficiency) and some measure of size (e.g., number of seats, weight, and/or wheel base). Furthermore, the UK used-car market survey by BCA (2006, p.76) reveals that environmental considerations were ranked 11th, in a set of 20 decision-making attributes. Although the RAC report on motoring (2006a) indicates that UK motorists recognize the environmental impacts of car use and that 50% of the inquiries would check emissions levels before purchasing their next vehicle, they also recognize that environmental attributes lag a long way behind the other criteria.

By the end of this chapter, we will have demonstrated that transplanted cars can be an attractive alternative for some segments of car consumers, under the assumptions of our analysis. This analysis includes economic costing as well that we present in this section.

[34] In Portuguese, "Imposto sobre veículos – ISV".
[35] In Portuguese, "Imposto Único de Circulação – IUC".

The present chapter provides a framework for understanding overall vehicle economics and key economic variables in relation to individual ownership costs, operating decisions and replacement intervals. We present the total car ownership costs (estimated in Euros) for the use of car over 20 years (our base case). Economic results include annual ownership costs, total lifetime ownership costs, life cycle pollutant damage costs (we consider CO_2 and criteria air pollutant, only), payback periods and net present values analysis. Standard economic calculations and spreadsheet models were used for TCO (Total Cost of car Ownership) estimates, including the analysis of car organ transplant costs. Firstly, we analyze the optimal replacement of cars based on standard economic calculations, for each scenario. Thereafter, we compare the total economic costs of all scenarios, for different swapping intervals. We also test the impact of considering different horizons of analysis on the optimal replacement intervals. Finally, we analyze the same situation relative to the comparison of scenarios including carbon dioxide emissions and criteria air pollutant emissions, also.

5.1. Background of lifecycle costing of car ownership

Amidst the vast literature on accounting methods to assess total costs of product and services, *life cycle costing*, *activity-based costing* and *total ownership costing* are recurrent methods. Depending on the field of expertise, different definitions of *life cycle costing* (LCC) have been suggested. LCC has its roots in the evaluation of military applications, and in the building and public sectors (Sherif and Kolarik, 1981). Since then, the concept has spread to the business sector and is used in new product development studies, project evaluations and management accounting. As there is high interest in life cycle cost analysis in maintenance, the International Electro-technical Commission published a standard for carrying out LCC in 1996, which was renewed in July 2004 (IEC 60300-3-3, 2004). Other authors such as Sherif and Kolarik (1981) or Woodward (1997) reviewed and contributed to the development of this tool for assisting management and decision-making. More recently, LCC emerged as a likely concept and tool for one of the sustainability pillars, i.e., economic issues – apart from environmental and social concerns (Hunkeler and Rebitzer, 2005). As referred previously, LCC refers to all costs associated with the system likewise LCA deals with environmental impacts. The definition presented here was suggested by Rebitzer and Hunkeler (2003): "*LCC is an assessment of all costs associated with the life cycle of a product that are directly covered by the any one or more of the actors in the product life cycle (supplier, producer, consumer/user, EOL-actor), with complimentary inclusion of externalities that are anticipated to be internalized in the decision relevant future*". As defined here, LCC method goes beyond the scope of our research since we are solely focusing on the consumer/user of the product life cycle, although many aspects of this technique are important for our analysis.

Activity-Based Costing (ABC) systems emerged in the mid-1980's to meet the need for accurate information about the cost of resource demands by individual products, services and customers. Whereas traditional accounting methods included direct costs (such as materials and direct labor) while ignoring overhead and other indirect costs (e.g., depreciation of equipment), ABC systems enable indirect and support expenses to be driven first to activities and processes, and then to products and services, giving the managers a clearer picture of the economics of their financial operations (Miller, 1995, Kaplan and Cooper, 1998). Although the spirit of ABC systems is inspiring for the accountability of total costs of car ownership, these are meant to management of organizations and not for individuals.

Total cost of ownership (TCO), or *total ownership costing,* can be defined as a support tool for investment decision-making that quantifies systematically all costs generated over the lifetime of a product or service, including all direct and indirect costs. Mostly embedded in the spirit of earlier methods, TCO determines a figure that reflects the total cost of the investment by the individual (and organizations, too), including one-time purchases and recurring costs (i.e., costs incurred on a periodic basis and originated from the use, maintenance, upgrades, annual licensing fees, insurances, taxes, depreciation, opportunity costs, as well as support of the application or investment – finance costs), not just the initial start-up cost (Ellram and Siferd, 1998).

As referred above, we assume that, at best, car consumers are concerned with life cycle costs of car ownership, which do not include environmental concerns, and they make their decision on the basis of total car ownership costs minimization, although this may not correspond to the behavior of all consumers. For modeling purposes, we consider that car consumers evaluate uniformly all items of TOC and they don't voluntarily shoulder the external costs of their activity. Ultimately, we are disfavoring environmental-friendly alternatives because they have higher purchasing costs for the time being (and presumably in the near and medium term) unless environmental costs are internalized, for example through taxes. Ultimately, when making their decisions based upon life cycle thinking, car owners might potentially achieve two major outcomes: 1) by balancing investment and operational costs (e.g., higher purchasing price for lower operational costs), they are *doing the right thing* (supporting strategic decision); and, 2) by planning expenses over the vehicle's life (e.g., careful maintenance of car and probably avoid unpredicted failures), they are certainly *doing things right* (supporting operational decision). This is possible only when car owners acknowledge the *total costs of car ownership.* The following table presents the items included in the TCO of a car estimated by different sources.

In the following sections, we describe the economic variables included in our model and present the parameters used to estimate the total costs of car ownership scenarios. In the case of transplanted cars, we include the costs of transplanting kits in the item of *purchasing price/financing* and review the fuel costs and taxes , as transplanted cars are expected to become more fuel and environmental efficient.

5.2. Description of car ownership costs

Economic variables and parameters impacting vehicle economic decisions and replacement intervals are discussed in the following sections. Six categories of private vehicle ownership and operating costs were compiled in each scenario: depreciation, financing, fees and taxes, insurance, fuel, scheduled maintenance and unscheduled repairs. We presented in this section the total costs of ownership of a generic gasoline-powered midsized car estimated by several sources. The items listed here do not include parking costs and tolls not only because they represent a smaller share of TCO – 8-13% of TOC, according to the estimates by Automobile

Club of France (2005) and Autopolis (Maxton and Wormald, 2004), but mainly because they are not affected by the fact of having a new, old or transplanted car.

Table 23. Total costs of car ownership

Motoring costs	Automobile de France [a]		RAC [b]	Edmunds.com [c]		TheAutoChannel [d]	Autopolis [f]		Average car
	France	UK	Germany	UK	USA	USA			
	Renault Clio	Ford Focus	VW Golf	Generic car	Ford Focus	Ford Focus	Generic car	Average costs	%-Share range
Depreciation	1,536 *(30%)*	2,569 *(36%)*	2,084 *(28%)*	3,035 *(44%)*	1,217 *(26%)*	1,128 *(24%)*	(36%)	1,928 *(28%)*	[24% - 44%]
Fuel costs	1,238 *(24%)*	1,897 *(27%)*	2,042 *(27%)*	1,395 *(20%)*	976 (21%)	1,278 *(27%)*	(21%)	1,471 *(22%)*	[20% - 27%]
Insurance	540 (11%)	560 *(8%)*	667 *(9%)*	516 *(7%)*	1,201 *(26%)*	857 (18%)	(11%)	724 (11%)	[7% - 26%]
Maintenance & repairs	639 (12%)	1,025 *(14%)*	1,136 *(15%)*	376 *(5%)*	680 (14%)	450 (10%)	(13%)	718 (10%)	[5% - 15%]
Financing	190 *(4%)*	279 *(4%)*	339 *(5%)*	1,304 *(19%)*	409 *(9%)*	351 *(8%)*	(13%)	479 *(7%)*	[4% - 19%]
Parking	489 (10%)	349 *(5%)*	607 *(8%)*					482 *(7%)*	[5% - 10%]
Fees & Taxes	338 *(7%)*	449 *(6%)*	333 *(4%)*	162 *(2%)*	215 *(5%)*	214 *(5%)*	(6%)	285 *(4%)*	[2% - 7%]
Opportunity cost						394 *(8%)*		394 *(6%)*	[8% - 8%]
Tolls	149 *(3%)*		256 *(3%)*					203 *(3%)*	[3% - 3%]
Other costs				158 *(2%)*				158 *(2%)*	[2% - 2%]
Total	5,119 27¢€/km	7,128 38€/km	7,464 40€/km	6,946 36€/km	4,698 25€/km	4,672 25€/km		6,840 32€/km	

Note: Motoring costs are described in section 5.2 (above);

[a] Automobile Club (2005)- Comparison of motoring costs of three equivalent gasoline-fuelled passengers cars from different EU countries. Depreciation is calculated by retrieving the remarketed car price after 4 years to its initial purchasing price. Annual mileage is approximately 19,000 km.

[b] Royal Automobile Club (RAC, 2006b)- The costs are an average from a set of 17 models (e.g., Toyota Yaris; Citroen C2; Toyota Prius; Ford Focus; VW Golf; BMW 3 Series; Peugeot 407; Mercedes C Class; Renault Espace; Porsche Cayenne). The item *'Other costs'* includes the RAC membership fee. Fuel costs consider a 12,000 annual mileage. Exchange rate is 1.254€ per £.

[c] Edmunds.com (2008)- Quotes for a 2008 Ford Focus obtained from the internet (04/04/2008). Fuel costs consider a 12,000 annual mileage. Exchange rate is 0.634€ per USD.

[d] AutoChannel.com (2008)- Costs calculation as previous note. Opportunity costs are considered using the cost recovery factor, $CRF = d / [1-(1+d)^{-n}]$, where d is the discount rate (3.8%) and n is the total time span before retiring the car.

[e] Maxton and Wormald (2004).

We recall that these scenario analyses are complementary to the analysis of the external costs of vehicle pollution – monetarised lifecycle inventory referred in the previous sections, with respect to CO_2 and air pollutants. The goal of this analysis is to identify the potential economic attractiveness of ownership strategies that include transplanted vehicles.

Specific cost estimation procedures and implications are discussed in the sections that follow, including the costs of organ transplants. Our TCO model builds on the analysis of automotive life cycle economics by Spitzley *et al.* (2004), on the analysis of annualized costs of motor-vehicles by Delucchi (1997), on the analysis of societal costs of cars with alternative fuels and engines by Ogden *et al.* (2004), on the report by Arthur D. Little (2002), on information available in the TREMOVE project regarding the European motoring costs, on additional information provided by the European automobile clubs, such as the UK's RAC (2006b) and Automobile Club of France (2005), and complementary sources depending on the cost being described.

5.2.1 Depreciation

Loss of vehicle value due to depreciation in the first few years of a vehicle's life is a critical factor in overall ownership costs, i.e. 24 - 44% of TCO according to the estimates collected and presented in Table 23 (p.150). Depreciation is the amount by which the value of a vehicle declines from its purchase price and can be calculated by deducting its residual value to the initial purchasing price. Among other factors, the residual value varies according to age, cumulative kilometrage and wear of the car. The rate of depreciation for a specific vehicle may also depend on several factors including: internal factors, such as brand image, mileage range, trim line and vehicle class; or external factors, such as new model pricing and purchase power of households.

Common methods to estimate the depreciation of used-cars are (for example, refer to Storchmann, 2004, illustrated in the figure below):

- 'One-hoss shay' by which it is assumed that the asset delivers the same services for each vintage (also known as the *light bulb model* of depreciation). If the discount rate is set to zero then the annual depreciation is constant over time and the one-hoss shay method becomes a straight-line depreciation (which is the simplest method used and is calculated by taking the purchase price of an asset subtracted by the salvage value divided by the expected service life years):
- Linear depreciation assumes that annual depreciation diminishes with time at decreasing rates.
- Geometric depreciation assumes that the asset's efficiency declines at a constant rate.

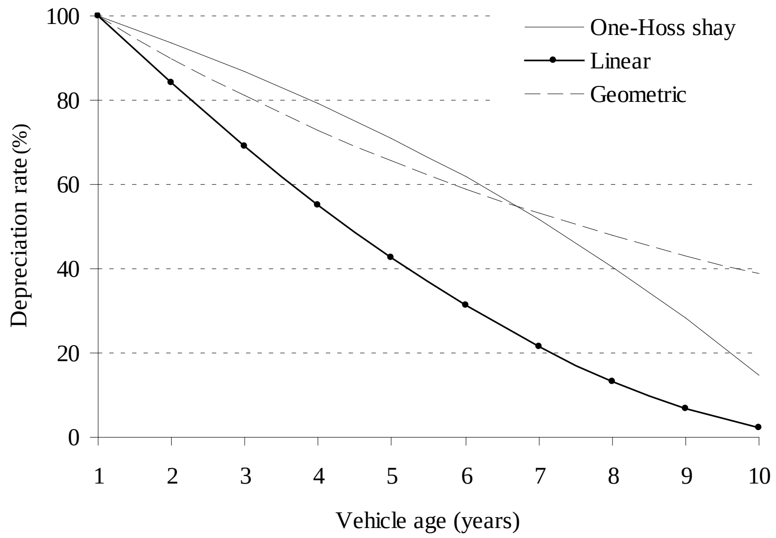


Figure 58. Illustrative curves of different depreciation models (discount rate = 3%) (based on Storchmann, 2004)

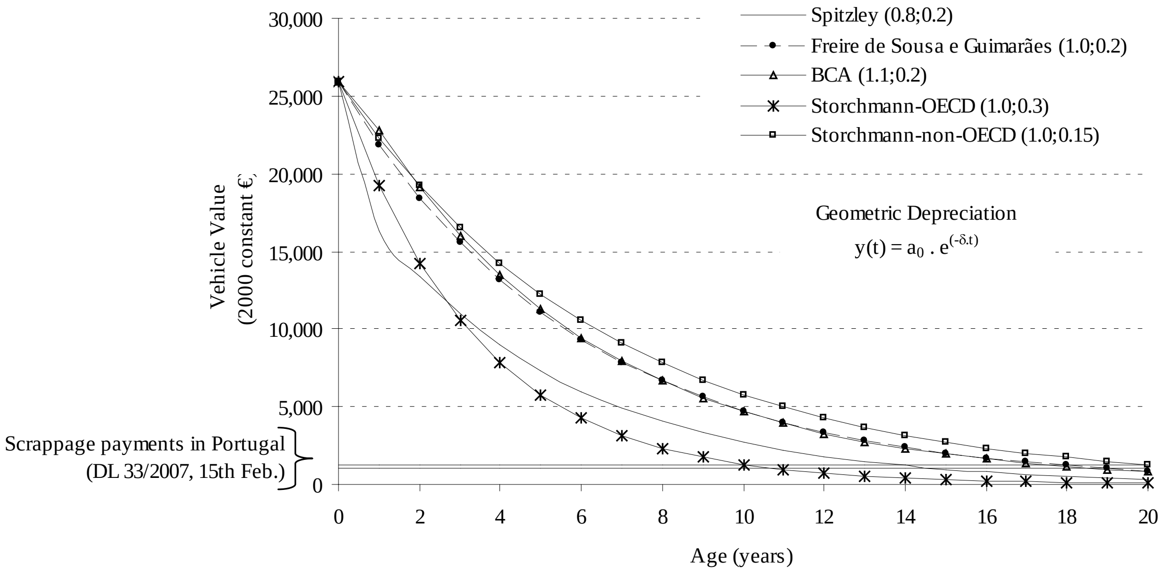
Linear and geometric depreciation models are both convex and geometric approach appears to be the better approximation to real depreciation rates (Storchmann, 2004).

Figure 59 illustrates our comparison of 5 depreciation curves collected from the literature, for a 2000 MY midsize gasoline car (purchasing price = 25,900€[36]): Spitzley *et al.* (2004) analyzed a generic depreciation curve in the USA; the BCA survey (2006) presents the average depreciation prices in the British used-car market; Freire de Sousa and Guimarães (1997) presents a depreciation curve for Portuguese used-cars (back in the nineties); and, finally, Storchmann (2004) estimated two depreciation curves for the OECD and non-OECD countries.

According to the depreciation curves we collected, vehicles depreciate faster in OECD countries than in non-OECD countries. The findings by Storchmann (2004) are not consistent with the figures of the UK and Portugal presented by BCA or Freire de Sousa e Guimarães, respectively (although the latter refer to the nineties where the car density was in the booming stage, yet). For example, the residual value of a vehicle with 10 year of age corresponds to 10% of the purchasing price in the case of Spitzley and Storchmann, whereas for BCA or Freire de Sousa e Guimarães, it corresponds to 20%. In our case, we opted for analyzing two curves: rapid and slow depreciations following the curves estimated by Storchmann (2004) for the OECD and non-OECD countries, respectively.

For reference, Figure 59 also includes the range of scrappage payments in Portugal. This scrappage program provides 1,000€ and 1,250€ as a compensation for vehicles that are 10 to 14 years of age or above 15 years, respectively (Portuguese Law, DL 22/2007, 15th of February). The compensation fare is deducted to the registration tax of the new car provided that the owner holds a certificate of destruction of the retired vehicle. Box 2 (p.154) presents a brief discussion on the early retirement program currently applicable, in Portugal.

[36] Purchasing price = Base Price (17,200€) × VAT (19%) + Registration tax (5,300€), for an engine size of 1,600 c.c.



Note: Values in brackets correspond to parameters a_0 and δ, respectively.

Figure 59. Depreciation profiles for a generic 2000 MY midsize gasoline-powered vehicle, according to different depreciation rates (based on Freire de Sousa and Guimaraes, 1997, Spitzley *et al.*, 2004, Storchmann, 2004, BCA, 2006)

5.2.2 Purchasing price and financing

The term financing is loosely used to mean that the dealership will either provide a loan (indirectly supported, or not, by a bank) to buy the car, lease or rent it (here, car renting is a financing service similar to operational leasing, and not conventional (short-term) car rental). The key difference in a lease is that after the lease expires, the lessee must return the vehicle to the dealer or buy it. The main difference between a car lease and renting is that the renting includes maintenance, repair and insurance costs (and fuel costs, as an option). Alternatively, the car can be purchased with one single cash payment. In such cases, there are no financing costs. Annex A.9 presents the main differences between a loan, a lease and car renting schemes (adapted from FRB, 2008).

In most cases, vehicle costs include financing costs associated with the loan or lease. Financing costs are the interest expense on a loan or a lease in the amount of the purchasing price including the applicable initial charges and fees, assuming a down payment (typically, 20%) and a loan or lease term of 3 to 4 years. The interest rates considered are the prevailing rate that banks and other direct automotive lenders charge consumers. As referred in the next paragraph, even if the vehicle is bought without loans or leasing, the inclusion of financing costs in determining TOC of cars could be appropriate because it would reflect the opportunity cost of the return you could have made if you had invested the purchase price elsewhere (where interest rates could be somewhat different depending on the investment made).

Box 2. Early retirement program in Portugal

From the figure above, we conclude that the probability for early retirements deriving from the program currently applicable in Portugal is higher for midsize gasoline cars above 15 years of age (except for the OECD countries curve, estimated by Storchmann). In a broader sense, medium or larger cars with 10 to 14 years of age have higher residual values than the compensation fares and thus owners prefer either to keep or remarket their used cars instead of looking for those compensation fares. Instead of aiming at the early retirement of more polluting cars (i.e., aged between 10 to 14 years), current compensation scheme is targeting smaller and/or older cars (i.e., aged more than 15 years). If at all possible, the government should aim to retire younger and more polluting vehicles, i.e. larger cars younger than 15 years of age, since these circulate more than older cars.

In order to obtain more effective results, the Portuguese authorities should review the compensation scheme. Instead of fixed compensation fares, the scheme could possibly be calculated through a formula levied on the critical factors that determine the gains of environmental efficiency of the car that is being purchased. Currently, the only eligibility requirement is that the used car can circulate safely. In addition, the compensation scheme should be index to the used-car market prices for different car types and vintages.

The parameters of such formula should be calculated in face of previously determined policy targets of vehicle retirement (nº vehicles/year by type and vintage). Furthermore, the program should be allowable to the purchase of used-cars also. As shown in future sections of the present chapter, buying used-cars can lower LC environmental burden when compared to buying new cars, depending on the vintage of the used-cars. The compensation scheme could include specific compensation fares in such cases, which would depend on efficiency gains of the remarketed car when compare to the retired vehicle. The calculation of the compensation fare could be based on the inspection reports (including emission rates), size and vintage of both the remarketed and retired vehicles. Finally, the applicant should demonstrate that the car being bought is X% more efficient that the car being retired. Today, smaller-retiring cars can get a compensation fare even when substituted by larger (and possibly more polluting) cars. Although safer, these cars are potentially less efficient.

Opportunity cost represents gains forgone by making one specific investment decision. It is difficult to estimate these costs since there is a very wide range of other investment decisions that could be made and that vary greatly with the investor's profile and socioeconomic context. Among other methods, opportunity costs can be estimated as the value of the best (i.e., more profitable) alternative investment that was not chosen in order to pursue the current endeavor or what could have been accomplished with the resources expended in the undertaking. For example, these can be estimated by calculating the return accruing from a banking investment of the car's purchasing price with prevailing bank interest rates (usually, 3-6%) during the lifetime of the vehicle.

However, we can argue that conventional car buyers do not typically consider opportunity costs when analyzing their investments. They might consider such costs intuitively when analyzing the trade-offs between the daily expenditures for example, 'buy a car or save and invest the money' but those costs are normally not considered by car buyers. Furthermore, all the alternatives we are analyzing here include car mobility, i.e. car owners have decided that they will buy a car, although they are still deciding which car they will buy. Therefore, the opportunities forgone (either costs or benefits) are not significantly different amid alternatives and, thus, do not influence the final decision of the car owner. Differently, we could say that these opportunity costs are embodied in the value of money when the car owners are analyzing their options.

Our calculations include financing costs of a three-year loan period, with a down payment of 20% a bank interest rate of 3% (conservative interest rate).

5.2.3 Fuel costs

These are determined by the total estimated consumption of fuel over the vehicle's life multiplied by fuel price. Estimates of fuel economy are presented in section 4.4.3 (p.127). Baseline gasoline prices (and diesel for section 8.3.1, p.238) were taken from the Portuguese National authorities (http://www.dgeg.pt, April 5th, 2006). Gasoline prices are the sales weighted average price for all gasoline grades (including taxes) as published by DGEG (stands for "Direcção Geral de Energia e Geologia").

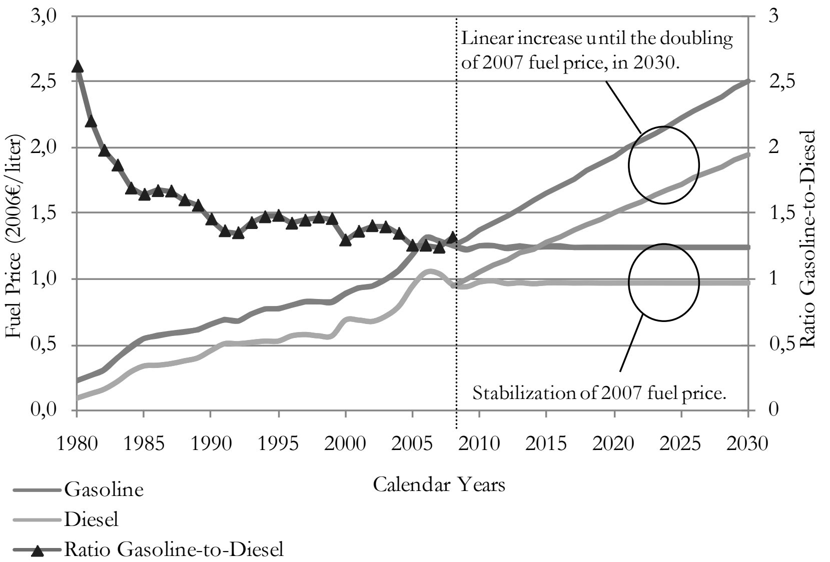


Figure 60. Fuel prices (based on data from Direcção Geral de Energia e Gelogia, http://www.dgeg.pt, April 5th, 2006)

From 2006 onwards, we considered two scenarios in an effort to determine the sensitivity of overall replacement decisions to changes in fuel prices, keeping constant the ratio of Gasoline-to-Diesel: 1) stabilization of price (moving average of the last five years); and, 2) linear increase until the doubling of fuel price in 2030. Only under extreme conditions, such as a jump in price of more than 100% from the baseline did the change in fuel price have a noticeable effect on the replacement optimization. Therefore, fuel costs are not expected to affect replacement decisions when we consider marginal improvements in fuel efficiency of vehicles[37].

5.2.4 Insurance

Insurance costs (including insurance tax) correspond to approximately 11% of TOC. This is the estimated average annual insurance premium being charged by insurers that is specific to vehicle make, model, model year, body type and the driver's personal information. Factors that affect the insurance rate usually include type of coverage, policyholder's age and gender, marital status, credit history, driving record, garaging address of your vehicle, among others, and these vary from country to country. The age of a vehicle is not expected to have a direct correlation with insurance cost due to the dominance of other driver and operating condition factors (Spitzley *et al.*, 2004). In our research, we use constant insurance costs defined as 3% of vehicle purchasing price (excluding VAT and registration taxes) following the methodology by TREMOVE (Ceuster *et al.*, 2007a). Potential changes in insurance coverage with vehicle age or other incidental occurrences (e.g., accidents affecting the cost of premiums) are not considered in the current analysis.

5.2.5 Scheduled maintenance and unscheduled repairs

From the approaches we reviewed, we could follow the approach by Freire de Sousa e Guimaraes (1997) who proposed a stochastic continuous function that generated exponentially growing maintenance costs. Alternatively, in the TREMOVE project (Ceuster *et al.*, 2007b), maintenance and repair costs vary with the car age and are calculated with predetermined percentages of the initial car price. Finally, Spitzley *et al.* (2004) formulated a discrete function composed by scheduled maintenance costs and unscheduled repair costs that occur after the 6th year of service. We opted to use the third approach and scheduled maintenance (and unscheduled repairs) activities and intervals were taken from Spitzley *et al.* (2004) that are consistent with the analysis conducted by Reis (1999), for example. The complete set of scheduled maintenance activities and associated costs is presented in Table 24. Costs of parts and components (expressed in 2000 Euros) were converted from the same survey at the exchange rate of 0.8861€ per US$. Calculation of annual scheduled maintenance cost assumes all events take place regularly and on time.

[37] We note that we did not consider an approximation between diesel and petrol prices as this exercise was performed before the recent oil price growth.

Table 24. Scheduled maintenance frequency and costs (Reis, 1999, Spitzley *et al.*, 2004)

Description of item	Cost (2000 €)	Periodicity ('000 km)	Frequency (over 300,000km service life)
Recurrent Scheduled Maintenance Group I	20	5	60
Recurrent Scheduled Maintenance Group II	25	20	15
Recurrent Scheduled Maintenance Group III	130	20	15
Recurrent Scheduled Maintenance Group IV	230	45	6
Spark plugs, inspect wires	55	45	6
Windshield wiper blade inserts	20	20	15
Transmission/Transaxle service	70	50	6
Power cooling system flush	70	60	5
Front disc brakes	160	90	3
Rear brake pads/shoes	130	90	3
Tires (set of four)	355	60	5
Muffler, exhaust pipe	245	100	3
Battery	75	100	3
Struts/shocks	530	130	2

Group I includes: lubricate and inspection of front suspension, change oil; change oil filter, refill windshield wiper fluid;
Group II includes: all of Group I, safety inspection, rotate tires;
Group III includes: all of Group I, tire rotation and wheel balancing, clean, inspect and adjust brake system, inspect cooling system, tighten hoses, inspect exhaust system and heat shields; Group IV includes: All of Group I: replace air filter, replace fuel filter, check engine timing, inspect cooling system, tighten hoses, inspect fuel tank cap and lines, tire rotation and wheel balancing, clean, inspect and adjust brake system, inspect exhaust system and heat shields.

Table 25. Unscheduled repairs frequency and costs (based on Spitzley *et al.*, 2004)

Description of repair activity		Cost	Periodicity *('000 km)*			
Parts	Components	(2000€)	No-repairs	Durable	Baseline	Unreliable
Engine	Valves and Gaskets	710	9,999	230	150	48
	Short Block	2,150	9,999	350	300	90
Cooling system	Water Pump	180	9,999	150	100	60
	Radiator and Hoses	320	9,999	230	190	120
Fuel	Pump	260	9,999	270	230	96
	Injector	540	9,999	270	230	96
	Control Module	220	9,999	150	120	48
	Oxygen Sensor	100	9,999	150	120	48
Ignition	Starter	190	9,999	230	190	60
	Alternator	195	9,999	230	190	60
Transmission	Transmission	1,330	9,999	170	120	48
Electrical appliances	Window Motor	150	9,999	120	80	48
	Wiper Motor	200	9,999	170	150	96
Air conditioning	Blower and Heater Core	505	9,999	230	190	120
	Compressor	425	9,999	150	100	60
Suspension	Tie Rod	100	9,999	150	100	60
	Ball Joint	180	9,999	150	100	60
	Struts/Shocks	550	9,999	230	190	120

As mentioned before, unscheduled car repairs depend on several factors, including driving behavior, compliance with scheduled maintenance, nature of the specific part to be repaired, etc. Hence, these are expected to show a very high degree of variability. Three additional repair scenarios were analyzed in an attempt to better capture the range of expectable repair costs (refer to Table 25): *Baseline* – car owner follows strictly factory recommendations; *Durable* – car owner strictly follows the factory recommendations and increases the durability of components not scheduled for routine replacement (protective driving behavior); *Unreliable* – baseline scenario is modified by decreasing the durability of parts and components (aggressive driving behavior); and *no-repairs* – this is a theoretical hypothesis by which there are no unpredicted replacement of parts and components.

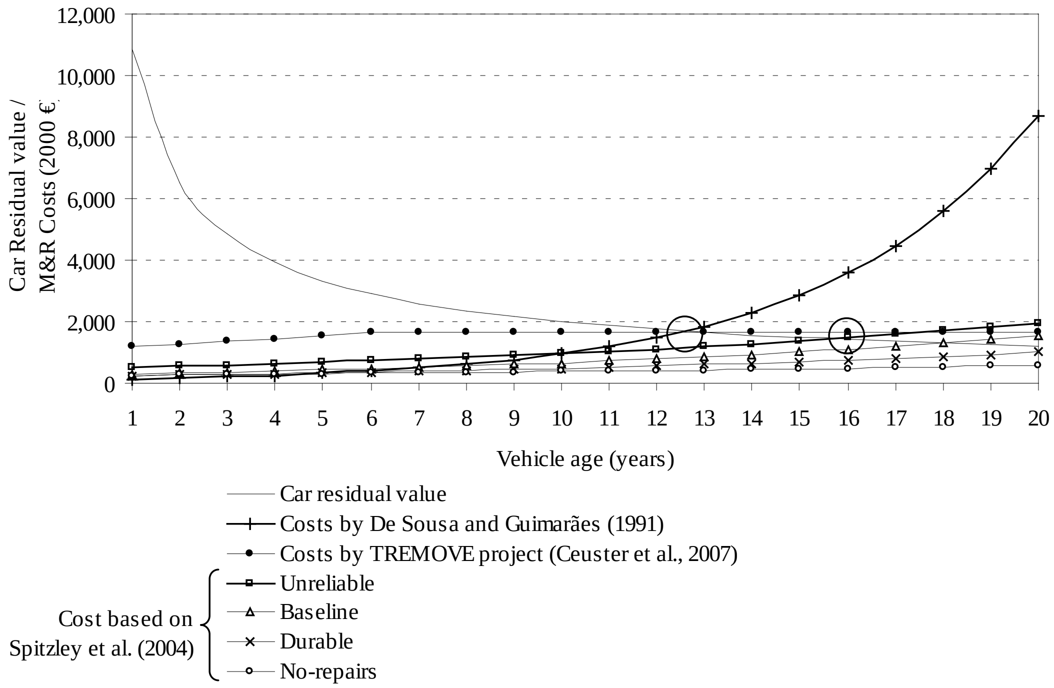


Figure 61. Residual value and maintenance & repair costs (Sources: author and Freire de Sousa and Guimaraes, 1997, Spitzley *et al.*, 2004, Ceuster *et al.*, 2007b)

Figure 61 illustrates the calculation of scheduled maintenance and unscheduled repairs (for all scenarios), over 20-years service life of a midsize gasoline-fuelled car. The figure includes also the maintenance and repair costs estimated by Freire de Sousa and Guimarães (1997) and by the TREMOVE project (Ceuster *et al.*, 2007b) and the vehicle's estimated residual value, over its service life. We conclude from the following figure that after 11 years of age, the estimates by Freire de Sousa and Guimarães (1997) experience a steep growth while the figures based on data reported by Spitzley *et al.* (2004) remain gentler. We highlight that the estimates by Freire de Sousa and Guimarães (1997) were presented for 15-years service life and we forecasted the costs for the remaining service years using the same formula (perhaps unduly). Costs estimated in the TREMOVE project (Ceuster *et al.*, 2007a) show little variation for different vintages and are higher than the remaining estimates until 13-years of age. Then, they remain closer to the estimates used here. Finally, we note that in the case of costs from Freire de Sousa and Guimarães (1997) or TREMOVE project (Ceuster *et al.*, 2007a), they intercept the car residual value car at the age of 12-13 years, whereas in our case it crosses at the age of 16 (in the worst case scenario, i.e. unreliable). Considering that this could be a decision for car replacement (i.e., '*global maintenance costs are higher than the residual value I can eventually recover*'), this observation has important implications in the swapping periodicity.

We do not include costs related with accidents in our calculation of TCO. As stated by Bédard *et al.* (2002), there are no consistent findings on the relationship between traffic accidents and the vehicle's model year. These authors report that the model year effect is extremely small when compared to other factors (e.g., age and gender of drivers, alcohol use, vehicle speed, etc.). Nevertheless, they also refer that other authors did find significant effects of car age on the number and severity of traffic accidents. The findings are inconsistent among researchers, probably due to methodological approaches and sample data used. Furthermore, we assume that transplanted cars are tested according to current homologation regulation and therefore they are considered as safe as conventional used cars (possibly safer since they are fine-tuned, also). This said, we do not consider accident damages of cars in our analysis, since they would impact all scenarios of ownership to the same degree.

5.2.6 Taxes and fees

As for insurance costs, taxes and fees vary greatly from country to country. They usually include base sales taxes, license and registration fees, and other taxes, such as gas-guzzler tax in the USA (applicable to some car categories, only). Fees and taxes are frequently based on a percentage of the purchase price and generally decrease as the vehicle ages and lose its value (unless they are levied on energy or environmental efficiency). With increasing environmental concerns, such economic instruments (those levied on energy and environmental efficiency) are being introduced. For example, the European Commission made a proposal for a Council Directive on passenger car related taxes (COM(2005)261 final) that introduces criteria such as CO_2 emissions. As mentioned in the introductory paragraphs of this section, the Portuguese authorities reviewed, in 2007, the passenger-car taxation both for acquisition (Tax on Passenger Cars[38]) and circulation (Circulation Tax[39]) that now are levied on the carbon efficiency of the vehicle and the vehicles engine size, and depends also on the fuel use. Importantly, a rebate of 500€ is provided for diesel vehicles emitting less than 0.005 g/km of PM. This will be discussed later in this dissertation when modeling the diffusion of conventional and transplanted alternatives for different circulation taxes and analyzing the potential impacts on the technological composition of the fleet (Chapter 9).

5.2.7 Damage environmental costs from air emissions

The total private costs of car ownership are complemented with a monetarized evaluation of the impacts striving from air pollutant and greenhouse gas emissions. These environmental external costs associated with airborne emissions from transportation reflect the potential for pollutants to impact human health (mortality and morbidity), building materials, crops, global

[38] In Portuguese, "Imposto sobre veículos – ISV".
[39] In Portuguese, "Imposto Único de Circulação – IUC".

warming, amenity losses (due to noise), ecosystems and land use change[40] (Bickel *et al.*, 1997). Additional societal costs related to issues such as infrastructure, accidents (human health), fuel security, water pollutants, solid waste, and congestion were not evaluated. The following table presents the monetary unit-costs used in our analysis (the average values).

Table 26. Damage costs from airborne emissions (adapted from Bickel and Schmid, 1999)

	Damage costs (2000€/kg of air emissions)		
Pollutants	Min	Max	Average
Carbon Monoxide (CO)	0.001	0.016	0.008
Nitrous Oxides (NO_x)	0.298	7.578	3.938
Volatile Organic Compounds (VOC)	0.209	1.380	0.795
Particulates	140	940	540
Carbon Dioxide (CO_2)	0.012	0.034	0.023†

† This value is confirmed by the PointCarbon[41].

Damage costs associated with individual emissions were calculated using the Impact Pathway Approach proposed by the ExternE project (Bickel and Schmid, 1999). This approach calculates a future stream of monetary values related to human health, natural and man-made environments based on pollutant emissions, site conditions, and the population exposed. Uncertainty is evident, since the maximum estimates are greater up to 25 times than the minimum estimates. These variations result from the compilation of several European cities studies – Brussels, Helsinki, Paris, Stuttgart, Athens, Amsterdam and London – and reflect the range of population densities in the cities studied with low values representing cities with lower population density, such as Helsinki (3,000 inhabitants/km^2), and high values applying to cities with higher population densities, such as Paris (6,000 inhabitants /km^2).

Due to the evident uncertainty involved here, the values in Table 26 are considered illustrative and are used only to provide an indication of how the ranking of the different car ownership scenarios based on TCO including private motoring costs only may vary from those including external costs from air pollutants, also.

5.2.8 Other costs

Although not included in our calculations, we briefly refer to other typical costs of car ownership. Parking and tolls costs are included since they constitute an increasing share in the car ownership costs, whether these correspond to the hourly cost of parking lots (or garage amortization) or to urban highways tolls and, more recently, congestion charges. As mentioned previously, Automobile Club of France (2005) and Autopolis (Maxton and Wormald, 2004) estimate that parking costs, tolls and other costs can reach 6 - 10% of TOC. With the increasing

[40] The costs for ecosystems and land use change are based on the concept of Eco-indicator99, Potentially Disappeared Fraction (Goedkoop and Spriensma, 2001).

[41] PointCarbon is a Carbon Market Monitoring company providing carbon price forecasts and analysis of greenhouse gas emissions trading markets. (http://www.pointcarbon.com)

share of urban drivers, these costs are expected to increase. There are other costs that are sometimes accounted for such as association/club memberships. Being a member of the national Automobile Association (or club) is a common practice since it brings multiple benefits to car owners (e.g., technical support, legal advisers, etc.). Nevertheless, these are not included in our costing methodology.

5.3. Costs of organ transplant in cars

In the case of costs involved in car technological transplanting (i.e. transplant costs), the information was obtained mainly from the reference report by Delucchi *et al.* (2000) where the authors breakdown the costs of producing a midsized gasoline-fuelled car for comparison with electric vehicles. Apart from this reference report, we also used values presented by parts and components suppliers, automobile magazines and sites dedicated to car customizing. Complementary information was also obtained from the well-to-wheel analysis conducted by Edwards *et al.* (2006) for the European Commission; from the review and analysis of the reduction potential and costs of technological measures to reduce CO_2-emissions from passenger cars by Smokers *et al.* (2006); from the study performed by Smith and Keoliean (2004) on remanufactured engines; from the book on *Engine Swapping Tips and Techniques* written by Ray Clarke (1990) and on the booklet written by Charles Ware on *Durable Car Ownership* (1982).

The following table presents our estimate of the costs breakdown of transplanting operations. Later in this dissertation, we present a sensitivity analysis to the total transplanting cost by assuming variations to the input parameters according to different probability density functions.

Materials and weight composition were obtained from several sources as described in section 1.3.2.5 (refer to Table 14, p.76). Regarding the weight-based costs, we adapted the materials costs description from Delucchi (1997, pp.186-187) for the same car type (i.e., midsize gasoline-powered car – e.g. Ford Taurus) and converted from US$ to € using the year 2000 exchange rate (1 US$= 0.8861€). The overheads referred in Table 27 include: all employee benefits (health benefits and paid vacations), full-salary-plus-benefits of working supervisors and plant managers, perishable tools in the plant, among few others (Delucchi, 1997). The overheads are expressed as a percentage of labor time (hour equivalent). For example, the overheads to produce and assemble the base engine correspond to 250% of the total time spent producing the engine, and therefore are calculated as follows: $OH_{\text{Base Engine}}=(13+6)\times 2.5=48$ hours-eq.

Table 27. Transplanting costs breakdown (source: author)

Parts	Components	Materials Used	Materials cost	Labor time (Overheads)							Manufacturing costs (€)				
				Manufact.		Assembly		Mounting		Total	Materials Production	Labor costs			Total
		(kg)	(€/kg)	(hrs)	(%)	(hrs)	(%)	(hrs)	(%)	(hrs)		Manufact.	Mounting	Overheads	
Engine	Base engine	149	1.06	13.11	250	6.00	250			47.78	158	406	0	1,015	1,579
	Other components	39	0.71	2.20	150					3.30	28	47	0	70	144
	Module	188						6.00	250	15.00	0	0	128	319	446
Transmission	Clutch & controls	4	0.71	0.05	150					0.08	3	1	0	2	5
	Transmission	30	0.71	4.30	150	2.87	250			13.63	21	152	0	290	463
	Module	34						6.00	250	15.00	0	0	128	319	446
Chassis components	Engine electrical	14	1.32	0.53	100					0.53	19	11	0	11	41
	Engine emission Controls	8	5.29	0.70	100					0.70	42	15	0	15	72
	Exhaust system	23	1.06	1.40	100					1.40	24	30	0	30	84
	Catalytic converter	13	5.29	0.60	250					1.50	66	13	0	32	111
	Oil and grease	3	1.41	0.60	150					0.90	4	13	0	19	36
	Air conditioning	31	1.06	0.15	150					0.23	33	3	0	5	41
	Heating system	10	0.71	0.15	150					0.23	7	3	0	5	15
	Accessories equipment	2	1.94	0.10	150					0.15	4	2	0	3	9
Other transplant costs	Adaptation equipment	5	2.82	6.00	250			6.00	250	30.00	14	128	128	638	907
Total		330						18.00		130.41	422	824	383	2,771	4,400

These overheads are then converted to € based on the labor costs expressed in €/hour. Labor cost is calculated based on hourly labor compensation, 21.25 €/hours[42], adopted from O'Mahony and Ark (2003) for the motor vehicle manufacturing category. Labor compensation is current price labor costs borne by the employer. It includes wages as well as the costs of supplements such as employer's compulsory pension or medical payments. It refers to compensation of employees only. Finally, we compared the parameters used here to other values in the literature regarding some selected powertrain components and found that they are consistent (refer to Table 28).

Table 28. Price of selected powertrain components

	Our parameters [a)]		Edwards *et al* (2006)	ADL (2002)	Ogden *et al* (2004)
Engine (100kW)	17	23	30	13	13
Transmission	6			n.a.	6
Electric motor (1.5kW)	27		27	20	

Notes: [a)] Based on Delucchi *et al.* (2000); values are expressed in €/kW; n.a. – not available.

Regarding transplant-specific operations, we assumed that the type of equipment that is required for transplanting new parts and components (possibly, tailor-made) costs 300% more than other engine components and the production time of those additional components lasts up to 6 hours. We assumed also that transplanting practices could increase the in-vehicle-mounting time by 50% compared to normal engine and transmission mounting, and overheads are equivalent to normal engine and transmission mounting. Exclusive transplanting operations (and not simple engine substitution) cost 900 €, i.e. 21% of total transplant cost.

Engine Repower Council (2006) refer that the cost of repowered vehicles corresponds to approximately 10% to 25% of a new car, depending on the car type (refer to Table 29). Apparently, our results are consistent with the costs they present for equivalent vehicles, if we assume that a new midsize gasoline car costs approximately 25,000€. In addition, Edwards *et al.* (2006) estimated incremental vehicle retail price due to technological improvements aiming to increase energy and environmental efficiency for midsize cars. In the case of technological improvements of current ICE systems, retail price increase could go up to 4,500€. Finally, Smokers *et al.* (2006) estimated that for most target-measure combinations they assessed, the manufacturer costs for reaching a 2008-target of 140g/km (compared to a baseline 2002 vehicle) and, subsequently, reaching a 2012-target of 120g/km (compared to average costs of the 2008 vehicle emitting 140g/km) are approximately €2,700 per vehicle. According to their accounts, this translates into an additional retail price of nearly €4,000 per vehicle. Again, we could say that our estimates are at best conservative if compared with the studies referred here.

In order to analyze the robustness of these estimates, we performed a sensitivity analysis according to the probability density curves associated to the input parameters as presented in the following table and used the @Risk software from Palisade (http://www.palisade.com/).

[42] According to the Eurostat long series data (http://epp.eurostat.ec.europa.eu), the average 2000 hourly labour cost, in the EU15, was 21.25€/hour.

Table 29. Costs of repowered[43] vehicles and prices of new vehicles (Engine Repower Council, 2006)

Engine and Vehicle Type	Repowering costs[44]				New Vehicle
	US$		% of new vehicle		US$
80-95 Full size V8 domestic Pickup	2,500	3,100	9	11	28,000
94-01 Fwd GM V6 3100-3400	2,850	3,500	12	15	23,000
96+ Explorer V6	3,600	4,400	10	13	35,000
96 Jimmy 4X4 \Astro van 4.3 V6	2,700	3,650	9	13	29,000
97+ Ford truck\van V6 4.2	2,800	3,600	12	15	24,000
96-01 Ford truck\van 4.6-5.4 V8	3,450	4,200	13	16	27,000
00 Ford Escort 2.0 SOHC	2,200	2,950	12	16	18,000
93+ Transport 97+ Venture	3,000	3,800	11	14	27,000
84-95 22R Toyota Pickup 4x4	2,650	3,500	15	19	18,000
00-01 2.7 Dodge Intrepid	4,190	5,600	19	26	21,500
Average	2,994	3,830	12	16	25,050

Table 30. Assumptions on the variation of input parameters to the transplant cost model (source: author)

Parameter Description	Unit	Distribution function			
		Type [a)]	1st par.	2nd par.	3rd par.
Unitary production cost of ...					
Base engine	(€/kg)	Triangular	0.5	1.06	3
Other components	(€/kg)	Triangular	0.5	0.71	2
Clutch & controls	(€/kg)	Triangular	0.5	0.71	2
Transmission	(€/kg)	Triangular	0.5	0.71	3
Engine electrical	(€/kg)	Triangular	0.5	1.320	5
Engine emission Controls	(€/kg)	Triangular	0.5	5.29	10
Exhaust system (without cat. Conv.)	(€/kg)	Triangular	0.5	1.06	3
Catalytic converter	(€/kg)	Triangular	0.5	5.29	10
Oil and grease	(€/kg)	Triangular	0.5	1.41	4
Air conditioning	(€/kg)	Triangular	0.5	1.06	3
Heating system	(€/kg)	Triangular	0.5	0.71	3
Accessories equipment	(€/kg)	Triangular	0.5	1.94	5
Transplanting adaptation equipment [e]	(€/kg)	Triangular	1	2.48	10
Labor cost	(€/hour)	Normal	21.3	10	(5/50)
Production time of additional transplant components	(hours)	Uniform	3.5	8.5	
Additional in-vehicle mounting time	(%)	Uniform	0%	200%	

Function parameters: Triangular (minimum, more likely, maximum); normal (μ, σ; truncate min/max); uniform (minimum, maximum).

[43] As defined previously, we consider that renovating an engine corresponds to restoring to a former better state, as by cleaning, repairing, or remanufacturing.
[44] These figures represent a range of possible prices for the vehicles listed. The price range typically includes the retail price of a custom engine plus the labour to install the engine. The estimate would also include the replacement of the thermostat and water pump and disposable parts including spark plugs, ignition wires, belts, hoses, filters and gaskets.

Figure 62 illustrates the distribution curve we fitted to the results obtained from our Monte Carlo simulation (1,000 iterations). The best fit was obtained for a normal probability density function with an average of 4,545 € and a standard deviation of 1,885 € (equivalent to a 40% deviation to the average transplant cost). Our reference calculation was 4,400 € (i.e., 3% below the average obtained for the normal pdf). We will analyze the influence of the transplant cost variation in the lifecycle cost comparison between car ownership scenarios, later in the sensitivity analysis section. In section 9.5.1 (p.299), we also address the implications of variation higher than 50% over the transplant base cost, on the final results of energy and environmental impacts of the diffusion of transplant technologies.

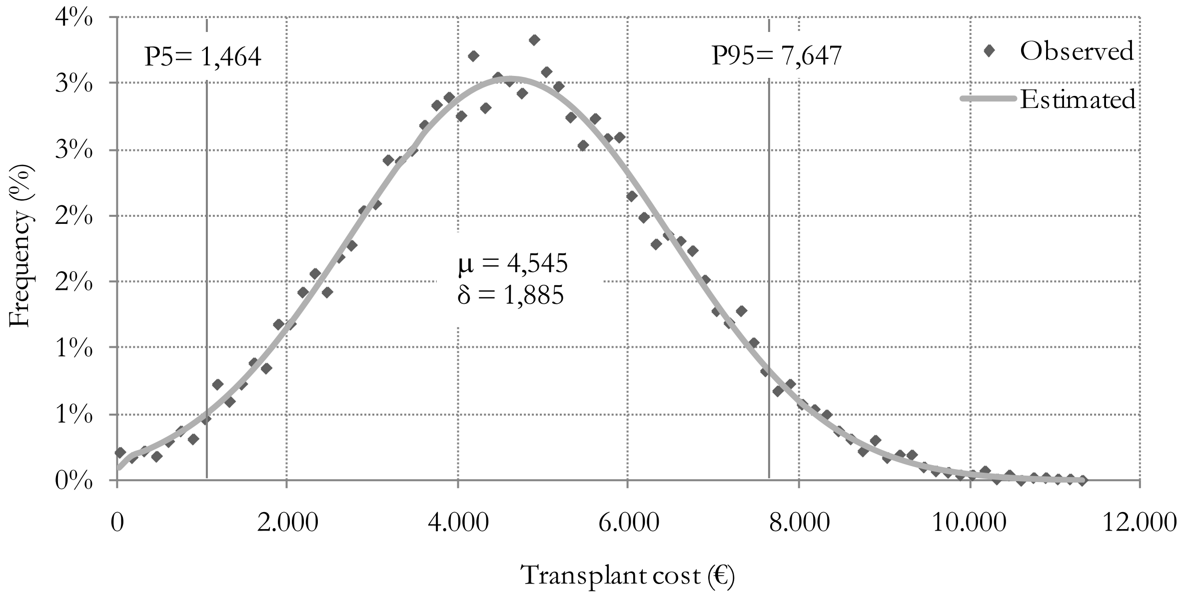


Figure 62. Estimated probability density curve of transplant cost for a midsize gasoline car [tc~NormalDist(4,545;1,885)] (source: author)

Sensitivity analysis is also used to identify the most critical inputs to the model in order to better understand what is driving the model and give an indication of where efforts should be focused for collecting additional and more accurate information. The following figures show the tornado graph obtained from our regression sensitivity analysis that relate the randomly generated inputs and the respective outputs calculated with our model for every iteration (and for which we obtained a high $r^2>0.9$).

Regression coefficients (p_i) are obtained from multivariate linear regression, through standard least squares fitting, between the standard deviation of the model outputs and the standard deviation of input variables. An pi value of 0 indicates that there is no significant relationship between the input and the output (Palissade Corp., 2008).

$$p_i = a_i \times \frac{\partial_{Input\ i}}{\partial_{Output}} \quad 5\text{-}1$$

where a_i is the multivariate regression parameter of the corresponding variable

The regression coefficients of 'Labor' and 'Base engine' costs are computed as 0.997 and 0.042, but these are in units of standard deviation of output per standard deviation of input. To obtain the unscaled coefficients, we multiply the regression coefficient (p_i) by the standard deviation of the output and divide by the standard deviation of the input. For example, the regression coefficient (p_i) for 'Labor' cost is 0.997 that we multiply by 1,885 (standard deviation of output) and divide by 10 (standard deviation of input) obtaining thus an unscaled coefficient of 188. The interpretation is that for 1€ increase of 'Labor' cost (*ceteris paribus*), we obtain an increase of 188€ in the output. Likewise, 1€ increase in 'Base engine' cost (*ceteris paribus*) implies an increase of 107€ in the overall transplant cost. These correspond to nearly 5% and 2%, respectively, of the total estimated transplant costs. As such, we consider that the model for transplant cost estimation is robust enough for the purpose of our analysis.

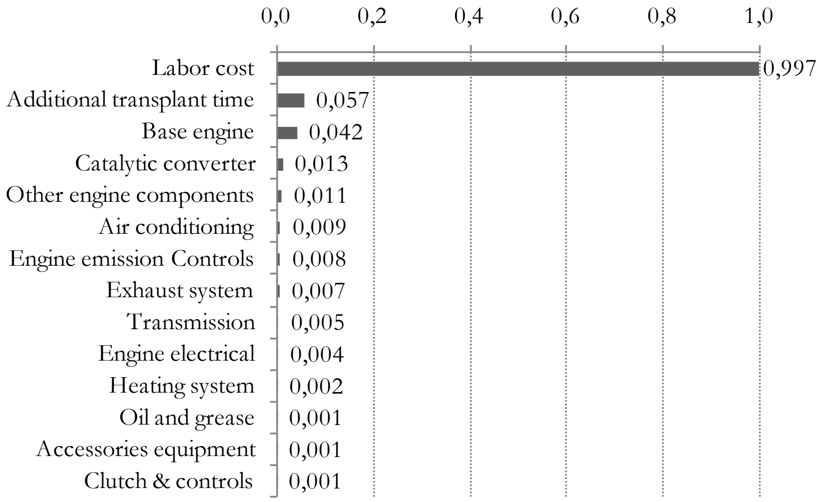


Figure 63. Sensitivity analysis to the Transplant Cost model (source: author)

The most influent parameter on the total cost of technological transplant being 'Labor' cost, its socio-economical determinants are external to our model and we would not expect any strong variation of the labor cost in developed countries. However, we can expect that the labor times for technological transplant could be subject to optimization – i.e., reduce labor hours through 'learning-by-doing' – and thus reduce the overall transplant costs. Still, variations occur to a small extent, since a one hour reduction of technological transplant would reduce overall costs by 85€ (over a basis of 4,400€).

Finally, our calculations depend on the weight composition of the transplanting kit – whether we refer to the components included or their corresponding weight – and the relationship between weight and final transplant cost is linear. However, there is little variation of the final costs due to the weight of the components – 10 kg weight decrease (over 330 kg) corresponds to 13 € decrease of total costs (*ceteris paribus*).

5.4. Economic analyses of car use and organ transplant

5.4.1 Vehicle lifecycle economic profile

We simulated the annual total ownership costs by summing cost estimates of the categories presented in the previous section, excluding emissions damage costs, for a 20-year service time. Figure 64 illustrates the life cycle profile of ownership costs for a 2000 midsize gasoline-powered car. The graph reflects the results obtained for a constant annual mileage (15,000 km), the base case scenario for maintenance and repair of the car (refer to section 5.2.5) and (fast) depreciation rates. We included a financing scheme of 3 years loan period with a down payment of 20% and an interest rate of 3%.

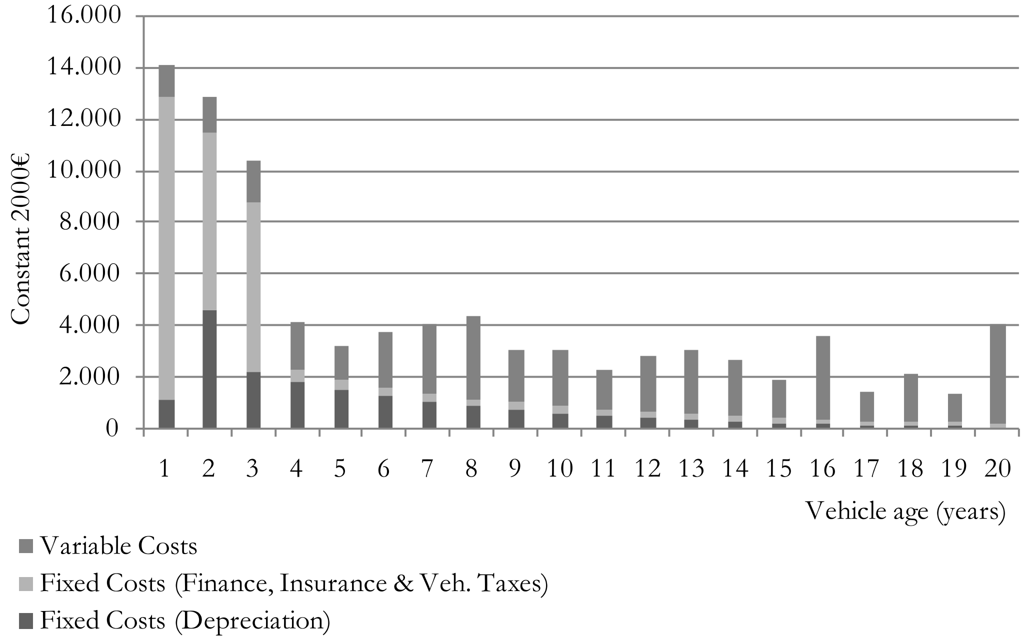


Figure 64. 20-year life cycle profile of ownership costs for a 2000 midsize gasoline-powered car (source: author)

We observe that fixed costs (including financing, insurance, and depreciation) exhibited a strong decrease with vehicle age (in constant 2000 Euros), principally due to the fact that we consider that the residual value of the used car depreciates strongly until its 7th year of age – we note that we assumed a payment period of 3 years with 3% interest rates. From the 7th year onwards, total ownership costs stabilize at approximately 2,000€/year (all costs included), although some variation can occur depending on the scenario of depreciation and maintenance and repair considered (this issue is addressed in the sensitivity analysis later, in this chapter). Interestingly, fuel costs correspond to more than 40% of annual ownership costs as from the 4th year of age (refer to section 5.1). Therefore, any increase of fuel efficiency (possibly due to powertrain transplant) after this age is more evident, all costs considered. Repair costs generally increase over time. However, we opted to follow the approach by Spitzley *et al* (2004) by which the more random nature of these costs leads to substantial fluctuations from year to year.

The next figure illustrates the total per km life cycle ownership costs for different horizons of analysis: 5, 10 and 20 years of service time. These are 69¢€/km, 48¢€/km and 35¢€/km, respectively. Spitzley *et al.* (2004) estimated 30¢€/km and 20¢€/km per km costs for 10 a 20-year service time, respectively. These are below our results possibly due to the lower capital investment and fuel costs in the USA. Additionally, annual per km ownership costs from different sources presented in Table 23 (p.150) ranged from 25¢€/km to 40¢€/km. All in all, our results are consistent with these sources.

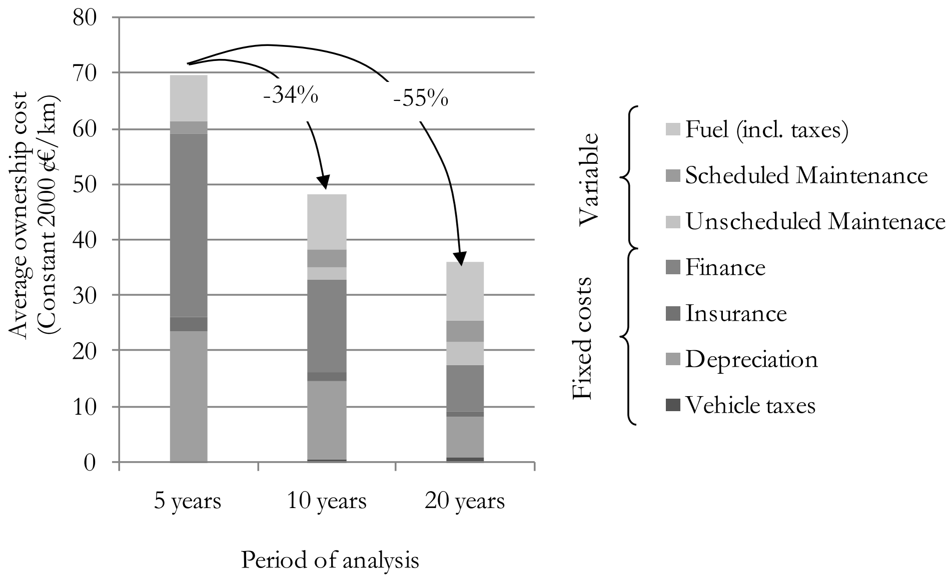


Figure 65. Per km life cycle costs of a 2000 midsize gasoline-powered car for different horizons of service time (source: author)

Fixed costs include financing, insurance and depreciation. Logically, as the service time increases, the higher capital investment costs (financing) are distributed over longer periods, since variable costs remain comparatively constant. In this sense, ownership cost can decrease more than 30% (and 55%) from 5 to 10 years (and 5 to 20 years) of car ownership. Still, we note that fixed costs correspond to 80%, 70% and 50% of total ownership costs depending on the service time considered (5, 10 or 20-years, respectively).

5.4.2 Transplant costs, payback period and net present value

At this point, we analyze how much savings the investment in organ transplant in a car adds to car ownership over a certain period. In this sense, we calculated two standard indicators of financial analysis of investments: payback period (PB) and net present value (NPV). In the first case, it indicates the amount of time (expressed in years) required for cumulative estimated future net benefits from an investment (here, savings in fuel cost, maintenance and repair cost and circulation tax) to equal the amount initially invested (here, transplant costs). NPV indicates how much value is added by an investment over some period of time, discounting the future cash flows of the project. These are used to compare alternative investment opportunities. In the present case, they are used to compare the alternatives of whether keeping the car as usual (scenario 1) or to transplant it with BAT[45] after some time (scenario 5).

The formulas used to estimate both PB and NPV are:

[45] Best Available Technologies.

$$PB = \frac{TC}{\frac{1}{p.i.} \times \sum_{k=1}^{p.i.} \frac{CF_k}{(1+d)^k}} \qquad 5\text{-}2$$

and,

$$NPV = -TC + \sum_{k=1}^{p.i.} \frac{CF_k}{(1+d)^k} \qquad 5\text{-}3$$

where,

TC are the transplant costs (for the scenario 1, $TC = 0$, whereas for the scenario 5, $TC = 4{,}400$€),

p.i. is the period of investment considered for the economic analysis (in the case of *PB*, we use the maximum expected service time of a car (20 years) to estimate the average annual cost and, in the case of NPV, we considered 5 to 10 years as intuitive time windows that people would consider when planning their private investment when considering private car swaping,

CF are the cash flows over one year and can be calculated by subtracting costs to benefits of some activity (here, benefits are intangible[46] and therefore CF refer to costs only),

k refers to calendar years, and

d is the discount rate (we considered 3% per annum).

Figure 66 (next page) presents the results of these indicators calculated for the differential between the alternatives referred in the previous paragraph and equations 5-2 and 5-3 are reformulated as follows:

$$PB = \frac{TC}{\frac{1}{20} \times \sum_{k=1}^{20} \left[\frac{-\Delta\left(fc_k + mr_k + ct_k\right)}{(1+d)^k} \right]} \qquad 5\text{-}4$$

and,

$$NPV = -TC - \sum_{k=1}^{5\ or\ 7} \left[\frac{\Delta\left(fc_k + mr_k + ct_k\right)}{(1+d)^k} \right] \qquad 5\text{-}5$$

where,

fc, *mr* and *ct*, refer to fuel costs, maintenance and repair costs and circulation taxes, respectively (we did not include the remaining cost items presented before since they are equal in both scenarios and, thus, their difference is null), and

---

[46] The benefits of car ownership can be: auto-mobility, accessibility, comfort, privacy, sense of control, etc.

Δ refers to the difference between those costs in scenarios 1 and 5.

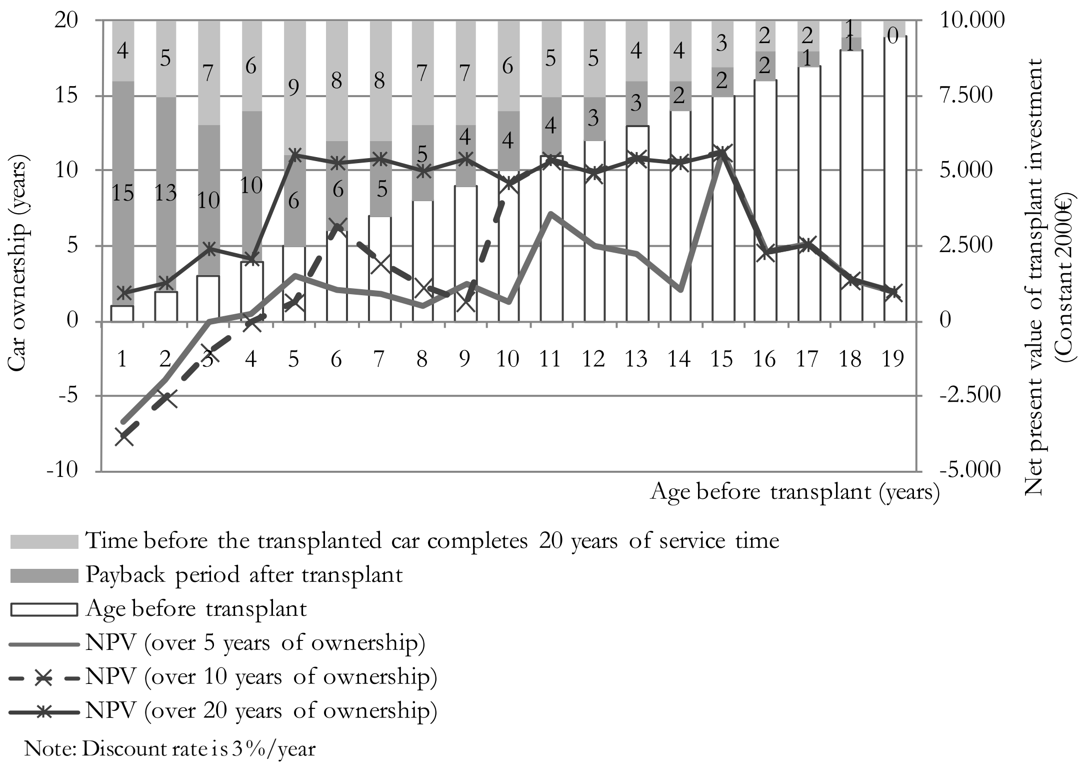


Figure 66. Payback period and net present value of transplant investment (source: author)

We will now analyze the previous figure providing a 'guided tour' on the various information we can take out.

- The white bars in the graph correspond to the time when the car is transplanted and during which technology gets outdated and loses efficiency.
- The dark-grey bars symbolize the period required to pay back the investment in organ transplant. We conclude that the payback period decreases as the age of transplant increases. As expected, the running costs of a car decrease as technology gets younger and updated (BAT) considering that all costs depend on the car's efficiency (including circulation taxes that depend on its carbon efficiency). Therefore, the bigger the gap between the model year of the car and that of the transplanted components, the lower is the payback period. Furthermore, if we add the age of transplant to the payback period (white bars) we obtain the total service time required before the payback period is completed. Interestingly, we conclude that if the car is transplanted with 5 years of age, the investment is cost-effective after 6 years (considering economic costs only and under our assumptions), reaching a total service time of 11 years. In this case, the investment is cost-effective for a 6% fuel economy improvement from 8.6 liters/100km to 8.1 liters/100km (considering that the car is used during 6 years after being transplanted). This results are consistent with the findings by Greene and Duleep (1992) who estimated that fuel economy improvements in the order of 7% to 11% are probably cost-effective – in their case, they estimated fuel economy improvements of new models. Furthermore, the report "*Making cars more efficient-Technology for real improvements on the road*", by the ECMT (2005), refers that under the assumptions of a gasoline vehicle used in Europe (for example, fuel prices), there are several technological

improvements in cars that are cost-effective from the consumer's viewpoint. For example, electric water pumps, efficient alternators, efficient air conditioners, automated (or shift indicator lights) manual transmission are paid for by fuel savings in 3 years or less, and should therefore be attractive to many consumers. According to the same report, the prospects for diesel-powered vehicles are not so promising party due to lower fuel cost savings and partly because diesel engines use less fuel during cold weather. Considering that the transplanting kit (as we conceived here) includes these technological improvements, we can conclude that our results are more conservative that those presented in the ECMT report.

- Light-grey bars symbolize the time left after the payback period and before the car ownership period we considered in our exercise, finishes. Correspondingly, they indicate the time during which the car owner accumulates net benefits after the payback period of the transplant investment. Again, these benefits are maximized if cars are transplanted at the age of 5.
- Lines with stars symbolize the Net Present Value for a horizon of analysis of 20 years. Accordingly, NPV[47] is maximized when the car is transplanted at the age of 5. We note that NPV remains quite constant if cars are transplanted until 15 years of age. However, if we consider different horizons of analysis (for example, 5 and 10 years – illustrated by the solid line and the dashed line with crosses, respectively), the age of transplant that maximizes the NPV is 15 years of age. In this case, the payback period would be 2 years leaving 3 years to complete the maximum service time (20 years). Realistically, only a very small share of car owners would opt for this alternative. Hence, we analyzed the second best NPV for both period of analysis and concluded that the corresponding ages of transplant are:
    - 11 years, if the car owner analyses her/his investment over 5 years, where the payback period is 4 years and the net benefits are obtained over 1 year (accounting for a minimum 16 years of service time); and
    - 6 years, if the car owner analyses her/his investment over 10 years, the payback period is 6 years, and net benefits are collected over 4 years (accounting for a minimum 16 years of service time, also).

After trying other periods of analysis (results not shown here), we conclude that the transplant ages that maximize NPV (other than 15 years) lie between 5 and 7 years, if the car owner analyses her/his decision up to 10 years. Importantly, if she/he considers investment periods of less than 5 years, the transplant ages raise to 15 years. Again, we think that only a very marginal share of consumers would opt for such an alternative.

We concluded from the sensitivity analysis to the transplant costs that our estimated are rather stable and would vary mainly if the labor costs involved would changed radically. However, transplant costs do not include any profit for the transplanter (i.e., those who perform organ transplant in cars – for instance, garages). As such, transplant prices are not expected to be the

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[47] We note that the "bumpy" pattern of the NPV curves in Figure 66 are mainly due to the random nature of maintenance and repair costs considered here.

same as transplant costs. In this sense, we analyzed situations where profits are added to transplant costs – 10%, 25%, 50% and 100% more than base costs. The following figure illustrates the payback periods obtained for profit range. We conclude that only a few car owners would transplant their cars if transplant costs would double (i.e., +100%). For instance, transplanting a car at the age of 9 years, would require a payback period of another 9 years, leaving 2 years before the end of car ownership we considered, here. Yet, the payback period for a car transplanted at the age of 6 years, would correspond to 7 years, if transplant prices were 50% of base costs. We will analyze the consequences of transplant price variation on the adoption of transplant technologies in Part C of this dissertation.

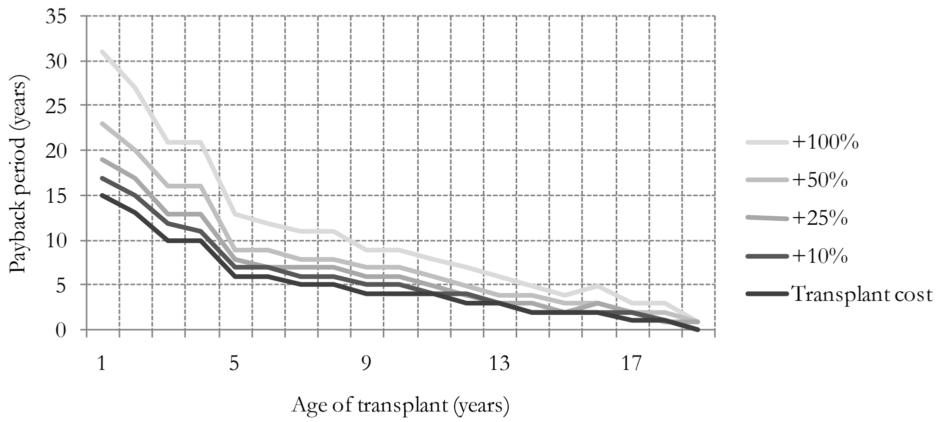
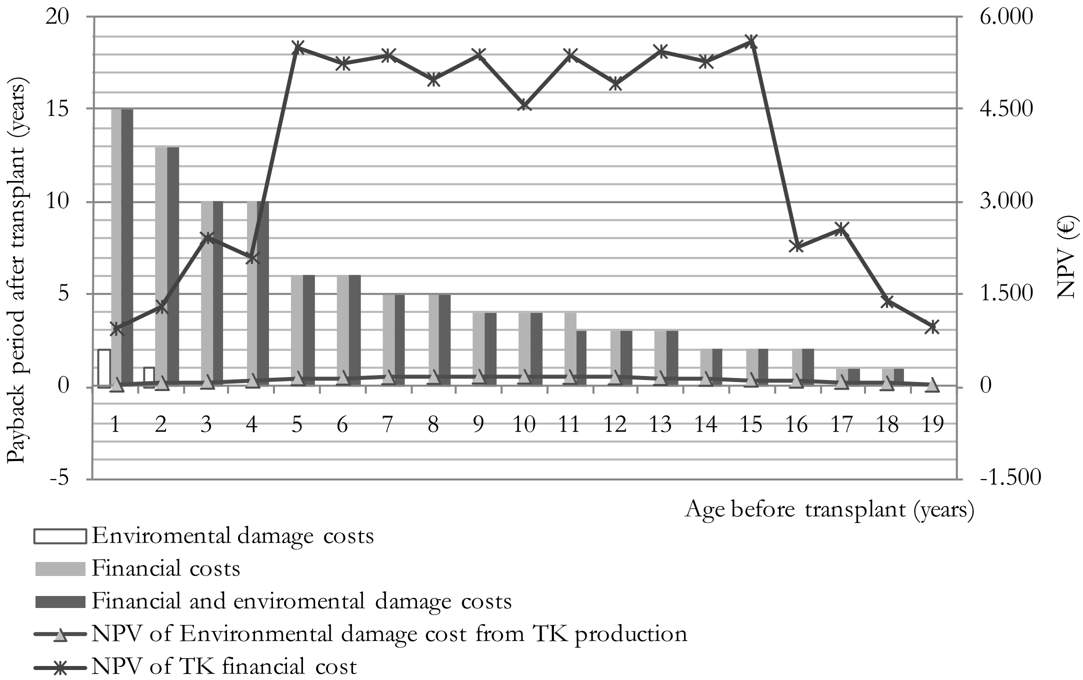


Figure 67. Payback periods for different profit ranges

We calculated payback periods and NPV indicators including environmental damage costs from both scenarios – we used the unit costs (€/kg $_{\text{pollutant}}$) presented in Figure 68 (next page). In previous sections, we explained that the environmental damage costs refer to air emissions, only, and that they include all lifecycle stages. As mentioned before, we calculate the gains from technological transplant on the operation emissions (including 'well-to-wheel' and maintenance related emissions), and estimate the payback period to recover the additional environmental damage costs from producing materials, manufacturing and assembling components, and handling the EOL of replaced components.

We note that the costs related to PM emissions were not included. According to the EMEP/CORINAIR Guidelines (EEA, 2002), PM emissions during the operation of gasoline-fuelled cars are minor. Conversely, these are important during the production of materials and manufacturing of vehicle components. If we include them in the present calculation, we would distort our results and mislead our conclusions since there is no impact from technological transplant on PM emissions (i.e., infinite payback periods if PM were considered alone). The next figure illustrates the results of our calculations and includes the payback period for environmental damage costs (white bars), the payback period of financial costs (dark grey bars), and finally, all costs considered together (light grey bars).



Note: Discount rate is 3 %/year for financial cost.

Figure 68. Payback period and net present value of transplant investment, including environmental damage costs (source: author)

Environmental damage costs are recovered sooner than economic costs, as from the transplant age of 3. In the case of younger used cars, the reduction of emissions striving from the gains of efficiency after technological transplant are not sufficient to offset the pollution from the production of transplanting kits. In reality, cars are not expected to be transplanted before 4 years of age. Figure 68 includes the NPV from both environmental costs (curve with triangles) and economic costs (curve with crosses) and shows the gap between them, in monetary terms. Environmental costs influence the payback periods from technological transplant only to small extent – i.e. one year increase of payback if the car is transplanted after one year. The remaining payback periods are mainly driven by the economic cost of technological transplant at different ages.

5.5. Summary and conclusions

We described in this chapter, the total car ownership cost model and the cost estimates of technological transplant. We observed that the highest costs of car ownership are related to the depreciation of the car over its service time. Per km unit cost of car ownership (all costs considered) decreases significantly (up to 55% for a 20-years service time) as the car ages. Interestingly, the fixed costs (which include financing, depreciation, insurance and taxes) of car ownership are dominant during the vehicle's service time. During the first 5 years, these correspond to more than 80% of total costs. Considering an ownership time of 20 years they correspond to 50% of total costs. These analyses suggest that, from the economic perspective, extending the service time of the car is a rational and more profitable option.

We conclude also from the previous analyses that technological transplant might be an interesting option for some car owners, since they can recover their investment after a reasonable period of time (i.e., approximately 5-7 years depending on the age of transplant, although this depends strongly on the transplant price to be adopted by transplanters). In addition, there are environmental gains from transplant operations by which increased emissions due to the production of transplanting kits and scrappage of replaced components are recovered after shorter periods of time (i.e., 4-5 years), as well. We recall that we do not include in this environmental damage accounts, the avoidance of raw materials consumption and waste production. Therefore, the payback periods should be even lower. Furthermore, if the transplanting kit includes remanufactured parts and/or components, the overall energy, environmental and economic burdens can be potentially lower. Refer to Smith and Keoleian (2004) for a detailed analysis on the lifecycle environmental impacts of remanufactured engines.

In the next chapter, we complement the previous analyses considering all scenarios of car ownership and conclude on the best strategy of ownership attending to economic and environmental damage costs (based on the assumptions of our research).

Chapter 6. Impact of transplant technologies on the car ownership strategy

This chapter presents the analysis of the potential impacts of technological transplant of cars on car ownership by comparing different approaches. In this sense, the following section presents the methods we used to analyze the competing ownership approaches. In this sense, we describe firstly what are the scenarios of car ownership we adopted (section 6.1). Thereafter, we delimit the scope of the comparative analysis by defining the system's boundaries and underlying assumptions. In section 6.1, we present the results from the application of the models presented in the previous chapters to each scenario, compare them and determine to what extent car technological transplant is one attractive option in terms of life-cycle energy and environmental performance of vehicles (including material consumption and waste generation) and/or constitutes a viable/attractive economic option for car owners. Finally, we make a sensitivity analysis to some of the critical variables and parameters and test the robustness of our conclusions (section 6.3).

6.1. Procedure for comparative analysis of conventional *versus* transplanted cars

6.1.1 Scenarios for analysis

As referred before, we address in the present chapter the lifecycle of a medium size gasoline-fuelled car, according to five scenarios of ownership in order to evaluate the impacts of technological transplant on car ownership. In section 4.2 (p.105), we described the functional unit associated to the LCI model. Now, we describe the scenarios of analysis that include the same functional unit but for different car ownership approaches. These scenarios are:

- Scenario 1 ("keep car"): the car owner keeps the same car over 20 years, which is retired in the end. At best, the owner recovers the salvage cost[48] of the car. As mentioned in the previous chapters, Scenario 1 corresponds to our base case. In the forthcoming analysis, we will analyze the remaining scenarios with respect to Scenario 1.

- Scenario 2 ("new car"): the car owner buys a new car periodically (7 years) and sells the used car and, hence, recovers its residual value.

We compared two surveys on optimal car swapping periodicities to minimize explicit economic ownership costs: Freire de Sousa and Guimarães (1997) found that the optimal replacement age for the first vehicle lies between 7 to 9 year (independent of total service time),

[48] Salvage value (or residual value) is the estimated amount that is recovered when it is disposed at the end of its useful life. It can also be defined as the corresponding utility it is expected to generate over the remainder of the assets useful life. Often the salvage value is estimated to be zero when assests are scrapped. In the case of cars, materials or components are valuable assets (e.g., metals or handles, respectively) that have an economic value.

while Spitzley *et al.* (2004) found that the optimization of private car ownership costs requires relatively long vehicle replacement intervals, i.e. approximately every 18 years over a 36-years time horizon. Both models account consider new cars only. The differences arise necessarily from the formulation of the optimization problem and on the input values, namely those regarding maintenance costs and depreciation of the car that account for more than 40% of TOC (on average, 10% and 30% of annual TOC, respectively). In the first case, it is assumed that cars should be replaced when the expectable maintenance and depreciation costs of the used car surpass the investment and operational costs of the new vehicle over some service time. Differently, Spitzley *et al.* (2004) estimates optimal replacement intervals based on the annual decision of a vehicle owner on whether to keep the existing vehicle or replace it with a new vehicle. The decisions are based on total life cycle costs over a 36 year time horizon. For our analysis, we assumed that the swapping periodicity is 7 years.

- Scenario 3 ("remarketed-car"): For comparison purposes, the 1st car is new and, thereafter, the owner buys remarketed cars every 7 years. Used-cars' probability of survival decreases with age (s-shaped curves as explained in detail in Chapter 8). For cars older than 20 years, we assume that they are scrapped afterwards and that they are worth their salvage value. To calculate the EOL lifecycle burdens, we multiply the corresponding environmental coefficient by the probability of scrappage of the used-car. In addition, we determined that the age of remarketed cars follows a Weibull distribution curve with the following parameters $age_{rkt} \sim WEIBULL(a=2.5;\beta=8.2)$, based on the Abmotors database we used in Chapter 8 and Chapter 9. Therefore the average age is $\mu = \beta \times \Gamma(1+a^{-1}) = 7.6 \times 0.88 = 7.7$, i.e. between 6 and 7 years of age. We will analyze this base case situation in the results section, later.

Differently, demand for 3 to 5 years-old UK's remarketed cars is higher (41%) than the remaining vintages, followed by cars aged 1 to 2 years of age (23%) (BCA, 2006), whereas German remarketed car buyers prefer vehicles aged 1 to 2 (17%)[49]. According to the same survey, both market segmentations are stable over time. Apparently, the replacement periodicity referred by Freire de Sousa and Guimarães (1997) that would rather privilege shorter (1st owner) service times is closer to the used car market we observe here. This said, we assumed that used-cars are remarketed with 6 years. The salvage value is calculated according to the car age. Hence, our assumption influences the attractiveness of this ownership scenario (such as the ownership scenario 4 described hereafter). For example, if a midsize gasoline car is remarketed with 4 years, in 2007 – i.e., the original model year is 2003 – its salvage price is approximately 12,5000 €. If it is sold after servicing 7 years – i.e., the original model year is 2000 – its value is much lower, i.e. approximately 8,000€ (in both cases, we considered a low depreciation scenario).

- Scenario 4 ("remarketed transplanted car"): Again, the 1st car is new and is replaced periodically (7 years) by used cars that are transplanted prior to being remarketed (with 6 years, also). Hence, these vehicles are used but equipped with BAT regarding the parts and

[49] Market shares are uniformely distributed (5-6%) among the cohorts from 3 to 10 years (decreasing slowly thereafter – cumulative share of cars aged more than 10 years is 36%).

components that influence the vehicle's energy and environmental intensities. If the car becomes older than 20 years it is scrapped and not remarketed.

Scenario 5 ("transplant own car"): the car owner decides to transplant his/her car (which he/she bought brand new) every 7 years. We note that in this case, the first transplant operation is equivalent to the previous scenario when the owner decides to swap his/her car after 7 years by a remarketed-transplanted car. Thereafter, the present scenario is different since the car is getting older than the cars considered in the previous scenario (which we recall are always 6 years of age). For this theoretical comparison, we consider that a vehicle is 'transplantable' several times during its lifetime, although this might be an abusive assumption. In Chapter 9, we are more conservative and assume that a vehicle is transplanted only once during its lifetime.

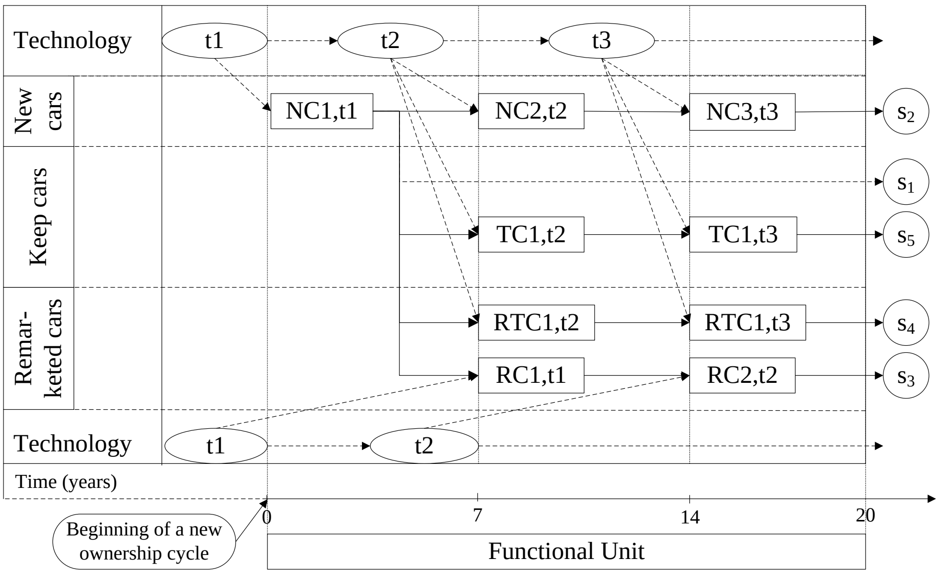


Figure 69. Illustrative diagram of the functional unit and scenarios of analysis (swapping period of 7 years over 20-years horizon) (source: author)

Figure 69 (above) presents an illustrative diagram that depicts the paths of analysis we used over our horizon of analysis, i.e. 20 years of ownership, starting from our base year 2000. In the diagram, rectangles represent vehicles, ellipses represent the technologies that diffuse differently in the stock depending on the car ownership strategy (s_1 to s_5). Dashed arrows represent time-technological precedence between technologies. For example, the difference between scenario S_1 and S_2 is that in the 1st case the car owner uses one (new) car over the 20-years time period (NC1→end) that maintains its original technology all along (t1→end), whereas in the 2nd scenario the owner buys new cars every 7 years (NC1→NC2→NC3→end), where technologies are up-to-date (t1→t2→t3→end), respectively. The difference between the scenarios that include *car transplanting* is that, in scenario S_4, car owners buy remarketed transplanted cars every 7 years (NC1→RTC1→RTC2→end) and, hence, technologies are also up-to-date (t1→t2→t3→end), whereas in scenario S_5, the owner transplants his car with the same periodicity (NC1→TC1→TC1→end) where changes reside in the technological upgrade (t1→t2→t3→end). Finally, the scenario S3 refers to the case where the owner decides to buy conventional remarketed cars every 7 years (NC1→RC1→RC2→end) and technologies are not up-to-date (t1→t1→t2→end), after as from the 2nd vehicle.

For comparison purposes, every scenario begins with the same car (2000 model year) following different ownership strategies, thereafter. Furthermore, we consider that the car owner follows the manufacturer maintenance recommendations, in all cases. If the vehicle is properly maintained (e.g., changing oil or tires at the necessary kilometrage point) and no external system problems occur, the transplanted parts and components will likely outlast the vehicle body and chassis sub-systems.

6.1.2 System boundaries and assumptions

Whereas the full LCA of new car includes all life cycle stages starting with material production and car manufacture throughout until its disposal phase, in the case of *remarketed* or *transplanted cars*, material production and car manufacture burdens are fully allocated to the original use of the car, i.e. we consider only the use and eol life cycle stages. In the case of transplanted vehicles, as new components are introduced we consider all life cycle stages of the transplanting kit when modeling the lifecycle inventory. This reduces the overall lifecycle burden of *remarketed* and *transplanted cars* by taking advantage of the energy and resources embodied in the used (and still usable) parts and components of the vehicle, although in the 2nd case additional burdens outcome from the production of the transplanting kit and the final disposal of substituted parts and components. All LCI analyses presented in the following sections include the upstream fuel lifecycle stages also and the energy consumption and emissions due to scheduled maintenance operations during the use phase of the car.

Figure 70 depicts a simplified car lifecycle, including transplanting or abatement options.

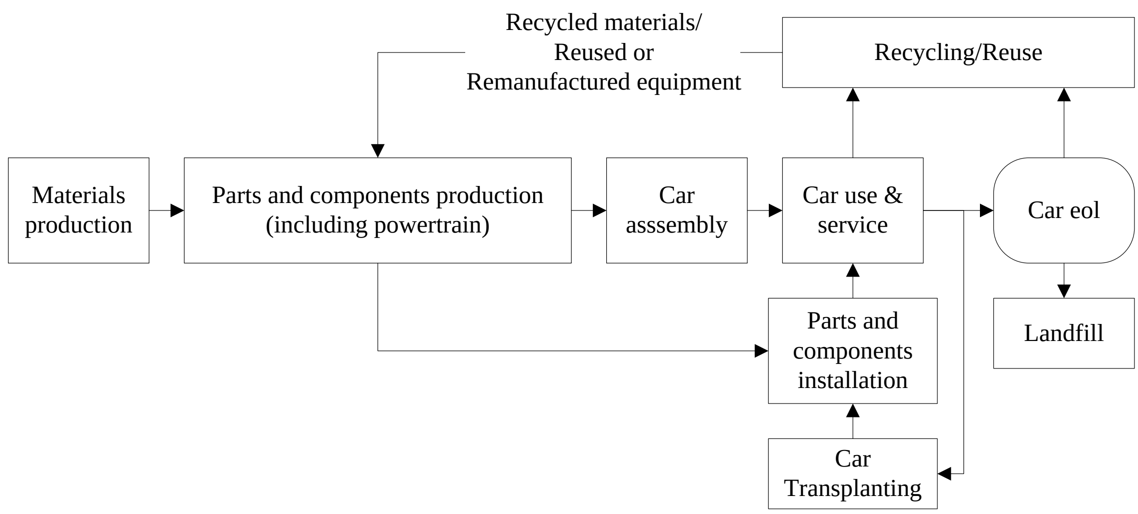


Figure 70. Life cycle of a car including technological transplant (source: author)

The car technological transplant stage of Figure 70 is further disaggregated in Figure 71.

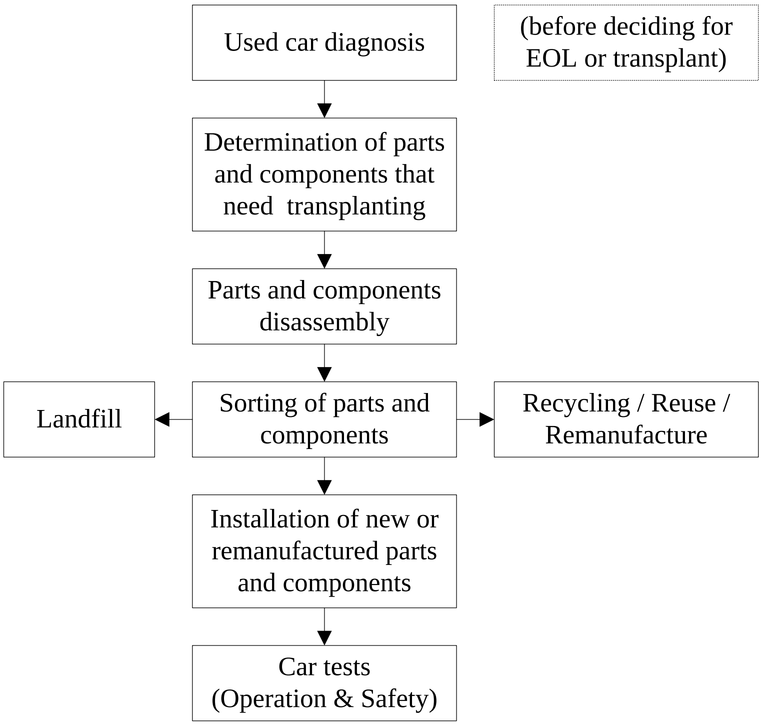


Figure 71. Proposed stages in the process of car technological transplant (source: author)

We note that inspection and car testing requirements are state regulatory responsibility. These requirements should define the sharing of liability in the operation stage of the car after transplant. These issues are further developed in chapter 9 (Part C of this dissertation), namely when we discuss liability issues and the Block Exemption European legislation.

The next figure presents a diagram that merges Figure 69 and Figure 70 (whenever possible) to illustrate the global boundaries of our LCI analysis. We illustrate 5 scenarios (S_1-S_5) of car ownership under analysis with the corresponding streams of lifecycle analysis: Scenario 2 includes the streams *carLCA1* to *3*, the use and maintenance stages, and finally the car EOL stage; in the case of remarketed cars, the streams *carLCA* are not included; and, if cars are transplanted, the steams *TK LCA1* and *2* are added to the use and EOL stages. We discuss the diagram in more detail hereafter:

- S1: Car ownership includes one (new) vehicle (NC1) over the time frame considered. Hence, the LCI is limited to the carLCA1 stream, which encompasses all life cycle stages, for one single car.

- S2: Car ownership is composed by three new cars over 20 years (NC1→NC2→NC3). The LCI includes the corresponding 3 LCA streams, i.e. carLCA1 to 3, plus the use and maintenance lifecycle stages. In this case, total LCI of car ownership is the sum of individual new-car LCIs. EOL stage is only accounted for the last vehicle.

- S3: This scenario includes one new car (the 1st one) and two remarketed-cars over the ownership period (NC1→RC1→RC2). As referred previously, we assume that the environmental impacts from materials production and car manufacturing are allocated to the first use of the car. Therefore, LCI includes only the use, maintenance and eol stages of the used-cars' lifecycle – and thus excludes the carLCA streams.

- S4: Remarketed transplanted cars are potentially cleaner alternatives to conventional remarketed cars. Again, we assume that the environmental impacts from materials production and car manufacturing are allocated to the first use of the car. Differently to the previous scenario, we include the lifecycle burdens associated to the production and installation (including materials production, parts and components manufacturing) of transplanting kits and the EOL management of the replaced parts and components. LCI includes the corresponding LCA streams of Figure 72, i.e. TK LCA1 and TK LCA2. As for scenario S2, total LCI of car ownership is the sum of individual LCIs of cars plus those from the transplanting kits, where both include the use, maintenance and eol stages of the replaced equipment. Expectably, the increased impacts from the transplanting kit production and scrapping of replaced parts and components are offset by the reduction of energy intensity and emissions of BAT transplanted into the older vehicle.

- S5: The difference of the present and previous scenarios arises from the fact that the car owner keeps his car and transplants BAT periodically into his/her own car over 20 years, instead of buying remarketed-transplanted cars. With respect to the 1st and 2nd cars, energy and environmental burdens are almost equal: firstly, because we assumed that the 1st car is new for all ownership scenarios; secondly, in the case of the 2nd car, buying a remarketed transplanted car with 6 years is just about equivalent to transplanting your own car at the age of 7 (since your car's residual value is similar to the one of a 6 years-old car). Total life cycle costs (either environmental or economic) impacts of both scenarios should differ only marginally, since technologies that affect energy efficiency and emissions are the same for both scenarios.

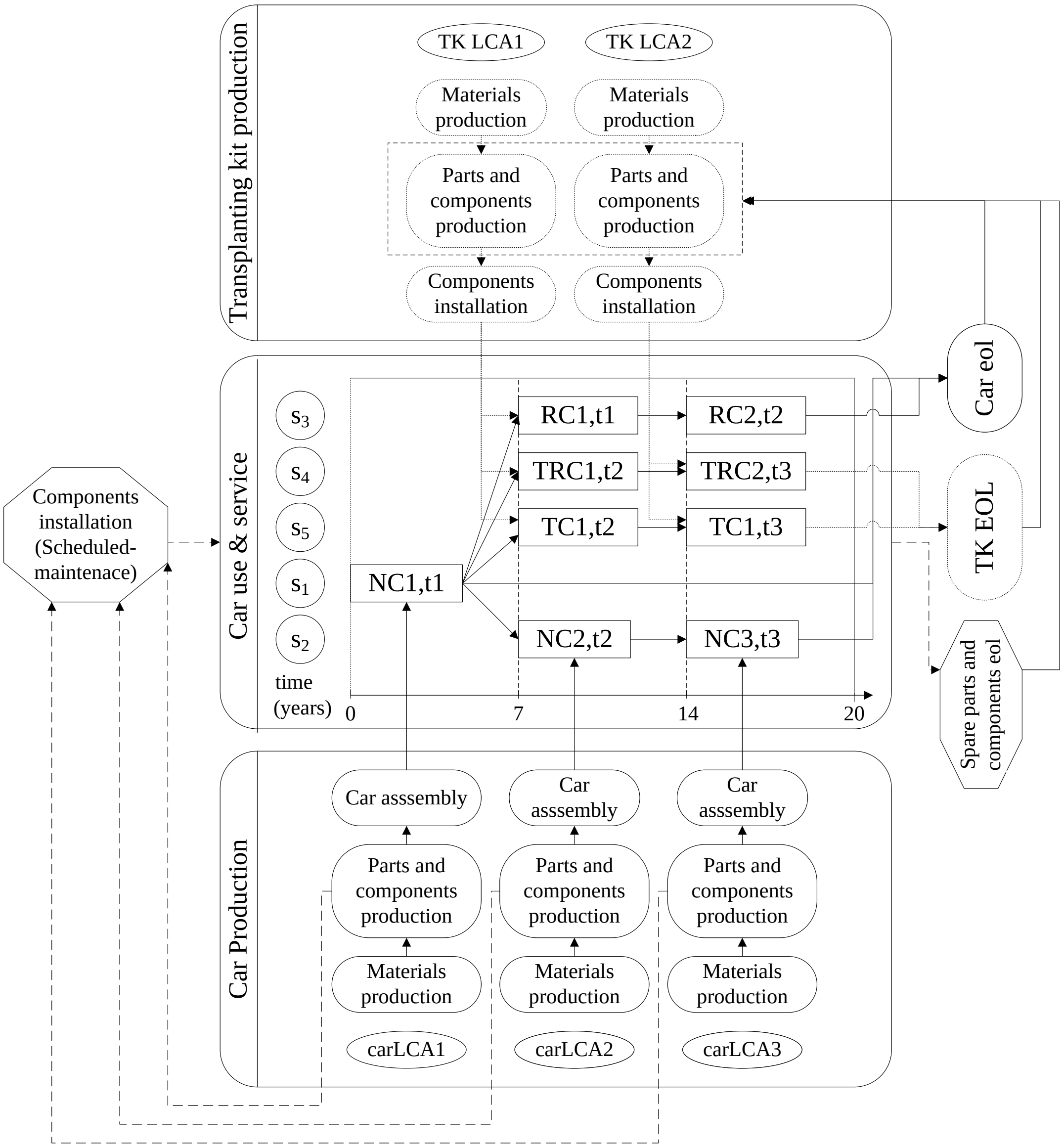


Figure 72. Diagram of car-ownership life cycle analysis scenarios (source: author)

As referred before, our LCI modeling of car ownership accounts for energy and raw materials consumption, air emissions, and solid waste generation. Furthermore, the well-to-tank LCI of fuel consumed is also considered, i.e. the average (and aggregate) upstream energy consumption and emissions of the refining, transportation and distribution stages of fuels, prior to the use of cars.

6.2. Comparison of energy, environmental and economic burdens of car ownership scenarios

We present firstly the results regarding the environmental analysis followed by the economic analysis. The latter includes environmental damage costs although these refer only to air pollutant and greenhouse gas emissions (and hence total costs and potential benefits are underestimated). We compare the lifecycle energy, environmental and economic burdens of all scenarios of car ownership considered.

6.2.1 Environmental implications of organ transplant in car ownership

Figure 73 (next page) presents the relative lifecycle energy consumption and emissions for the different scenarios indexed to the values obtained for scenario 1. According to our assumptions, buying three new cars over 20 years (S2) is the most energy intensive alternative of car ownership, i.e. 10% higher than the base case – although new technologies are more efficient during car use, more cars are produced and thus more energy and materials are consumed such as pollutants and waste are generated. The most significant increases were observed for the material production and manufacturing stages, where there were 165% and 178% increases (respectively) as a result of the production of the new vehicles, making this scenario more material intensive, also.

With respect to the remaining scenarios, they all showed a small reduction (2-3%) of lifecycle energy consumption below scenario 1. Importantly, scenarios 4 and 5 show similar reductions than scenario 3, meaning that transplanted BAT generate savings in the order of 8% during car use that outweigh the increase of energy consumption related to transplanting kits production (42%). Interestingly, buying 6-years old remarketed cars (scenario 3) also generates savings during car use in the order of 3% over 20 years. These results suggest that buying remarketed cars, transplanted cars or transplanting our own car is less energy intensive than keeping a car over 20 years or buying new cars every 7 years.

We note that our assumptions on fuel efficiency evolution are critical given that car use accounts for more than 90% of the vehicle's lifecycle energy consumption. We assumed a 1% annual growth of fuel efficiency to be attained with near future technologies. For illustrative purposes, let us consider that a midsize gasoline-fuelled car would consume approximately 400 GJ over 100,000 km (which is slightly over our estimates, considering 'well-to-wheel' stages). Transplanting the car at the age of 7 (~100,000km) is equivalent to increasing fuel economy by approximately 7% (=1% × 7), i.e. saving 28 GJ (=400 × 7%) over 100,000km, if the car's service time is extended by another 7 years. Considering that producing a transplanting kit consumes approximately 25 GJ, it is outweighed by the efficiency gains and energy savings would be 3 GJ (= 28-25). However, if fuel efficiency is to grow at slower rates, a 0.1% difference (=3/28 × 1%) would negate the savings offered by technological transplant, which is a small variation.

We recall that fuel efficiency growth considered here is conservative compared to other forecasts, as referred in section 4.4.3 (p.123). For example, it is nearly half of estimates by Edwards *et al.* (2006). In this case, a 2%/year fuel economy increase would generate energy savings over 30 GJ (=2×28-25), instead of 3 GJ. We conclude that our research problem holds on the basic assumption that transplanted cars increase their overall efficiency to the condition of the equivalent new model year and that there is no difference between the fuel economy of the transplanted used car and the new car. In reality, the possibility of decreased fuel efficiency of a transplanted car is a hardly conceivable scenario here. This said, our results depend strongly on this assumption and we will be considered it in our final conclusions.

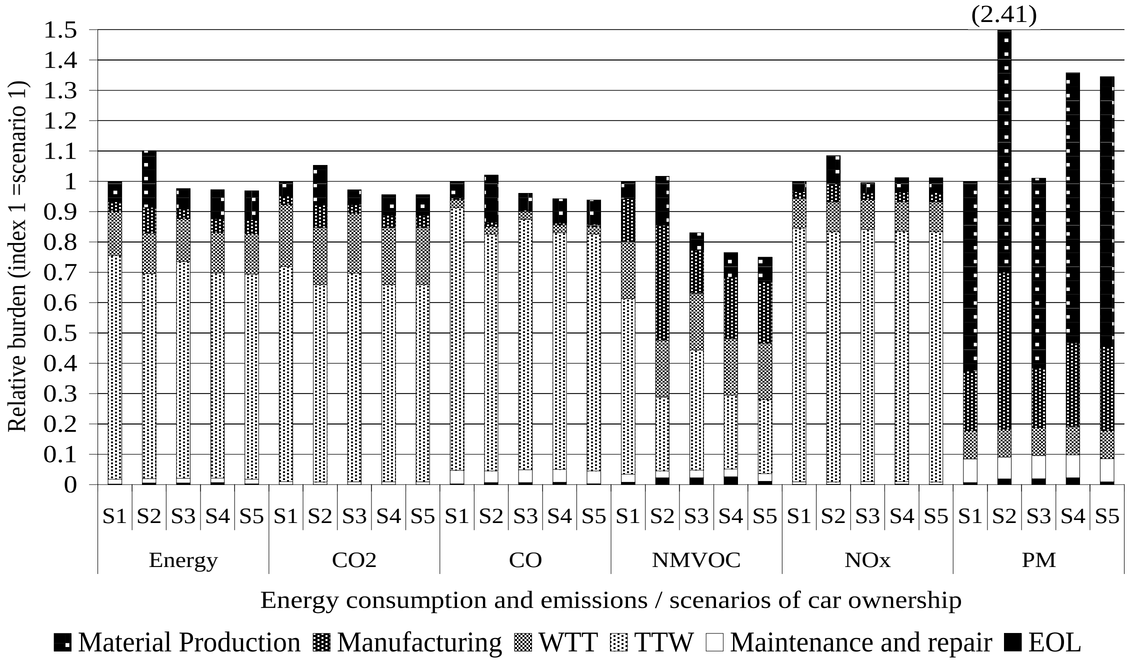


Figure 73. Relative lifecycle energy consumption and emissions for different car ownership scenarios (source: author)

Regarding air emissions, scenario 2 is again the more intensive alternative of car ownership (5% more CO_2, 2% more CO and NMVOC, 8% more NO_X, all relative to scenario 1). For example, the production of one new car generates nearly 6 tones of CO_2 while the production of transplanting kits results in 1.5 tones of CO_2. In addition, scenarios that involve transplant technologies (S4 and S5) offer CO_2 reductions of 4%, CO reductions of 5% to 6%, and NMVOC reductions of 23% to 25%. Only NO_X and PM emissions increase with transplant operations since the gains of efficiency do not suffice to offset emissions during the production phases. In such cases, buying remarketed cars proved to be the more interesting option, although reductions are small (less than 1% over 20 years).

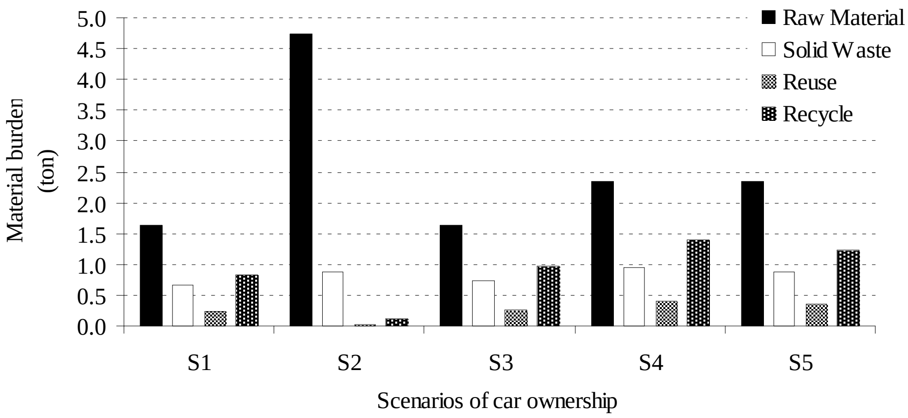


Figure 74. Lifecycle raw material consumption and solid waste generation for different scenarios of car ownership (source: author)

The 7 major materials used in the production of the transplanting kit (as determined in our research), in descending order of consumption, include: 250 kg of iron ore, iron scrap and steel scrap; 37 kg of bauxite ore; 11 kg of primary copper; 2 kg of primary lead and zinc; 10 kg of raw materials to produce plastics (which include crude oil and natural gas, among others); and, 11 kg of raw materials to produce miscellaneous materials – raw energy is not mentioned here and include coal and natural gas. As illustrated in Figure 74 (above), Scenario 3 presents the same level of material consumption as scenario 1 since we do not account for raw materials of remarketed-cars (that were allocated before when these were produced brand new). Scenarios 4 and 5 consumed 40% more raw materials to produce the transplanting kits. However, all scenarios are less material intensive than scenario 2 – according to our assumptions, it consumes 190% more than scenarios 1 and 3, and 100% more than scenarios 4 and 5.

As referred in section 4.5 (p.141), the production of a car generates almost 6 times more by mass of solid waste than is generated during transplanting kits production. This is reflected in the waste production of the several scenarios. Except for scenario 3, all others produce more waste than our base case. Interestingly, the production of two new cars (scenario 2) over 20 years generates as much solid waste as producing two transplanting kits and scrapping replaced equipments. Scenario 4 generates the highest quantities of solid waste since the probability of scrapping used cars is higher than remaining scenarios, except scenario 3, and it accounts for waste from transplanting kits production (41% more than scenario 1 and 3, or 10% more than scenarios 2 and 5). Finally, scenario 2 involves the smallest share of reused of recycled materials. This derives from our assumption by which in this scenario all cars are remarketed after their first owner, conversely to other scenarios by which used cars may be scrapped depending on their age. Scenarios 4 and 5 generate more reused and recycled materials because they produce more solid waste related to the production of transplanting kits although they show higher reuse and recycling levels compared to a full car (refer to the previous section).

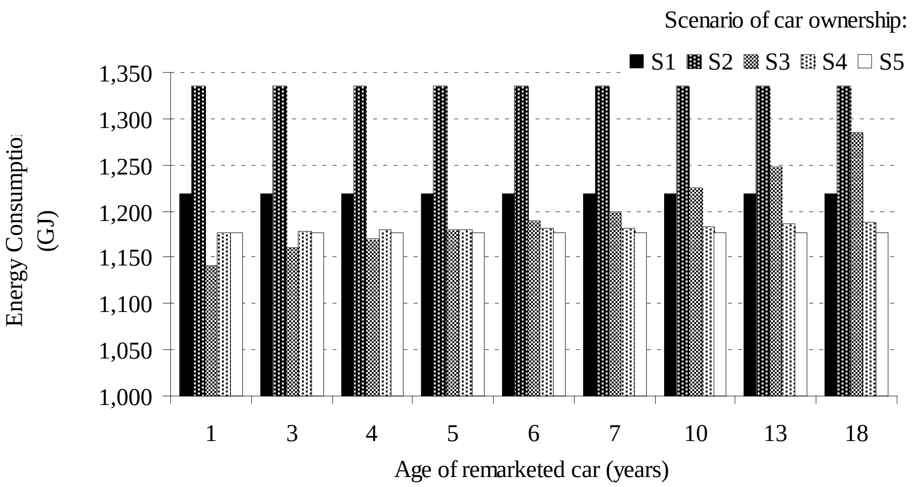


Figure 75. Lifecycle energy consumption for different ages of remarketed cars (source: author)

Figure 75 shows the lifecycle energy consumption of all scenarios according to the variation of remarketed cars' age (for swapping periodicity of 7 years over a period of 20 years). Logically, values for scenarios 1, 2 and 5 do not vary since they preclude the purchase of remarketed cars. Conversely, variation is visible for scenario 3 where energy consumption increases 12% between the first 1 and 18-years old used cars. Interestingly, if they are younger than 10 years, buying remarketed cars every 7 years is less energy intensive than keeping the car over 20 years. Comparatively to scenarios 4 and 5, it is more attractive only for cars younger than 5 years. Scenario 4 shows much smaller changes, since it is assumed that if the car is transplanted with BAT and therefore they are 'like-new' cars with respect to energy consumption during car use. Still, variations occur since the older remarketed cars are, the heavier they tend to be and thus related energy and environmental burdens increase, although to a smaller extent (<1%).

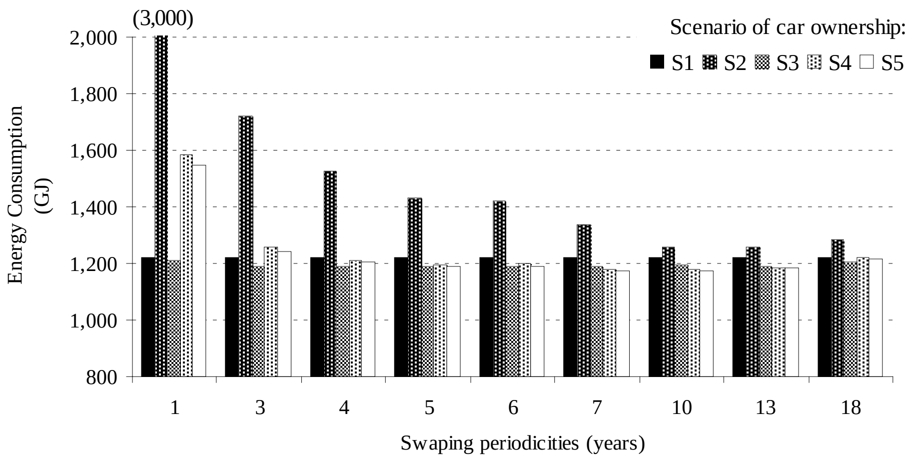


Figure 76. Lifecycle energy consumption for different swapping periodicities (source: author)

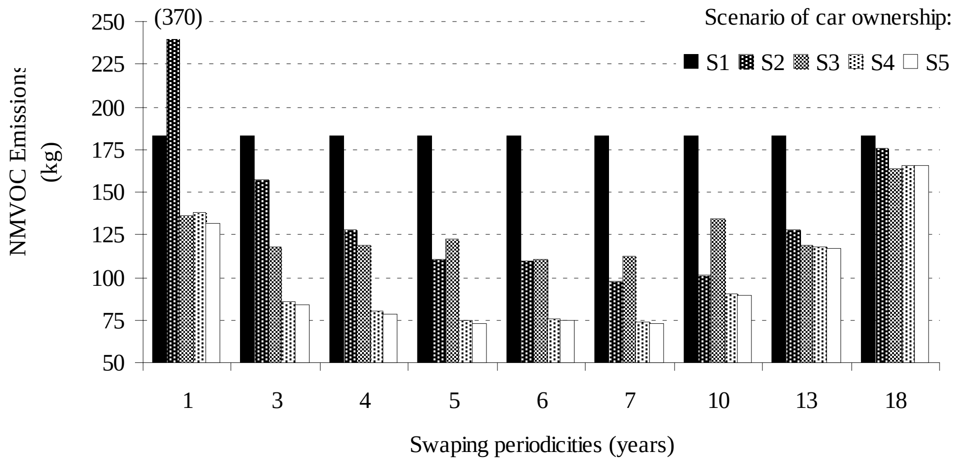
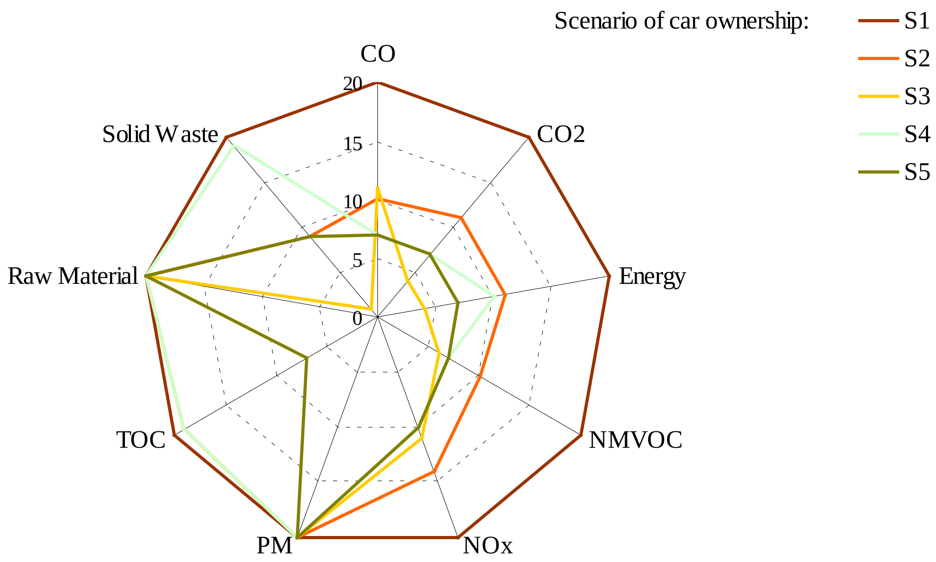


Figure 77. Lifecycle NMVOC emissions for different swapping periodicities (source: author)

Figure 76 and Figure 77 illustrate the variation of scenarios' lifecycle energy consumption (CO_2 emissions follow similar patterns) and NMVOC emissions (the remaining pollutants follow similar patterns), according to different swapping periodicities. All scenarios show a similar behavior as swapping periodicity increases, i.e. burden decreases until a minimum is arrived at, after which it starts increasing. These minima are reached when the reduction of energy consumption or and emissions during car use striving from efficiency gains is offset by energy consumption and emissions from production and scrappage stages. As shown in the following *radar* graph, the swapping periodicity at which minimum burdens are reached varies across scenarios but across energy and environmental burdens, also.



Notes: Remarketed cars are 6-years old; TOC stands for Total Ownership Economic Cost. Swapping periodicity is fixed at 20 years for scenario 1.

Figure 78. Optimal swapping periodicities to minimize TOC and environmental burdens (source: author)

Regarding CO_2 (for example), emissions are minimized if new cars (S2) are swapped every 11 years, while they are minimized if 6-year old remarketed-cars (S3) are bought every 4 years or if cars are transplanted (S5), or bought transplanted (S4), every 7 years. In the case of CO emissions, transplanted-car emissions are minimized if cars are swapped every 7 years, which faster than for new (10 years) or remarketed[50] (11 years) cars.

Interestingly, lifecycle solid waste generation is minimized if new cars (S2) are swapped every 9 years. On one hand, more materials are wasted during production stages if car swapping is more frequent (since more cars are produced) and, thus, swapping periodicity should be smaller to reduce material losses. On the other, the probability of car scrappage increases if they are substituted later and, thus, the quantity of material disposed increases. Alternatively, the production of solid waste is minimized if cars are transplanted (S5) every 7 years. Surprisingly, solid waste generation is minimized for remarketed-cars swapped every year (Scenario 3 of Figure 79). This is because material losses during vehicle's production are allocated to new cars and therefore are not included here (according to our system boundaries and underlying assumptions). Furthermore, the probability of used cars being scrapped increases with age and solid waste generation, also. Therefore, replacing cars often by younger (and lighter) remarketed cars reduces solid waste production. In the case of remarketed transplanted cars (Scenario 4 of Figure 79), losses during the production of transplanting kits are considered and, hence, frequent car swaps increases lifecycle waste generation. Here, minimum solid waste generation is obtained with 6, 10 and 19 swapping periodicities (equivalent solid waste generation for used cars aged below 6 years).

[50] As the remarketed-car age gets younger, the swaping periodicity becomes shorter – e.g., 6:11; 5:5; 3:4; 1:3.

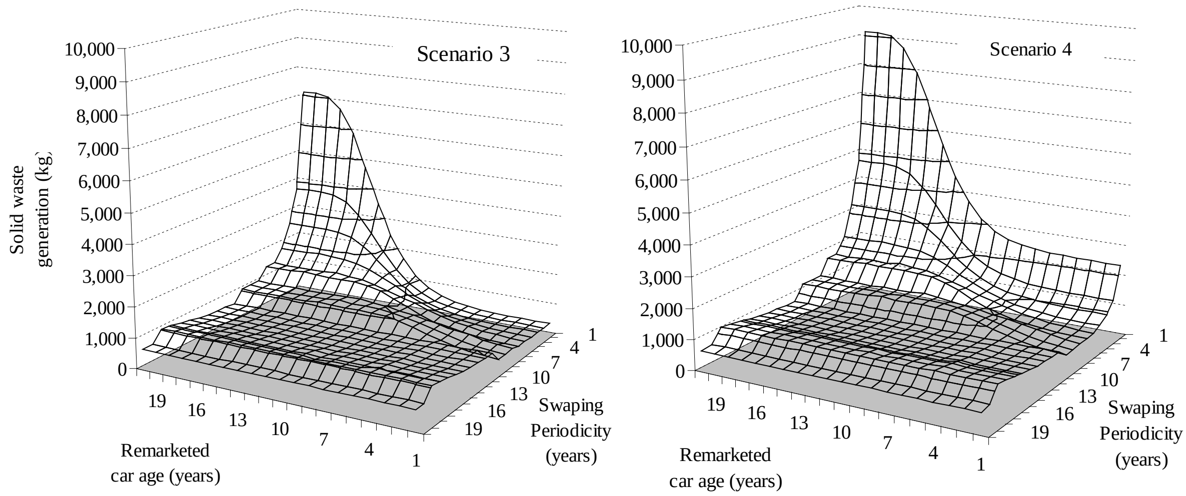


Figure 79. Solid waste generation with varying remarketed car age (scenario 3 and 4) (source: author)

Logically, raw materials' consumption increases as more cars or transplanting kits are produced and the minimum burden is obtained with the no replacing or transplant option (i.e., swapping periodicity equal to 20 years).

All in all, we conclude that, under some circumstances, technological transplant can contribute to the reduction of energy and environmental burdens (material flows included). The following section addresses the economic costs of car ownership, including environmental damage costs also.

6.2.2 Economic implications of organ transplant in car ownership

Our analysis combines economic costs with pollutant damage costs to provide a more comprehensive cost evaluation. Table 31 (next page) presents the total lifecycle ownership costs separated by economic and environmental damage costs. As referred in the previous section, we used a multi-objective function to calculate weighted-environmental costs. Importantly, we preclude the cost of energy that is accounted for in economic costs. Raw material and solid waste related environmental damages were not included, also.

According to our results, the lifecycle environmental damage costs correspond to nearly 4,000€ and total economic ownership costs are approximately 90,000€ (both for the scenario 1). Economic costs dominate overall costs by more than 95%. This conclusion is consistent with the results from Spitzley *et al.* (2004) and Greene and Duleep (1992) who refer that emissions (together with other social costs such as safety) are relatively minor components in overall cost benefit analysis of automobiles. Our estimates of environmental damage costs are consistent with those by Ogden *et al.* (2004). However, the total lifecycle costs these authors calculated are much lower (possibly) because they did not include all private costs (e.g., vehicle depreciation).

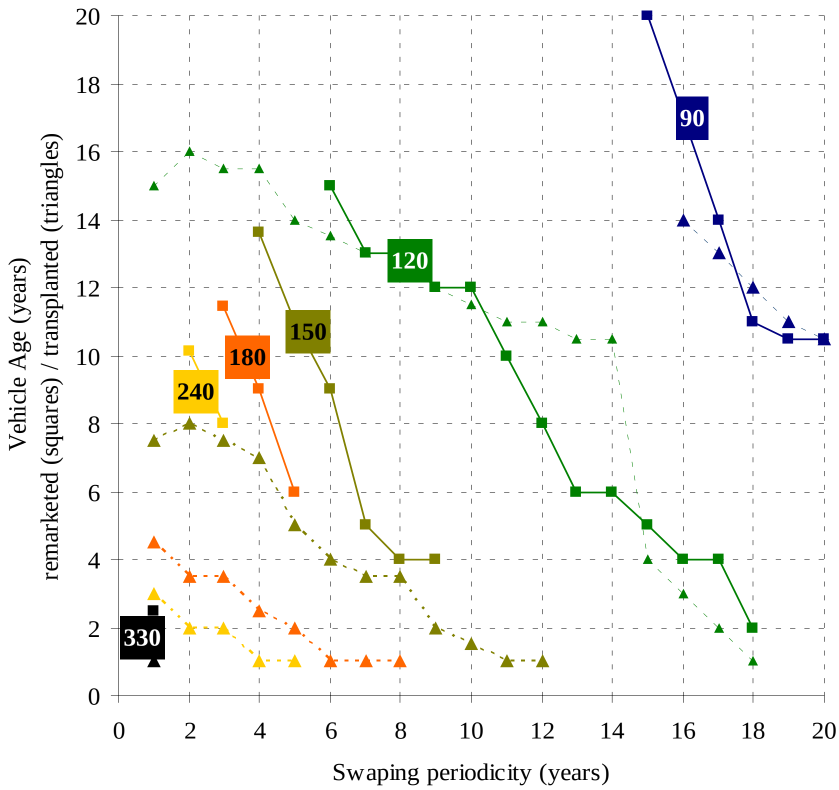
Table 31. Lifecycle car ownership cost for different scenarios (source: author)

	Ownership scenario ('000 €; in brackets are % var. relative to S1)				
	S1	S2	S3	S4	S5
Total economic cost	88.7 (-)	122.6 *(6%)*	99.5 *(-2%)*	97.5 *(-3%)*	84.4 *(-3%)*
Total environmental damage cost	3.6 (-)	3.9 *(37%)*	3.6 *(12%)*	3.5 *(9%)*	3.5 *(-5%)*
Total lifecycle cost	92.3 (-)	126.4 *(38%)*	103.1 *(12%)*	101.0 *(10%)*	87.9 *(-5%)*

Note: Swapping periodicity is 7 years and remarketed/transplanted cars are 6-years old (when applicable).

Apparently, transplanting cars periodically is the more attractive option of all car ownership scenarios, considering total lifecycle costs (both economic and environmental): - 5% than scenario 1 (which is the 2nd best alternative) and -30% of scenario 2 that is the most costly option. Buying remarketed cars (S3) or transplanted cars (S4) are both more costly than keeping the car over 20 years. On the contrary, they are both less expensive (approximately -20%) than buying new cars (S2). Although differences are small, scenario 3 is less attractive than scenario 4. Buying remarketed-transplanted cars (S4) is a better solution than buying conventional remarketed cars (S3), according to our assumptions. The relative difference between scenario 3 and 4 is low (less than 2%).

We explore this issue further by calculating the indifference TLC curves of remarketed (S3) and transplanted (S4) cars, for different pair wise combinations of vehicle age and swapping periodicities (Figure 80, next page). Each indifference curves represent an average level of TLC and standard deviation of approximately 7% (for lower values). In the graph, squares represent remarketed cars (S3) whereas triangles represent transplanted cars (S4). Interestingly, we observe that up to 150,000€ there is a match of both indifference curves, i.e. remarketed or transplanted cars are equivalent in terms of total costs (±7%), independently of their age or swapping periodicity. With respect to total lifecycle costs over 150,000€, there is a shift of the transplanted cars curves towards shorter swapping periods and younger vehicles, i.e., for the same lifecycle costs, younger and more performing vehicles are potentially more attractive. This observation is determinant for the potential diffusion of transplanted vehicles in the used car market. In C.Chapter 8 (p.227), we explore this issue in detail using a discrete choice model to evaluate to what extent used car buyers might choose transplanted cars, based on typical choice attributes such as price, fuel costs, vehicle size, etc.

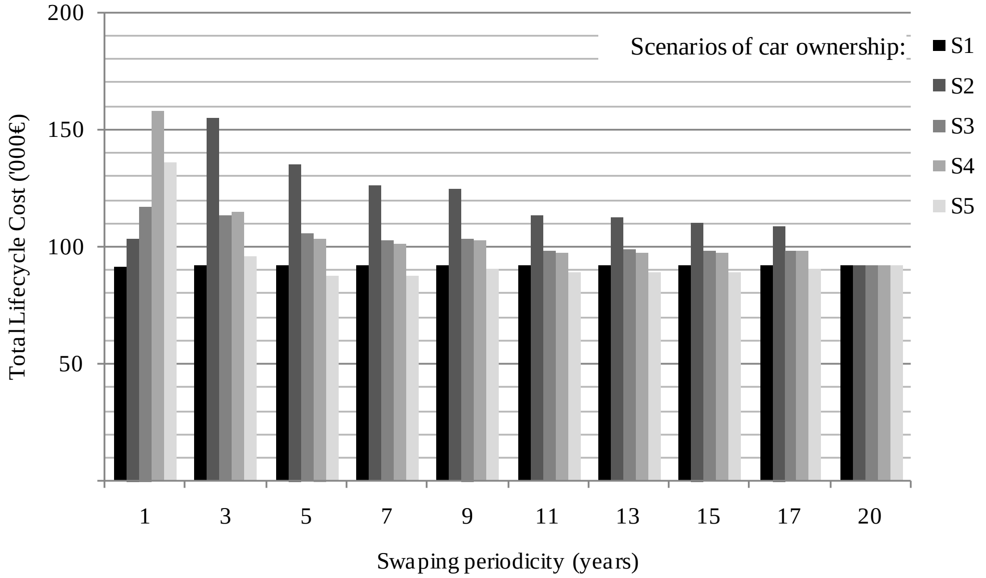


Note: Squares represent remarketed cars (S5) and triangles transplanted cars (S4).

Figure 80. Indifference TLC curves of remarketed and transplanted cars, for different swapping periodicities and vehicle ages (source: author)

As shown in Figure 81 (previous page), total lifecycle costs (including both economic and environmental) decrease significantly up to a swapping periodicity of 10 years (i.e., 1 car replacement or transplant, over 20 years). Thereafter, it stabilizes. Exception is made for scenario 3, where swapping cars every year is more profitable[51]. According to our results, the most profitable multi-objective alternative is to transplant your own car every 7 year (i.e., twice over 20 years), which corresponds to minus 2,500€ (i.e., -4%) than the minimum cost of other scenarios (for which the minimum cost is obtained with no swapping or transplanting of cars).

[51] Importantly, we considered for comparison purposes that all scenarios begin with the same conditions by which the 1st car is new. Thus, if the car is sold after 1 year (i.e., swaping periodicity = 1), then there the car barely depreciates (<10%) and the car owner has net benefits if he buys a remarketed-car aged 6 after selling the previous 1 year-old vehicle.



Note: We consider that cars are remarketed with 6 years of age.

Figure 81. Lifecycle economic costs of car ownership for different swapping periodicities (source: author)

We analyzed also to what extent the age of remarketed cars together with the swapping periodicity influence the total lifecycle costs. As shown in Figure 82, car organ transplant can have some impact on the total lifecycle costs of used-cars, by reducing fuel costs and, to a smaller extent, circulation taxes and environmental damage costs. Whereas buying older remarketed cars does have economic and environmental negative implications, buying transplanted cars does not.

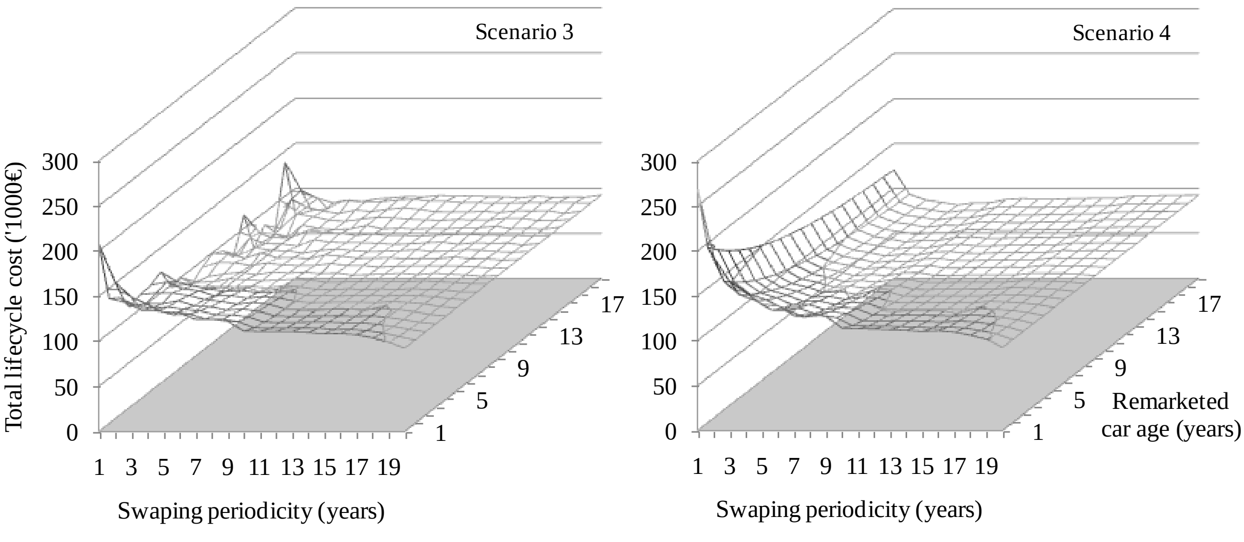


Figure 82. Total lifecycle costs of car ownership (Scenarios 3 and 4) (source: author)

Finally, we conclude that transplanting cars every 7 years is the most attractive options both in economic and environmental terms. Depending on the vehicle age and swapping periodicity, buying remarketed or transplanted cars can be equivalent alternatives in terms of lifecycle ownership costs (over 20 years). Although more costly than keeping the car over 20 years or transplanting own cars, they are still good options (~40% more than scenario 1 or 5, but less 10% than scenario 2). This said, technological transplant has favorable conditions to succeed, considering the assumptions used here. We will analyze this issue in detail in Chapter 9.

In the following section, we perform a sensitivity analysis to our assumptions to evaluate the robustness of our results and identifying the most sensitive parameters.

6.3. Sensitivity analysis to criteria parameters

Scope, boundary definitions and modeling assumptions are critical for any LC study, particularly for a comparative assessment. We examine now several model assumptions (regarding both the LCI and TCO models) and highlight their significance by analyzing the impacts of input parameter variation on the comparative analysis of car ownership scenarios. In this sense, we use the @Risk software from Palisade (http://www.palissade.com). Likewise for the analysis of robustness of our estimates of technological transplant costs (Chapter 5), we performed a sensitivity analysis to the input parameters as presented in the following table, assigning probability density functions (*pdf*) to each parameter. The output results we analyze are the total lifecycle costs (including economic and environmental damage costs) of each scenario for a swapping periodicity of 7 years and remarketed-car age of 6 years (when applicable).

Up to now, all our calculations were based on constant 15,000 annual kilometers. As referred previously, we should analyze to what extent using diminishing annual kilometers (according to the Eq.4-4, p.121) would affect the ranking positions between car ownership alternatives. The following table illustrates the differences between TLC over 20 years for each scenario and for both mileage curves.

Table 32. Constant *versus* diminishing mileage curves (source: author)

Scenarios	Constant Mileage		Diminishing mileage		% var. between curves
	(€)	(Index 100 = S1)	(€)	(Index 100 = S1)	
S1	93,232	100	82,757	100	-11%
S2	146,348	157	146,325	177	0%
S3	129,519	139	121,096	146	-7%
S4	133,497	143	128,354	155	-4%
S5	89,680	96	84,707	102	-6%

As shown in the previous table, adopting diminishing mileage as car ages does not change the relative positions of car ownership alternatives (except for transplant scenario 5 that becomes less interesting than keeping the car over 20 years-S1), although it influences total lifecycle costs and relative differences between scenarios. In absolute terms, all costs decrease although, in relative terms, the difference between scenarios increase (refer to indexes in the table). Logically, cars that are used longer with their original powertrain benefit from reducing mileage as age increases, since fuel economy and emissions factors deteriorate accordingly. Our sensitivity analysis hereafter includes a test to the sensitivity of TLC to the variation of the mileage reduction over the car's service time.

Table 33 presents our assumptions regarding the possible variation of selected input parameters to our LCI and TOC models. The Monte Carlo simulation for the TLC of all scenarios stabilized after 400 iterations. Table 34 (next page) presents the main descriptive statistics of our sensitivity analysis and Figure 83 (p.193) illustrates the main results obtained.

We conclude that expected values of TLC for all scenarios (with diminishing annual kilometers) show little variation (<2%) – refer to the intervals of confidence, for α=0.05.

Table 33. Assumptions on the variation of input parameters to the LCI and TOC models (source: author)

Parameter Description	Label	Unit	Distribution function			
			Type [a)]	1st par.	2nd par.	3rd par.
Mileage variation	Idem	-	Normal	-1801	900	
FE growth	Idem	-	Triangular	-0.036	-0.0181	-0.017
FE deterioration with age	FE Deg	-	Triangular	0.001	0.005	0.05
Vehicle depreciation rate	Idem	-	Triangular	50	96	200
Discount Rate	Idem	(%)	Triangular	0.05	0.25	0.5
Env. damage cost of CO	uCO	(€/kg)	Normal	0.58	0.58	
Env. damage cost of NMVOC	uNMVOC	(€/kg)	Normal	2.51	2.33	
Env. damage cost of NOx	uNOx	(€/kg)	Normal	5.35	5.10	
Env. damage cost of PM	uPM	(€/kg)	Normal	540	400	
Env. damage cost of CO_2	uCO_2	(€/kg)	Normal	0.02	0.02	
Technological Transplant costs	tc	(€)	Normal	5290	1830	
CO EF deterioration with age	CO_ Deg	(% var. of rate)	Triangular	1	2.48	10
NMVOC EF deterioration with age	NMVOC_ Deg	(% var. of rate)	Uniform	-0.5	0.5	
NOx EF deterioration with age	NOx_ Deg	(% var. of rate)	Uniform	-0.5	0.5	
Maintenance and repair periodicity	Maint. and Repair	(% var. of km)	Uniform	-0.5	0.5	

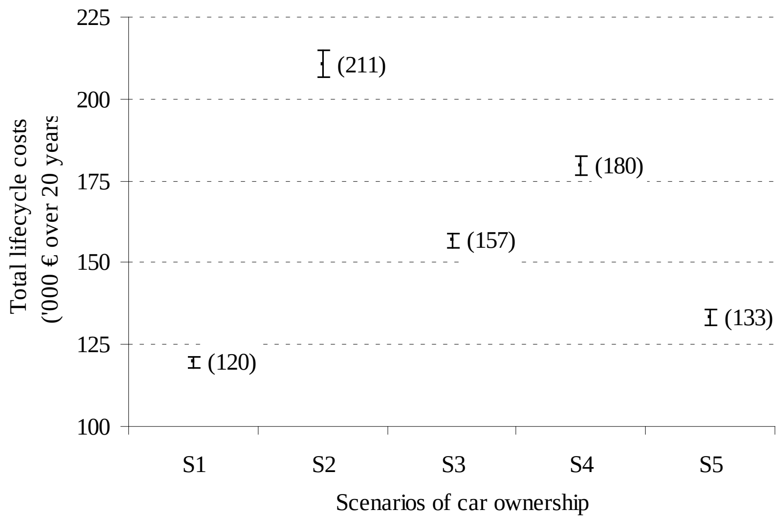
Notes: FE – Fuel economy; EF – Emission factor; Env. Damage – Environmental damage; [a)] Function c: Triangular (minimum, more likely, maximum); normal (μ, σ); uniform (minimum, maximum).

Table 34. Descriptive statistics of the sensitivity analysis to car ownership LC costs (source: author)

Scenarios	S1	S2	S3	S4	S5
Mean	119,566	210,600	156,764	179,518	133,192
Standard Error	912	2,095	1,021	1,522	1,215
Median	119,371	209,515	156,602	179,505	132,331
Standard Deviation	18,243	41,900	20,421	30,437	24,295
Minimum	69,688	98,334	101,566	86,967	63,500
Maximum	167,726	328,636	208,220	272,380	197,971
Interval of confidence (α=0.05)	1,788	4,106	2,001	2,983	2,381
Percentile 5%	88,985	142,961	123,522	132,320	93,720
Percentile 50%	119,371	209,515	156,602	179,505	132,331
Percentile 95%	150,267	281,854	190,906	227,208	175,469

As shown in the following figure, ranking positions of scenarios remains the same – i.e. S1 < S5 < S3 < S4 < S2 – and intervals of confidence (error bars) never overlap suggesting that the difference between the scenarios is significant. For confirmation purposes, we tested the hypothesis of TLC expected values of one scenario being superior or equal to the remaining scenarios (pair wise). We rejected the null hypothesis in all cases (two sample t-test statistic and a level of significance of 95%).

Hence, we can confirm that TLC expected values of the scenarios analyzed are not expected to be equal with a level of confidence of 95%. Correspondingly, we can state that their relative ranking positions are not expected to change – if our initial parameters remain within the intervals we define and according to the probability distribution we determined before and presented in Table 33.



Note: Values in brackets correspond to the average values obtained from the sensitivity analysis output results and error bars represent the interval of confidence (for α=0.05).

Figure 83. TLC average and respective interval of confidence (α=0.05) (source: author)

As referred before, sensitivity analysis is also used to identify the most critical inputs to the model in order to better understand what is driving our LCI and TOC models and give an indication of where efforts should be focused for collecting additional and more accurate information.

Figure 84 (next page) shows the tornado graphs obtained from our regression sensitivity analysis that relate the randomly generated inputs and the respective outputs calculated with our model for every iteration. We find (*ceteris paribus*) that, for scenario 1:

- A one standard deviation increase in PM's environmental cost *per kg* increases by 0.82 the standard deviations of TLC, i.e. the former influences decisively the variation of the latter.
- In the case of maintenance and repair periodicity (expressed in terms of km between events) and discount rates of economic costs, one standard deviation growth decreases TLC standard deviation by -0.43 and -0.27, respectively.
- Mileage reduction over the vehicle's service time has a lower influence (0.24) on the TLC standard deviation.
- The remaining factors are not so important (p_i< 0.1).

The previous observations are valid for the remaining scenarios and the ranking of the parameters remains the same, although some variation occurs on the magnitude of their regression coefficients. Exception is made for the technological transplant costs that, in the case of scenario 4 (i.e., buying transplanted cars), have decisive influence on the variation of TLC

(r^2=0.54, 2nd in rank). In scenario 5 (i.e., transplant own car), transplant costs have less influence on the variation of TLC, although they occupy the 4th position (p_i =0.1).

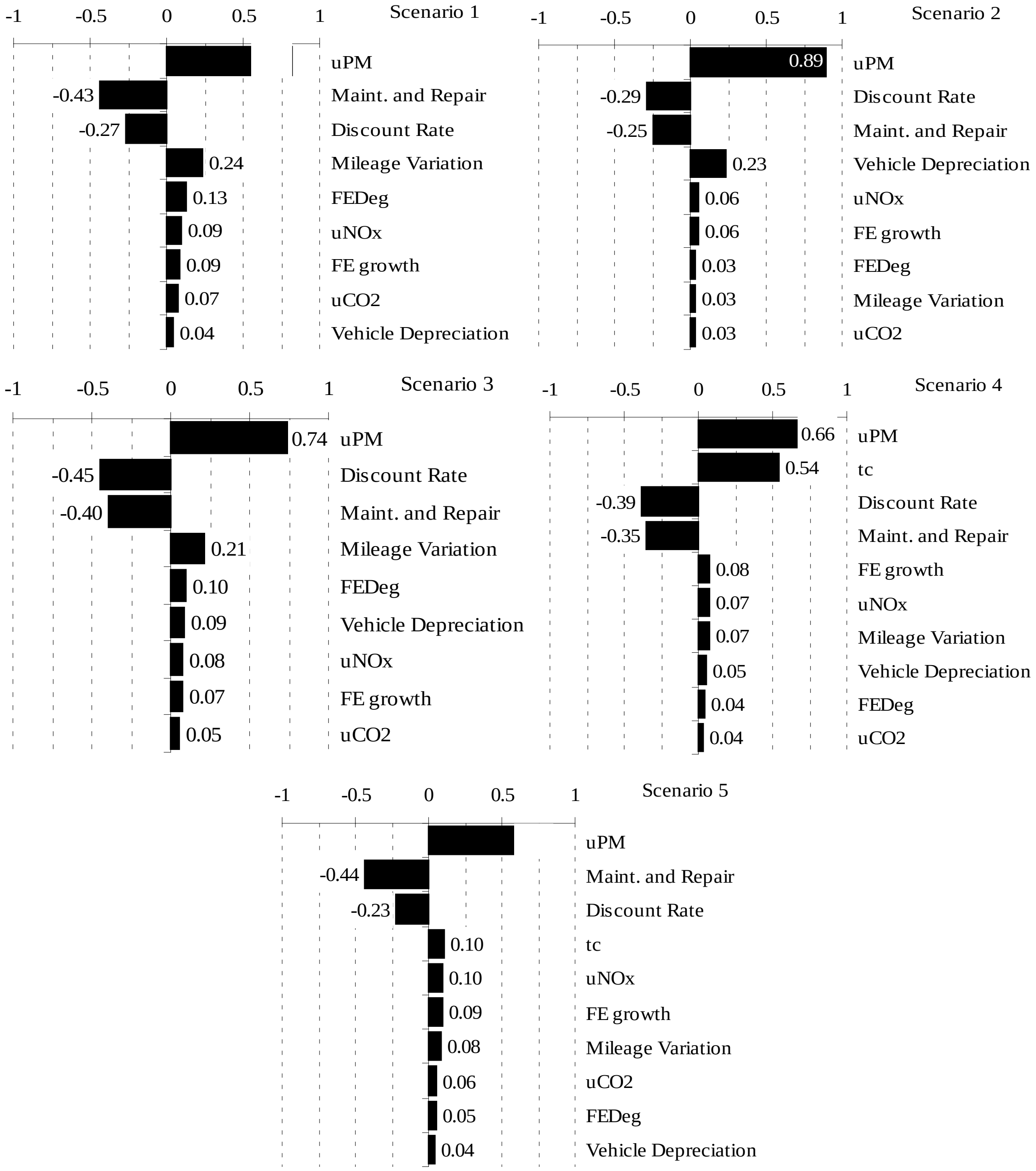


Figure 84. Sensitivity analysis to the LCI and TOC models for each scenario (source: author)

PM emission's costs are decisive mostly due to the fact that they are two orders of magnitude higher than the remaining pollutants. This suggests that estimates of PM emissions should be analyzed more carefully and that emissions during car use should be calculated for gasoline cars also, although the methodology we used here considers those emissions negligible. Apart from this parameter, maintenance and repair proved to be influent. As referred in section 5.2.5 (Chapter 5, p.156), the methodology we used (based on Spitzley *et al.*, 2004) presented lower costs than those presented by the TREMOVE project (Ceuster *et al.*, 2007a) or Freire de Sousa and Guimarães (1997). Higher maintenance and repair costs over time would have two possible ways of increasing TLC: either by increasing TLC if cars are not replaced more often, or by replacing cars more often and increasing investment costs. Although decisive in the variation of TLC, they do not alter the ranking position of car ownership scenarios. This point should be analyzed more thoroughly in future research. Discount rates are used to discount the expected future cash flows into a present value. Although decisive in the variation of TLC, it did not influence the ranking position of car ownership alternatives, also. Finally, transplant costs proved to influence TLC of scenarios 4 and 5 (the remaining scenarios do not include transplanted vehicles). Importantly, they did not influence the overall ranking positions, not forgetting that we performed our sensitivity analysis for a swapping periodicity of 7 years and for 6-years old remarketed vehicles. The influence of such parameters was analyzed in previous sections.

6.4. Summary and conclusions

We analyzed in this chapter the LCI and total economic costs of owning cars over 20-years for several ownership strategies. Ultimately, we evaluated the potential environmental and economic benefits of technological transplant when compared to conventional cars (new or used). The car LCI encompassed all life-cycle stages, i.e., materials production, components manufacturing and parts/car assembly, fuel production, car use, maintenance and repairs, EOL processing. In the case of transplanting kits, we considered three lifecycle stages: material production, components manufacturing and parts assembly, and EOL processing of replaced components. As referred in section 3.2.2 (p.66), the selection of the transplanting kit parts and components was based on the influence these might have on the energy and environmental efficiency of the car and, in short, they include the components of the powertrain, electronic command and control, climate control and exhaust systems.

We used the same environmental coefficients (and material load factors) to estimate energy consumption and emissions (and material burdens) from the production and scrappage of complete cars or transplanting kits. Energy and emission coefficients during the operation stage were calculated with the EMEP/CORINAIR guidelines and for the remaining stages we used values from several sources – both academic and from the automotive industry. The modeling of transplanting kit costs was based mainly on the breakdown analysis of a complete car by Delucchi (2000) and completed by other sources. TOC cover all costs from the moment cars are bought until they are sold or disposed and include fixed (financing, depreciation, insurance, taxes) and variable costs (fuel and maintenance and repair).

The cornerstone fact of the present analysis is that, according to our assumptions, one transplanting kit weights nearly 80% less than a car. Considering that our calculations were performed on a weight-basis, a transplanting kit can be produced with approximately 80% less energy and materials than for a car, while avoiding 80% emissions and solid waste. In addition, producing a transplanting kit costs less 75% than producing a new car.

We compared the LCI and TOC of five scenarios for 20-years car ownership: keep car (S1), buy new car (S2), buy remarketed cars (S3), buy transplanted cars (S4), or transplant own car (S5). We assumed a base case where cars are replaced or transplanted every 7 years and remarketed cars are bought with 6 years of age (when applicable). If we compare S1 and S5, our analyses show that technological transplant (S5) provides significant reductions in overall energy (-3.1% than keeping the car over 20 years), air emissions (-6.2% for CO, -25% for NMVOC and

-4% for CO_2) and solid waste production (-20%). Technological transplant is (logically) more material-intensive (more 40%) than keeping a car over 20 years. Still, transplanting cars consumes half of the raw material used if cars are replaced by new cars periodically (e.g., every 7 years). Importantly, additional environmental burdens from technological transplant are recovered over a reasonable number of years, given the gains of efficiency achieved – we obtained 6 years for a car transplanted at the age of 5, based on a multi-objective function. On one hand, energy consumption and emissions are cut down as a result of the installation of BAT that increases the efficiency of the vehicle. On the other, car demand is restrained due the extension of cars' service time after technological transplant. Consequently, car production and scrappage is avoided and material use and waste generation are reduced.

Exceptions are made for PM and NO_X emissions. In the first case, PM emissions produced by gasoline-fuelled cars are not significant and, therefore, reductions from technological upgrades are null. This is not the case of diesel-cars for which technological transplant contributes to the reduction of lifecycle PM emissions (we analyze this in Chapter 8 and Chapter 9). In the case of NO_x, additional emissions due to the production of transplanting kits and replaced equipment scrappage are not recovered over the vehicle service time, showing an increase of 34%. Conversely to other pollutants, NO_x emissions are not reducing as strongly, over the last years.

Finally, we conclude also that technological transplant contributes positively to the reduction of TOC and transplanting the car twice over 20 years reduces overall costs by 4% when compared to keeping the car over the same period of time. The extent of the LC gains (whether environmental or economic) varies with the age of the transplanted car. All costs and pollutants considered, maximum benefits are reached at the age of 9 (and 5) for environmental damage (or economic costs). However, reasonable payback periods (less than 7 years) are obtained if cars are transplanted after the age of 5. After that payback periods decrease (almost linearly) as the transplanting age increases. Technological transplant is potentially attractive for car owners, considering that the break-even of the initial investment is reached over a reasonable time horizon, while contributing to reducing LC environmental impacts.

When comparing all scenarios of ownership, we conclude that transplanting the car twice over 20 years (S5) results in the smallest economic ownership costs. Conversely, buying two new cars in 20 years (S2) is the least attractive economic option, according to the assumptions used here. Although the total environmental costs differ little between scenarios, the best alternative is to transplant cars (S5) or buy transplanted cars (S5), whereas the worst alternative is to buy a new car every 7 years (S2, again). On one hand, transplanted cars (S4 and S5) consume fewer materials than new cars (S2) and, on the other, they are more efficient than conventional used (S1) or remarketed (S3) cars. The analysis conducted here suggests that the automotive industry can envisage a new approach to car ownership and that consumers could be guided to consider technological transplant when deciding to swap their car.

C. CAR FLEET, TECHNOLOGICAL TURNOVER, ENERGY AND ENVIRONMENTAL BENEFITS

While the functional unit analyzed in Part B (and Chapters 4 to 6) was centered on the ownership of cars, the following chapters (which form Part C) present the "fleet-centered" analysis of the concept explored here, i.e. car organ transplant. Based on the models developed before, we extrapolate the results obtained before for a single car ownership and extend the car organ transplant concept to an entire car fleet. Consequently, lifecycle energy and environmental burdens arising from the car fleet are a consequence of all units in service and, therefore, they are summed up. By doing so, we explore the pervasive potential of transplant technologies.

As mentioned earlier, we use the Portuguese car fleet as our case-study that serves as a basis for comparative analysis. We recall that our analyses rely to a large extent on existing information that includes databases provided by ACAP (ACAP/AUTO INFORMA, 2007) or the TREMOVE project (Ceuster *et al.*, 2006a) as inputs for the car fleet model and database from Abmotors for the calibration of the discrete remarketed-car choice model. We used the EMEP/CORINAIR guidelines (EEA, 2002) to calculate energy consumption and emissions coefficients for the tank-to-wheel stage of car's lifecycle (likewise in Chapter 6) while for the remainder lifecycle stages we collected scatter information from reviewed papers, official documents from the European Commission and data from the automotive industry. In addition, we used the material load factors presented by Ginley (1994) to estimate raw material consumption and solid waste generation. Finally, the models were developed in Excel spreadsheets (specific functions and routines were programmed in Visual Basic), except in the case of the calibration of the logit models where we used LIMDEP (v.7).

Chapter 7 delineates the car fleet model development that simulates the evolution of the Portuguese car fleet and consequently delivers the expectable technological turnover of the stock over time. The time horizon for analysis is 2030. In this sense, we begin with a review of the modeling theory of car fleet (section 7.1) and present the mathematical model we used (section 7.2). The model we develop here is not intended to reproduce (nor forecast) accurately what is or will be the fleet's dimension or its technological composition for Portugal, but instead to build a reasonable approximation of the real world and the basis for the evaluation of the possible future diffusion of transplanted cars over time. We recall that the core issue here is to assess the impact of transplant technologies on energy and environmental performance of the Portuguese fleet. Figure 85 (next page) illustrates the model used to estimate the car fleet evolution and its performance, which includes two parts: the vehicle stock module and the energy and emissions module.

The vehicle stock module is separated into four sub-modules: vehicle stock, new cars, remarketed cars (both conventional and transplanted) and End-Of-Life (EOL) disposal of vehicles. The model is described in the following paragraphs whereas methods and necessary data collection are explained over the next chapters, in detail.

In broad terms, the model starts with a forecast of the baseline evolution of the size of the fleet from 1995 to 2030 (vehicle stock sub-module), which corresponds to an exogenous estimate of the global demand of cars in Portugal. Each year, EOL vehicles are retired (EOL sub-module) and new cars enter the stock to match the demand (New Cars sub-module). In this sense, the amount of new cars is determined endogenously and is calculated by the difference between the aggregate demand of cars and those retired every year. Annual technological mix of new cars is determined exogenously using the distribution matrices from the TREMOVE model (Ceuster *et al.*, 2006b). Importantly, we highlight that we analyze the impact of ICE vehicles, only, and do not include electric-drive vehicles whether these are hybrid, fuel-cell or pure electric. The reason to exclude such options is that these would constitute more radical transplant operations for which deeper and more speculative cost analyses would be required. Still, we do not rule out such alternatives in the future in a 'drive-by-wire' paradigm where 'plug-in, plug-out' modular solutions might become even more promising for car organ transplant. We will discuss this issue later.

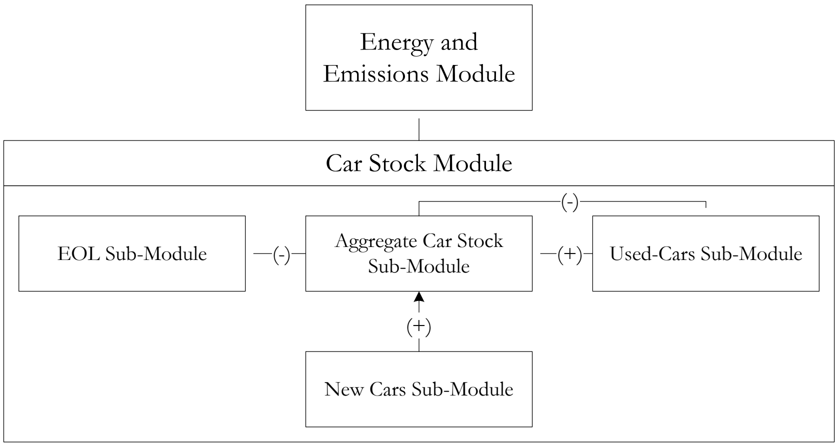


Figure 85. Simplified model of the car fleet dynamics (source: author)

Using constant and decreasing (age-based) mileage curves for each type of car considered here, energy consumption and energy emissions are calculated (energy and emissions module) by means of environmental burden coefficients referred in the introductory paragraphs and described in Chapter 1. In section 7.3, we present the parameterization of our model applied to the Portuguese case-study and set the baseline scenario by characterizing a 'business-as-usual' baseline evolution with respect to stock size and its technological composition (according to the fuel type, engine size and EURO regulations). Our model details six types of car (3 passenger car sizes – small, medium, big – and 2 types of fuel – gasoline or diesel).

Although the remarketing of used cars does not influence the technological structure of the fleet (because cars continue to be used independently of the car owner[52]), we develop a discrete choice model (Chapter 8) to simulate the options of consumers when facing a finite set of remarketed car alternatives (included in the 'used-cars sub-module' in Figure 85) in order to include the option of transplanted cars and analyze potential diffusion of such technologies in the future. Transplanted-cars are included after calibrating the base remarketed-car discrete choice model. After providing some theoretical background on discrete-choice modeling (section 8.2), we describe our modeling procedure (section 8.3). The calibration had to deal with data availability that is a key constraint of our research. We had to used the remarketed cars database of Abmotors (one consultant of the Portuguese car market) as proxy of revealed preferences to calibrate our base discrete choice model since we did not succeed (to this date) to

[52] Although we could argue that the drivers behavior does influence significantly the fuel consumption and emissions.

get hold of the official database of remarketed-car trades after several contacts with the Portuguese authorities (since early 2005). Consequently, the proxy-revealed preferences include systematic and technical car attributes while precluding socio-economic characteristics of car traders and consumers.

Chapter 9 presents the results obtained with the models developed before. In section 9.2, we describe additional model specifications related to transplanted-car alternatives to be included in both models. Thereafter, we analyze the potential diffusion of transplant technologies in the Portuguese car fleet and assess their pervasive potential until 2030 (section 9.3). Then, we present the energy and raw material consumption and emissions and solid waste generation for the baseline car fleet and evaluate the impact of transplant technologies on the energy and environmental performance of the baseline fleet (section 9.4). Section 9.5 presents our sensitivity analysis to criteria parameters that affect both car fleet and discrete choice models and analyze the robustness of our results.

Chapter 7. Car fleet model

7.1. Background of car fleet modeling

Numerous researchers have approached car ownership modeling from several viewpoints and therefore with different methods. The broad categories can be distinguished between:

- economic approaches, using financial parameters as explanatory variables;
- system dynamics that approach the problem in a causality driven and analytical manner; and
- engineering approaches, which being primarily based on empirical analysis, account only implicitly (if at all) for the influence of explanatory variables (e.g., financial) and usually are less sophisticated.

Jong *et al.* (2002, 2004) performed a comprehensive literature review of existing car ownership models for the Dutch Ministry of Transport, Public Works and Water Management. In the context of analyzing the dynamics of evolution of technological change in transport, Grübler (1990) reviews extensively the formal characteristics and properties of various growth, diffusion and substitution aggregate models. Grübler's approach focuses more on "biological models" that fit into the more aggregate engineering approach referred above (and, thus, not detailing the types of technologies – for example, he refers to "cars" generically and not to the numerous models available). The following authors focus mainly on economic approaches and detail the qualitative choice model (possibly, these authors are more interested in the "makes & models" of cars).

Ben-Akiva and Lerman (1985) and Train (1986, 2003) present methods of qualitative choice analysis and, more particularly, Train (1986) suggests a car ownership model that explores the consumer demand for automobiles. Likewise, Ortúzar and Willumsen (2002) and Hensher and Button (2000) present in their handbooks ("*not so deep"*) reviews of the principal methods for modeling car ownership, while covering discrete choice mathematical methods applied to other transport modeling problems (e.g., modal split). Apart from these authors, many others have dedicated their research to modeling car ownership since the 1960's, using single methodological approaches for specific case studies. For instance, Mogridge (1967) developed an econometric model that relates car ownership of households with income and uses national income distribution and its growth to predict future car stock evolution. The majority of these authors are mentioned in the reviews referred above and this section presents a summary of the main conclusions and sets the basis for the model to be developed in the present research. Based on the review by Jong *et al.* (2004), we group car ownership models into 9 types as described hereafter.

1. *Aggregate time series* usually contain a sigmoid-shaped function for the development of car ownership over time (it can also be a function of income or gross domestic product, GDP) that increases slowly in the beginning (at low income or GDP/capita), then rises steeply until it saturates. Zachariadis *et al.* (1995) used this model to estimate the evolution of the car density (vehicles/1000 inhabitants) in several EU countries as a basis

for determining the EU countries' stock of vehicles. For an comprehensive review and mathematical modeling specifications of aggregate time series refer to Grübler (1990).

2. *Aggregate cohort models* segment the population into groups with the same birth year and then shift these cohorts into the future, describing how the cohorts behave, as they become older, acquire, keep or lose cars.

3. In *aggregate car market models*, car ownership depends on car prices, income, variation of income and development over time in the utility of using a car. These models are set apart from aggregate time series as they predict both demand and supply of cars in the car market.

4. *Heuristic simulation models* use as starting points the assumption of stability of household money budget for transport (as a fraction of the household net income) over time (refer to Schafer and Victor (2000) for an international evidence corroborating these assumptions). First for each household, annual income and annual car kilometrage are drawn at random from household type specific distributions. The household then chooses the car category (or categories) of which the costs are closest to the budget. Households with low incomes may not be able to afford any car and will not own one. This mechanism is based on the hypothesis that households will be striving to maintain their (car) mobility; they are unwilling to give up kilometrage. A characteristic of the underlying mechanisms is that car type choice can only be influenced by the fixed and variable costs per car category. Heuristic simulation models of car ownership do not offer extensive possibilities for including many car types. On the other hand, they can be used fruitfully for predicting the total number of cars resulting from different policy settings.

5. *Static disaggregate car ownership models*. There are many different models fitting in this category, but all have the common feature of addressing the demand side of the car market only. The models are based on household car ownership choice through logit models, estimated on disaggregate data (either stated or revealed preferences, or a combination of both). These models contain discrete choice models (multinomial, logit, nested-logit, mixed-logit, probit, etc., depending on the problem under scrutiny and the methodological approach) that deal with the choice of a car type, usually at the household level. They are based on the random utility maximization theory and account for the impact of car ownership costs, the number of license holders within the household and company car holders, among other more specific variables that may arise depending on the modeling exercise (the theory underlying discrete choice modeling is reviewed extensively in Chapter 8). For example, in urban areas, parking costs can be an influential explanatory variable for car ownership estimation. The role of the disaggregate model then is to subdivide the total (e.g., national or regional) supplied by an external model (obtained through aggregate models) over zones and households. These models do not worry about the choice of a particular car type by households.

6. *Indirect utility car ownership and use models*. These models explain household car ownership and car use (the only ones that integrate these two aspects) in an integrated micro-

economic framework. In the first approach ('statistical' model), the basic idea is that decisions of households on car ownership and car use are strongly correlated and should be studied together. The second approach (the 'indirect utility model' that attracted more attention) is based on the hypothesis that households compare combinations of car ownership and car use with each other and choose the combination that gives them the highest utility. Discrete choice modeling is also used here.

7. *Static disaggregate car-type choice models*. Whereas the disaggregate models for the number of cars per household have usually been developed to provide inputs for multimodal transport model systems, these ones mentioned here usually form a part of standalone models to forecast the composition of the car fleet, such as the car stock model of the TREMOVE model (Ceuster *et al.*, 2006a). This model is based on three building blocks: prediction of transport flows and modal choice by passengers; prediction of the car stock (through *aggregate time series*, referred previously) and fleet composition according to changes in demand due to changes in price structure of different modes and different types of vehicles; and, it also include a model for the calculation of energy consumption emissions. *Static disaggregate car type ownership* models can give a time path for the car fleet if it is assumed that in each period a household compares all vehicles and chooses the alternative with the highest utility, as already mentioned. However, this static equilibrium assumption for every period considered can lead to an unrealistically high number of transactions, unless this is made unattractive by introducing dummies for not changing the household fleet. These models are based on different datasets that are used complimentarily. These datasets can be: historical/statistical data, used to characterize car supply (vehicle quantity and characteristics) or demand (cross-sectional data including different attributes of families and companies); and stated (SP) and revealed (RP) preferences, used to model demand behavior with more detailed and specific modeling objectives. Finally, these models consider a rather diversified group of alternative vehicles, classified according to a detailed set of attributes, including body type, engine size, fuel, ownership (private/company), etc.

The static car ownership models and the discrete car-type choice models with many car types are less suitable for short- and medium-run predictions, due to the assumptions of an optimal household fleet in every period, eventually leading to an unrealistically high number of transactions (as referred previously). For such time horizons, it is much better to predict only the changes in the car fleet, instead of predicting the size and composition of the entire car fleet in each period. For a long-term prediction of the number of cars and the distribution over households and car types, these models are more suited, although cohort effects on total car ownership might not be well represented.

8. *(Pseudo)-panel method* is a relatively new econometric approach to estimate dynamic demand models that circumvents the need for panel data and their associated problems. A pseudo-panel is an artificial panel based on (cohort) averages of repeated cross-sections. Extra restrictions are imposed on pseudo-panel data before one can treat them as actual panel data. The most important is that the cohorts should be based on time-invariant characteristics of the households, such as the birth year of the head of the household. By defining the cohorts, one should pursue homogeneity within the cohorts

and heterogeneity between the cohorts. One important feature of pseudo-panel data is that averaging over cohorts transforms discrete values of variables into cohort means, thereby losing information about the individuals. These methods rely heavily on data collected in cross-sectional or panel analysis of the population, for example the panel analysis carried out by Hanly and Dargay (2000) using data from the British Household Panel Survey. Pseudo-panels offer an attractive way to get short- and long-run policy sensitive forecasts of the total number of cars (including the cohort effects), but cannot take over the role of a choice-based model for the number of cars and car type.

9. *Dynamic Car Transactions Models with Vehicle Type Conditional on Transaction.* Dynamic transaction models include duration models for the changes in the car ownership states of the households, and in this respect are a continuous time alternative of the discrete-time panel models. They have been combined with detailed policy sensitive type choice models. For short-to-medium-term forecasts, this combination seems a highly attractive option. Long-term changes in the supply of car types can be simulated through scenarios.

In many respects, the methodology used in the present chapter follows the TREMOVE approach (Ceuster *et al.*, 2006a). Still, there are many specifications due to the particular requirements of our research problem that focuses the technological-transplant problem and the Portuguese car fleet. We develop here a combined model of *aggregate time series* to estimate the car demand (the running stock) over time with a *static disaggregate car-type choice* model to build a reasonable approximation of the Portuguese car fleet, where policy sensitive variables are included to explore different policy scenario analyses. The following sections describe in detail the model illustrated in Figure 85.

7.2. Mathematical description of the car fleet model

7.2.1 Modeling the evolution of the aggregate car fleet

Like many other population growth curves, "car populations" also fit s-shaped curves (see Figure 86). When referring to s-curves, the indispensable ingredients for growth are the ability of a "species to multiply" and a "finite niche capacity" (Modis, 2007). In our case, the "species" are cars within a specific technological and mobility system, where there is some "genetic" stability, i.e. no radical breakthroughs that would change the paradigm of personal mobility.

As conjectured by Grübler (1990), the natural global (world) multiplication (or diffusion) of cars is characterized by three periods:

- the spectacular growth up to the 1930s, where cars mainly replaced horse driven carriages – and where its comparative advantages were decisive[53];
- then, the diffusion into market niches, usually held by railways, or
- the expansion by creating new niches[54], like weekend travel, commuting, leisure, etc.

The competition for limited resources, which is also an essential feature for s-curve fitting, is twofold. Firstly, families and companies must bear the economic burden of car ownership (investment + operating + servicing) and, ultimately, the "finite niche capacity" is determined by physical space availability to operate and store cars (for instance, urban streets, public or private parking lots), particularly in more densely occupied territories, such as urban areas.

We fitted an s-shaped curve for the Portuguese motorization rate (cars/1,000 driving license holders). The car fleet population baseline scenario was then estimated by multiplying the motorization rate by the Portuguese population of driving license holders. Presently, Portuguese car fleet is reaching maturity[55] and therefore no abrupt changes of the total car volume are to be expected, although some variation can occur.

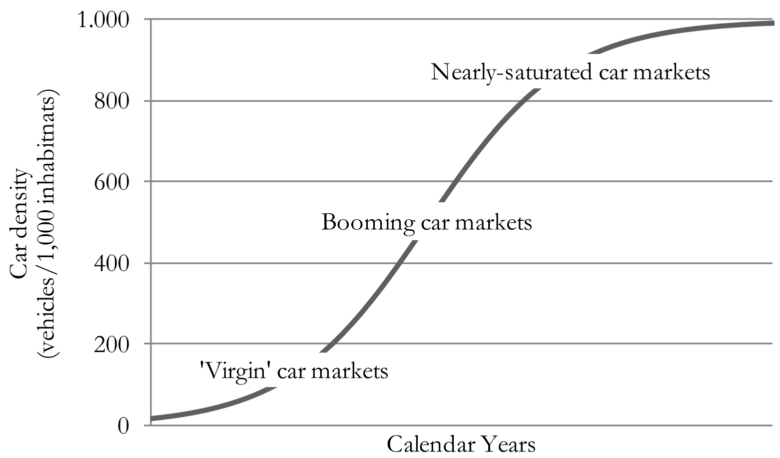


Figure 86. Car density as a function of time (example) (Zachariadis *et al.*, 1995)

In the previous figure, it is assumed that car density increases asymptotically towards a maximum K that, in theory, would be equal to one car *per* driving-license holder of the population if we admit that just a small part of the population is willing to own more than one car per person. Even if this was the case, it is not important for energy and emissions accountability since one person can only drive one car simultaneously.

Figure 86 illustrates the standard growth pattern and it is possible to identify three distinct parts of the s-shaped curve: "virgin" car markets that corresponds to an early phase of car fleet growth (under $K/5$); booming car markets that occur around the inflection point of the curve

[53] At first, cars were perceived as a welcomed opportunity of reducing or even eliminating the growing urban problem of horse manure, while dead horses in the street were not uncommon either (Murphy, 1908).
[54] For an illustrative description of the advantages of motor cars over railways when sight-seeing the British landscapes in the early 19th century, refer to Murphy (1908, pp-5-8).
[55] See Figure 94, p.222.

(i.e., $K/2$ and halfway to the saturation level); and, nearly-saturated car markets that usually occur in industrialized/developed economies. With this respect, Grübler (1990) concluded that motorization processes seem to be captured in an "automobile bandwagon" phenomena by which car density increases more rapidly for latecomers to the motorization era (for instance, countries like China), but motorization maximum (K) is expected to be lower. Generically, industrialized countries have been approaching saturation since the beginning of the present century (including Portugal).

The mathematical modeling commonly used for simulation of car density evolution is based on the logistic function[56] or the Gompertz function[57].

The mathematical formula of the logarithmic function is:

$$y = f(t) = \frac{K}{1 + e^{T_i + b_i t}} \qquad \text{7-1}$$

, where t is the time in years (e.g., 0 for 2000 (base year), 31 for 2030, etc.),

T_i, b_i are parameters of the function, and

K_i is the saturation level for the vehicle type i: $K_i = \lim_{t \to \infty} f(t)$

By re-writing Eq.7-1 with a linear right-hand side, we obtain:

$$\log \frac{K_i - y}{y} = T_i + b_i t \qquad \text{7-2}$$

The mathematical formula of the Gompertz function is:

$$y = f(t) = K_i \, e^{-e^{T_i + b_i t}} \qquad \text{7-3}$$

Again, the Gompertz function can be re-written with a linear right-hand side, also:

$$-\log \log \frac{K_i}{y} = T_i + b_i t \qquad \text{7-4}$$

The 'linear' versions (Eqs. 7-2 and 7-4) of the two functions are particularly helpful to calibrate the parameters of the function for each population of vehicles through a linear regression of past y values and years t and analyzing the corresponding correlation factor R^2. Besides these parameters, the saturation point K must be preset for calibration procedure. As referred in Zachariadis *et al.* (1995), the saturation point cannot be defined accurately for every type of

[56] The logistic function was first proposed by Verhulst (1838) to model the population growth of France, Belgium and the Essex county.

[57] Gompertz (1825) proposed a non-symmetric growth function (conversely to the logistic function that is symmetric) for the description of human population growth.

vehicle. However, we would imply from Grübler's findings on the "automobile bandwagon" that if industrialized countries approached saturation at the turn of centuries no country will surpass the maximum American car density, i.e. approximately 1,060 car/10^3 inhabitants, in 2006 (Davis and Diegel, 2006). After presetting K=1,060, an iterative procedure is pursued until the correlation between estimated *y*-values and real data converges to the highest R^2.

The last step in determining the total number of cars before moving on to the simulation of the fleet turnover is, obviously, to multiply the car density by the total population of the country (or group of countries) being studied. Accordingly, past and forecasted demography data must be collected. In our case, we use data from the Portuguese National Institute of Statistics-INE (more details are presented in section 7.3).

7.2.2 Evolution of the car stock

The previous section described the procedure to estimate the aggregate evolution of the car stock over time. Assuming that these results correspond to the global demand for cars and knowing how many vehicles are scrapped yearly (for the scrappage distribution curve dependent on the vehicle's age, refer to section 7.2.3, p.210), we estimate the number of new vehicles entering the car stock each consecutive year $t, t+1, \ldots, t+n$, where $(n-1)$ is our target year. In simple and aggregate terms, the fleet turnover can be expressed by the following equation:

$$C_i(t) = C_i(t-1) - S_i(t) + N_i(t) \qquad 7\text{-}5$$

, where $C_i(t)$ and $C_i(t-1)$ are the total number of vehicles of type i in years t and $t-1$,

$S_i(t)$ is the number of scrapped (or retired) vehicles in year t, and

$N_i(t)$ is the number of new vehicles entering the stock in year t (age=0 year).

The estimation procedure of $S_i(t)$ and $N_i(t)$ will be described in sections 7.2.3 and 7.2.4, respectively. We note that our research does not include migratory movements of used cars from Central Europe (e.g., Germany) to Portugal, although these are growing (see Figure 87).

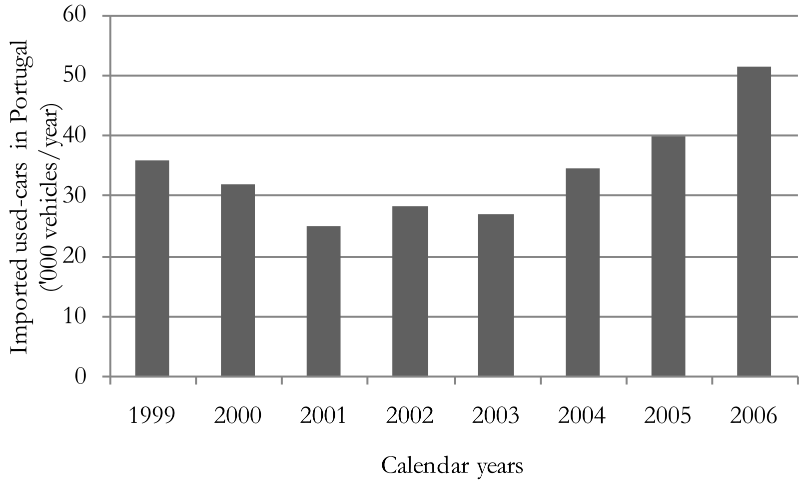


Figure 87. Imported used cars to Portugal (1999-2006) (ACAP/AUTO INFORMA, 2007)

In 2006, they represented less than 15% of new cars operating in Portugal. We exclude these from our universe, since we do not have detailed data on the characteristics of these vehicles, although we can refer that the majority are medium to big cars (engine size bigger than 1.5 liters) and older than 6 years of age. These migrations are mainly related with the current Portuguese taxation of new and used-cars (M.A.I., 2007) that penalizes severely new or recent models with bigger engines (above 1.5 liters).

7.2.3 Scrappage of cars

Scrappage of vehicles is a function of the technical lifetime of the car, the probability of breakdown before the end of the planned technical lifetime (by the carmakers), the probability of car wreckage (e.g., after car accident) and the probability of the car being replaced by a new or used car, which depends on car costs and policies that directly or indirectly affect such costs (e.g. purchase taxes and earlier retirement incentives).

The statistical analysis of lifetime has become a topic of considerable interest to statisticians and workers in areas such as engineering, medicine, and the biological sciences. For example, in the automobile industry, the trade-off between maximizing a car's attractiveness for consumers (for example, extended warranty period with free-repair schemes included) whilst reducing the costs for the automaker and car retailer relies heavily on the estimation of part or total failure probabilities of the car components. Although it is an interesting and influent topic, the present thesis does not intend to explore the lifetime data methodologies (refer for instance to Lawles (1982) and Meeker and Escobar (1998), for theory on lifetime and reliability statistics).

In order to illustrate how the problem of car lifetime can be analyzed, we refer to Manski and Goldin (1983) stochastic modeling approach of scrappage probability of a car. The authors separated the problem in two terms: the *endogenous scrappage*, which reflects the failure probability (p_f) and thus incorporates the influence of the planned lifetime of the vehicle, driver's behavior and maintenance/repair procedures, mainly; and, the *exogenous scrappage* (p_s), which reflects the external influence on car ownership and thus determines the relative attractiveness of keeping a car compared to scrapping it and buying a new or used-car. The latter can also be referred to as the probability that the sum of maintenance/repair costs plus the vehicle's residual value exceeds its market value after repair. The car scrappage probability (s) of a car during one year is:

$$s = p_f \, p_s \qquad 7\text{-}6$$

The failure probability p_f is likely to increase as the car becomes older. For very old cars, however, utilization is lower and, hence, the value of p_f may be low as well. Exogenous scrappage p_s is influenced by external economic variables such as repair costs, new car prices, household income, new car taxes levied on technological performance, etc. For example, if repair costs rise (which typically occurs whilst car ages) or new car prices fall, then p_s is likely to increase. From both scrappage components, we can expect that s increases non-linearly with age (k) and, consequently:

$$s_k \leq s_{k+1} \qquad 7\text{-}7$$

However, the progression can be inverted in the case of older cars – over 17 years, as referred by Jorgensen and Wentzel-Larson (1990) – and , as such;:

$$s_k \geq s_{k+1} \tag{7-8}$$

We did not follow the modeling approach proposed by Manski and Goldin (1983) since it requires specific and detailed data of car scrappage for econometric calibration, which are not available for the Portuguese stock. Instead, we assumed a simpler approach where cars have a survival probability depending on their age.

Waloddi Weibull proposed in his seminal paper "A statistical distribution function of wide applicability" (Weibull, 1951), a continuous probability function that is a popular model in reliability engineering and failure analysis, widely used in industrial applications and recognized in the estimation of vehicles lifetime by the auto/industry as expressed in the Automotive Handbook by Bosch (2004).

The general formula for the cumulative Weibull distribution is:

$$\Phi(k) = 1 - e^{\left[-\left(\frac{k-g}{\beta}\right)^{\lambda}\right]} \tag{7-9}$$

The corresponding probability distribution function (reliability or survival curve) is:

$$X(k) = e^{\left[-\left(\frac{k-g}{\beta}\right)^{\lambda}\right]} \tag{7-10}$$

, where, for both equations, k is the age of the car, expressed in years,

g is the age at which scrappage starts (where $g \geq 0$),

λ is the failure steepness (the higher λ is, the longer cars have the probability to survive), and

β is the scale parameter (can be viewed as the maximum life expectancy, expressed in years).

Eq. 7-10 can be interpreted as the probability of a car's lifetime being greater or equal to k. Zachariadis *et al.* (1995) suggested a "modified Weibull" whereby it is assumed that g=-λ and thus reducing the number of calibration parameters, making the regression exercise simpler.

$$X_i(k) = e^{\left[-\left(\frac{k+\lambda_i}{\beta_i}\right)^{\lambda_i}\right]} \text{ and } X_i(0) \cong 1\text{, where } i \text{ is the type of car} \tag{7-11}$$

For the calibration of β_i and λ_i, we followed the same procedure used to determine the K parameter of the population s-curve, i.e. maximize iteratively the correlation factor R^2 between real data and estimated values.

The number of scrapped cars (s_i) of age k for each consecutive year t, is given by:

$$s_i(t,k) = c_i(t-1,k-1) \times \left(1 - \frac{X_i(k)}{X_i(k-1)}\right) \quad \text{7-12}$$

, where $X_i(k)$ and $X_i(k\text{-}1)$ are the survival probabilities of car type i with age k and $k\text{-}1$, respectively; and $c_i(t\text{-}1,k\text{-}1)$ is the number of cars of type i in year $t\text{-}1$ with age $k\text{-}1$.

The second term of Eq. 7-12 is a conditional probability such that if Y is a variable expressing the number of scrapped vehicles with age k and $Y \sim X(k)$ and the probability of Y surviving at age k during year t, can be expressed as follows, knowing that Y existed during year $t\text{-}1$ at age $k\text{-}1$:

$$P(Y \geq k \mid Y \geq k-1) = P[(Y \geq k) \cap (Y \geq k-1)] = \frac{P(Y \geq k)}{P(Y \geq k-1)} = \frac{X(k)}{X(k-1)} \quad \text{7-13}$$

The probability of Y being scrapped is given by the complement of $\left(\frac{X(k)}{X(k-1)}\right)$, i.e. $\left(1 - \frac{X(k)}{X(k-1)}\right)$.

Consequently, the total number of scrapped cars (S_i), used in Eq. 7-5 in section 7.2.2, is

$$S_i(t) = \sum_{k=1}^{n} s_i(t,k) = \sum_{k=1}^{n} \left[c_i(t-1,k-1) \times \left(1 - \frac{X(k)}{X(k-1)}\right)\right] \quad \text{7-14}$$

, where n is the maximum service lifetime of a car. In our study we considered $n \approx 30$, since we admit that there is a smaller amount of vehicles over 30 years and that they have smaller annual mileage.

The USA and Belgium have detailed registrations of scrapped cars over long periods and therefore it was possible to determine survival distribution functions for different vintages (Figure 88). This is barely the case for most industrialized countries, as is the case of Portugal, which is the focus of our research. Samaras *et al.* (2002) followed the approach described previously in the TRENDS project and calibrated different scrappage curves (constant over decades and across vehicle types), for 12 EU countries, which results were also used in the TREMOVE project and will be used in our research, as starting values. The plausibility of assuming scrappage rates constant over time and across vehicle types is, of course, open to debate since uncertainty rises. Bigger (over 2,000 c.c.) diesel-powered cars will probably last longer (in average) than a smaller (less than 1,000 c.c.) gasoline-powered car. On the other hand, cars from different decades have different lifetimes, as illustrated in the following figures.

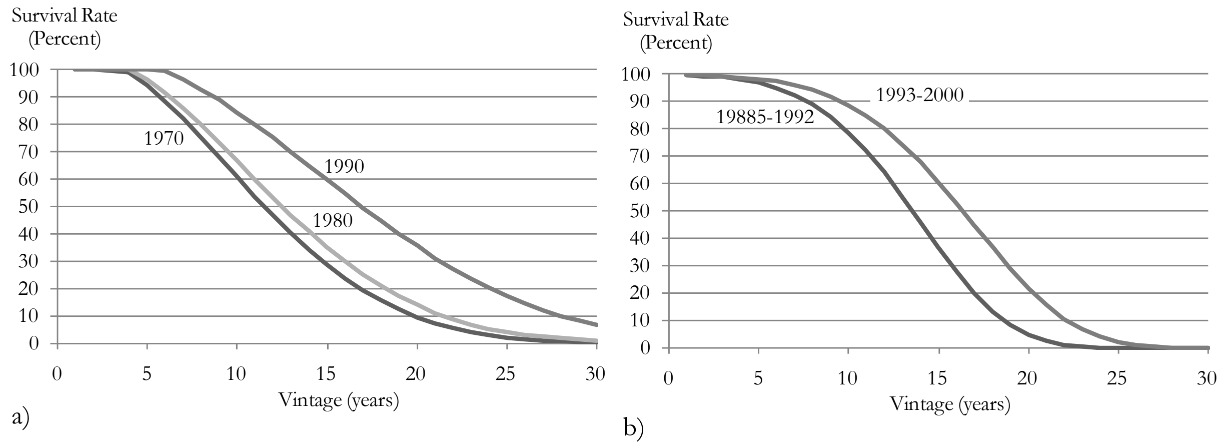


Figure 88. Survival probability of Passenger Cars for the (a) USA (Davis and Diegel, 2006) and for (b) Belgium (Samaras *et al.*, 2002), for different vintages

Finally, the quantity of cars scrapped in the Portuguese car fleet, each year, is determined by the following equations:

$$S(t) = \sum_{i=1}^{v} \sum_{k=1}^{n} s_{i,k}(t) \tag{7-15}$$

where,

$$s_{i,k}(t) = c_{i,k-1}(t-1) \times \left\{ 1 - e^{\left[-\left(\frac{k+\lambda_i}{\beta_i} \right)^{\lambda_i} \right]} \right\} \tag{7-16}$$

Moura *et al* (2007) are currently developing the CAReFUL project[58] that includes the calibration of the Portuguese car lifetime curves for different vehicle types and EURO standards (scrappage curves are determined for different time periods). The present research will be updated after the CAREFUL results are published. Figure 89 illustrates the Portuguese scrappage curve estimated by Samaras *et al* (2002) and used in the TREMOVE project.

[58] CAReFUL (Title: Car fleet renewal as a key role for atmospheric emission reduction) is funded by the Portuguese National Foundation for Science and Technology (FCT).

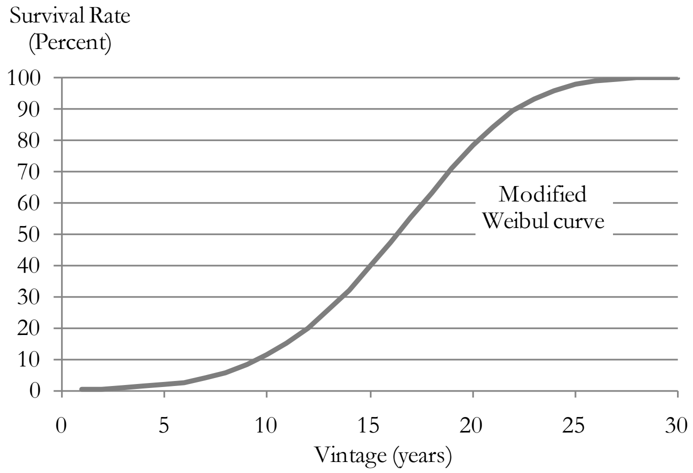


Figure 89. Scrappage distribution curve for the Portugal car fleet (λ=15, β=30) (Samaras *et al.*, 2002)

Transplanted cars have different scrappage curves. Although our main objective with technological transplants is to make cars cleaner during their normal lifetime, it is expectable that used transplanted cars experience a product life extension, since they are re-equipped with new components (chiefly, the engine). However, it is not foreseeable that they restart a normal product lifetime just as if they were new cars and last another 30 years (for example) starting from the transplant date. Since there is no data available on cars that have been transplanted (although they exist, as referred in Part B of this dissertation), we assumed an extension of the current survival curve for transplanted cars as described in section 9.5.5.

7.2.4 New cars

New car sales (N) can be divided in two groups: new cars (*NR*) that replace the number of scrapped vehicles in the same year; and, new entering cars (*NE*) that are responsible for the growth of the car fleet. The Portuguese car stock is reaching maturity and therefore it is expectable that the new car sales stabilize soon (see Figure 90), although some fluctuations are expectable due to population variation (in terms of total inhabitants but, more importantly, its demographic structure) and variations on the quantity of new cars sold (influence probably by the motorization rate and socio-economic context) and equivalent scrapped cars after their service time has finished (these depend also on public car retirement policies).

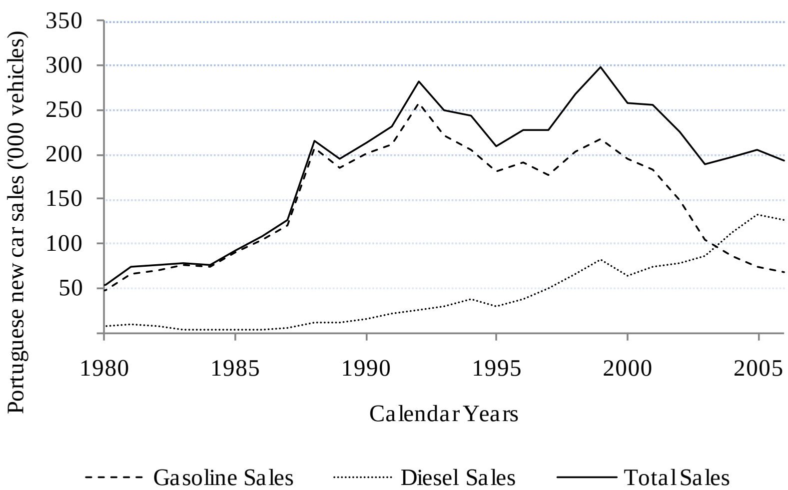


Figure 90. Portuguese new car sales over time (ACAP/AUTO INFORMA, 2007)

The estimation of new car sales from 2007 onwards will be performed using Eq.7-17:

$$N(t) = C(t) - C(t-1) + S(t) \qquad 7\text{-}17$$

Accordingly, we can distinguish three cases where:

1. $C_i(t) = C_i(t\text{-}1)$, which is equivalent to say that the fleet is constant, and thus N(t) = S(t), i.e. new cars replace the scrapped vehicles only, whether these are conventional or transplanted;

2. *Ci(t) < Ci(t-1),* which means that the fleet is reducing, and thus *N(t)<S(t)*; and

3. *Ci(t) > Ci(t-1),* which means that the fleet is increasing, car demand exceeded car abatement, i.e. *N(t)>S(t)* and there are new entering cars in the fleet.

As we mentioned before, the energy consumption and emission behavior of cars depends, among other factors, on the *size of the engine*, on its *technological attributes* and on the *operating conditions*[59]. The technological attributes that are considered in our study are *fuel type* and *propulsion and environmental control systems* that vary with EURO standards (and, consequently, with the car vintage), as described in the EMEP-CORINAIR methodological guidelines (EEA, 2002). While in Part B, we used fuel consumption and emissions factors for the operation stage of the lifecycle of a midsize gasoline-fuelled car, in the present part, we are addressing the overall Portuguese fleet of passenger cars.

As such, after estimating the quantity of new cars that are needed to fulfill the demand of the overall stock, we need to characterize the type of cars that are chosen each year, i.e. the technological distribution of new cars. We adopted the technological matrices of new cars estimated by Ceuster *et al.* (2007b) in the TREMOVE project. These matrices result from the calibration of discrete choice model that these authors calibrated for all EU countries, including Portugal. For details on the modeling approach and assumptions refer to Ceuster *et al.* (2007a). We note that Chapter 8 reviews the theoretical grounds of car type discrete choice, since we had to characterize the technological distribution of remarketed cars over time, to simulate the diffusion potential of transplanted cars. However, the theory presented then is valid for any type of vehicle (new, used or transplanted cars) provided that they can be characterized according to a utility function and appropriate attributes (e.g., price, circulation costs, size, etc.). The following section presents the mathematical specifications to calculate the numbers of car within each type considered here (according to fuel type and engine size).

7.2.5 Technological distribution of the car fleet

We described previously how new cars are estimated. We need now to characterize the corresponding technological distribution of the new cars entering the stock. In this sense, we

[59] Urban, rural and highway driving conditions categories are used in the European Driving Cycles and fuel consumption and emission factors are dependent on the speed.

have to characterize the technological distribution matrix where we can find the probability of each car-type available in the new car market being chosen. The number of each car-type *i* (which we recall are small, medium or big, combined with the fuel types, gasoline or diesel-powered) among new cars is obtain as follows:

$$\begin{bmatrix} n_{PCGS} & n_{PCGM} & n_{PCGB} & . \\ n_{PCDS} & n_{PCDS} & n_{PCDS} & \end{bmatrix} = \begin{bmatrix} p_{PCGS} & p_{PCGM} & p_{PCGB} & . \\ p_{PCDS} & p_{PCDS} & p_{PCDS} & \end{bmatrix} \times N(t) \qquad \text{7-18}$$

N(t) are all new cars calculated with Eq.7-17 (p.215).

, where n_i is the number of new cars of type *i*,

p_i is the fraction of car type *i* that is calculated using Eq. 8-20, and

N(t) are all new cars calculated with Eq.7-17 (p.215).

As we will explain in forthcoming sections, we opted to use the technological matrix calculated exogenously by the TREMOVE project (Ceuster *et al.*, 2007b). As referred previously, the authors calibrated car discrete choice models (Nested Logit) for each EU country and used the same car classification adopted here. We describe in Chapter 8 the mathematical modeling used to estimate the technological distribution of the annual remarketed-car stock.

7.3. Model specifications and baseline car fleet

7.3.1 Introduction

As referred in the beginning of this thesis part, we seek to extrapolate the results obtained in Part B to the Portuguese car fleet and have an estimate of the number of transplanted cars until 2030 and the corresponding implications in terms of energy consumption and environmental burdens (including all lifecycle stages).

In this section, we present the baseline of the Portuguese car fleet (section 7.3.3) that corresponds to a 'business-as-usual' evolution of the stock, i.e. without the alternative transplanted cars. We recall that the scenario presented here aims to reproduce a reasonable approximation of the real world. In this sense, we will compare our figures to data and estimates presented in other references. In Chapter 8, we describe the specifications of the discrete remarketed car choice model. We firstly present our data sources and describe the data treatment process and then the modeling and calibration procedures. The estimated impact of transplanting alternatives on the fleet's technological composition is presented in Chapter 9 (p. 259).

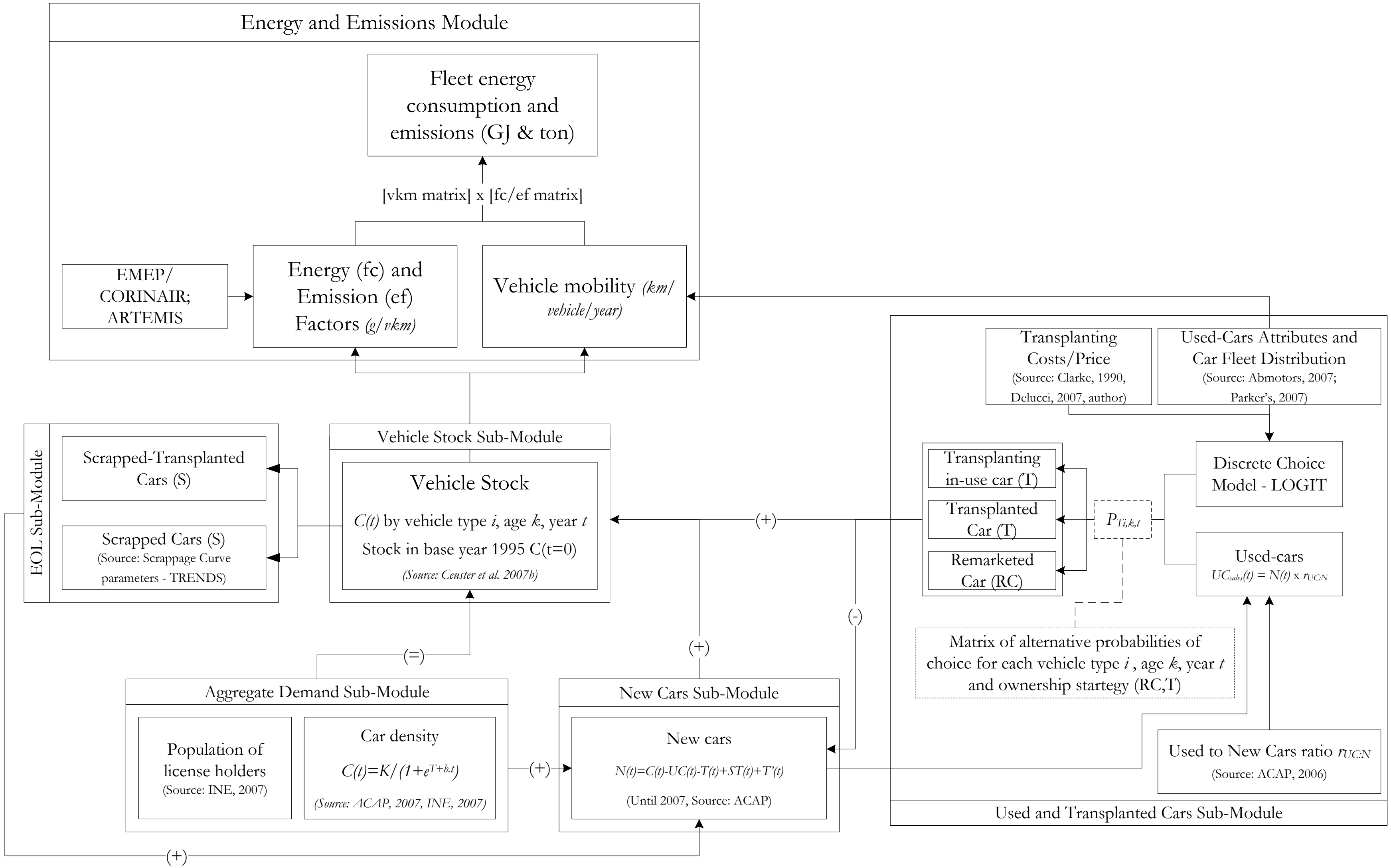


Figure 91. Conceptual model of the car fleet dynamics (source: author)

The figure (above) is a detailed diagram of our modeling approach in this part of the dissertation. In the introductory paragraphs, we presented a simplified version of this diagram (Figure 85, p.200) and, in the Chapter 8, we describe in detail the sub-module used to estimate the stock of remarketed and transplanted vehicles. As referred in the first sections of the present chapter, the overall concept used here is that we assume an s-shaped growth of the Portuguese car density that is capped by the asymptote of 900 vehicles *per* 1,000 license holders (refer to forthcoming paragraphs). The global demand for cars is then estimated by multiplying the car density by the total number of license-holders each year. After retrieving the vehicles scrapped during year *t-1*, we estimate the number of new cars needed to match the total demand of cars in year *t*. The basic logic of our model is illustrated with the sub-modules 'Vehicle Stock', 'EOL' and 'New Cars', and respective linking arrows.

In the next section, we present the "Baseline" car fleet including its detailed technological composition since 2007 up to 2030, both for new and used-cars. No considerations on transplanting technologies are included at this point.

7.3.2 Base data and model specifications

We based the calibration of the Portuguese private car density growth curve on the data provided by ACAP[60] (2006) complemented by the data on license-holders and demography provided by INE (2007). Failing to have accurate figures on the real Portuguese in-use fleet (since there haven't been realistic registers of the cars retired in the past decades), ACAP provides statistics on the number of new cars sold every year. ACAP also provides an annual estimate of the total number of cars being used. Table 35 (next page) presents the base data we used to estimate the car density evolution from 1990 to 2006. The parameters of the logistic curve[61] were calibrated with standard method of least squares and optimized to maximize the coefficient of determination r^2. We obtained a maximum value K of 893 cars *per* 1,000 license-holders (i.e., approximately 900 cars/1,000 license holders, as mentioned previously).

After determining the growth curve of the vehicle stock, we calibrated the scrappage curves. The base year considered is "1995". The characterization of the Portuguese car fleet composition, provided by ACAP, by age and/or engine technology, is not sufficiently disaggregated at the level required for our modeling exercise. Therefore, we decided to use TREMOVE's technological distribution for the Portuguese case in 1995 presented in Table 36, next page (Ceuster *et al.*, 2007b). Again, this starting point for our modeling exercise is disputable since the distribution used in TREMOVE is itself an approximation of reality.

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[60] ACAP – Associação Automóvel de Portugal (www.acap.pt).

[61] We used the logistic function presented in equation 7-1 (p.163) since it fitted better than the remaining options.

Table 35. Base data for the calculation of the Portuguese car density and logistic growth curve parameters

Calendar Year	License Holders ('000 persons)	Car Fleet ('000 vehicles)	Car Density (observed)	Car Density *(estimated)*
1990	4,879	1,630	334	334
1991	4,875	1,829	375	374
1992	4,878	2,053	421	416
1993	4,885	2,247	460	458
1994	4,897	2,445	499	500
1995	4,909	2,611	532	541
1996	4,923	2,809	571	581
1997	4,940	3,021	612	618
1998	4,959	3,239	653	653
1999	4,981	3,469	696	684
2000	5,011	3,593	717	713
2001	5,047	3,746	742	739
2002	5,085	3,885	764	762
2003	5,118	3,966	775	781
2004	5,144	4,100	797	799
2005	5,163	4,200	813	813
2006	5,186	4,290	827	826

Note: Parameters of the Logistic Curve: a=-0.189; b=378; K=893, where R^2=0.99.

Table 36. Technological composition of the Portuguese car fleet in 1995 (Ceuster *et al.*, 2007b)

	Vehicle type					
Vehicle Age	PCGS	PCGM	PCGB	PCDS	PCDM	PCDB
0	119.035	63.962	10.242	0	12.883	8.588
1	117.154	62.951	1.008	0	12.679	8.453
2	11.087	59.575	9.539	0	11.999	7.999
3	104.284	56.036	8.972	0	11.286	7.524
4	95.019	51.058	8.175	0	10.284	6.856
5	89.711	48.205	7.719	0	9.709	6.473
6	83.309	44.765	7.168	0	9.016	6.011
7	75.795	40.727	6.521	0	8.203	5.469
8	70.283	37.766	6.047	0	7.606	5.071
9	65.303	3.509	5.619	0	7.067	4.712
10	6.246	33.562	5.374	0	676	4.506
11	56.942	30.597	4.899	0	6.163	4.108
12	53.074	28.519	4.566	0	5.744	3.829
13	47.421	25.481	408	0	5.132	3.421
14	41.567	22.335	3.576	0	4.499	2.999
15	32.013	17.202	2.754	0	3.465	231
16	21.201	11.392	1.824	0	2.294	153
17	11.167	6	961	0	1.209	806
18	4.095	22	352	0	443	295
19	1.132	608	97	0	123	82
20	102	55	9	0	11	7

Note: We recall that PC stands for Passenger Car, D or G stand for Diesel or Gasoline-fuelled, and S, M or B stand for Small, Medium or Big engine size. Furthermore, we note that PCDS were not sold before early '00s.

We started our calibration procedure by computing Eq.7-6, for the period 1995-2006: $C_i(t) = C_i(t-1) + N_i(t) - S_i(t)$, where C is the vehicle stock, N are new vehicles and S are the scrapped vehicles. The aggregate variables of this equation are decomposed according to the age and technological structure assumed in our research according to the procedure specified in section 7.2. The calibration objective was to match our estimates of aggregate car stock and new car sales with the values published by ACAP, by changing the parameters (β and λ) of the scrappage curves every year (scrappage curves are illustrated in the following figure). The starting values of both parameters (refer to section 7.2.3, p.214) were those published by Samaras *et* al. (2002). We obtained acceptable matching rates (below 5% difference) between our estimates and ACAP's values. For simulation purposes, we admit that all vehicles have the same scrappage curve from 2005 onwards, i.e. $\lambda = 11$ and $\beta = 34$.

We present also the survival curve based on the data by VALORCAR (2007). We conclude that the curve obtained from VALORCAR data indicates earlier retirement of vehicles than our calibrated data. Paradoxically, the total volume of scrapped that reported by VALORCAR is 45 thousand vehicles in 2007, while our estimates amount to approximately 150 thousand vehicles for the same year (3 times greater). In fact, VALORCAR is the company responsible for organizing and managing the reception, treatment and recovery of end-of-live vehicles in Portugal, in order to comply with EU Directive 2000/53/EC and the national Decree-Law no. 196/2003. The explanation for such discrepancy relates probably to the fact that there is still a significant amount of vehicles that are not used for circulation (and, as such meeting national car demand) and that are not abated.

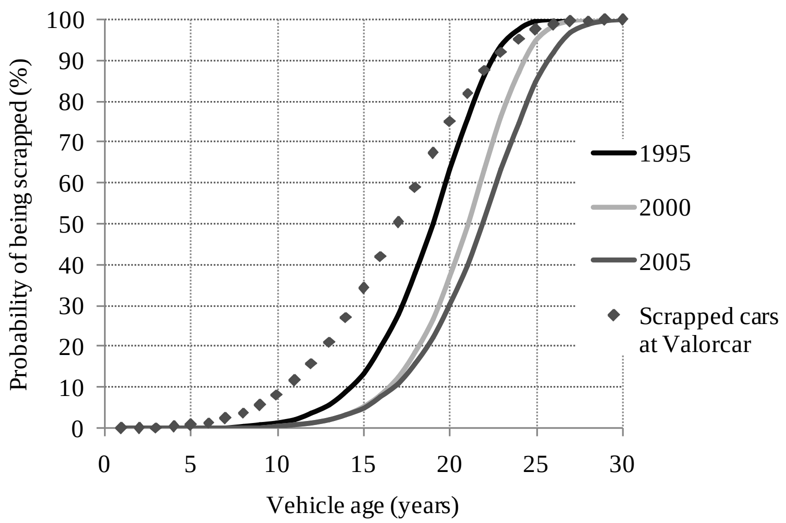
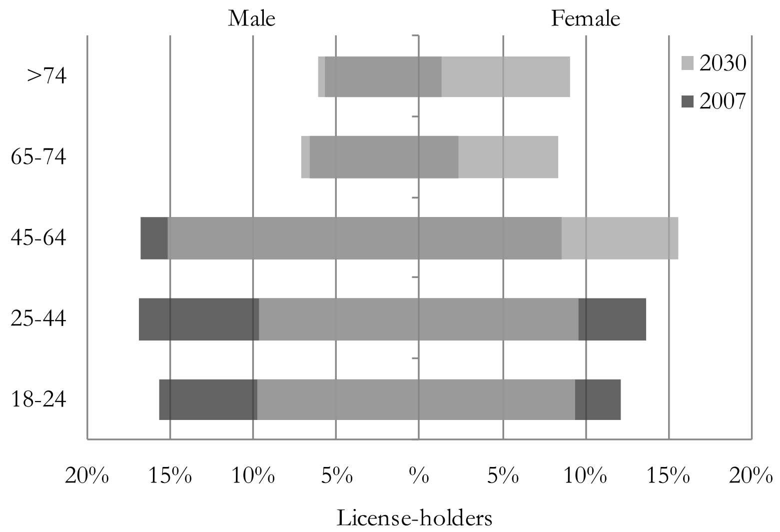


Figure 92. Estimated survival curves (1995: λ=11, β=31; 2000: λ=13, β=35; 2005: λ=11, β=34) compared to VALORCAR's survival curve (source: author based on data by ACAP and VALORCAR)

In addition, we notice that the calibrated curves indicate that cars are being scrapped later as time passes. On one hand, we observe a strong increase of car sales during the '90s (Figure 90, p.214) and, thereafter, a stabilization period occur although with some fluctuations. On the other hand, we obtained a smooth evolution curve for the Portuguese car fleet (Figure 94, p.222) although the observed values indicate that some fluctuation occurred also. Therefore, the delay of the scrappage curves observed before might simply be due to modeling manipulation by which our estimates were obtained in other to force the model to calculate the amount of retired vehicles to match global demand after deducting the observed car sales. In this sense, these scrappage curves are somehow non-realistic (i.e., they may not be an accurate approximation of the real world, although they are reasonable). Alternatively, we could argue that more recent model years are more resistant and, consequently, they are scrapped later.

After calibrating the vehicle stock and the scrappage curves, we forecasted the explanatory variables to calculate the baseline scenario from 2007 to 2030. The car-density growth curve depends only on the calendar years and is presented in Figure 94 (right-hand side y-axis). Regarding the number of license holders, we used the demographic forecast by INE (2004) and their analyses on the demographic structure of the license holders (INE, 2007). The following figure illustrates the starting (2007) and ending (2030) pyramids of the license-holders population. We assumed that women would have the same percent distribution as men, by 2030.



Note: The medium grey bars in the middle result from the overlap of the dark and light grey bars, which correspond to the two time periods analyzed, 2007 and 2030 respectively.

Figure 93. Demographic structure of the Portuguese license-holders, in 2007 and 2030 (source: author)

The growth of female license holders is striking, principally in the age cohort of women older than 45 years. This is due mainly to the relative increase in the number of women having their driving license in the future, but also to the increase of the life expectancy. The number of younger drivers is expected to decrease due to the expected absolute decrease of this age cohort in the future and absolute increase of older cohorts, in Portugal.

The following figure illustrates the expected growth curve of the Portuguese car stock. We compare this growth with the car density and the license holders' curves in the future. While the growth of the vehicle stock until 2010 (approximately) is mainly due to the increase of the car density, after that it is mainly driven by the expected growth of the number of license holders, which are mainly women and elderly people in general. We also compare both curves with the values from ACAP (triangles and diamonds curves) that illustrates that our regression curves present good fits.

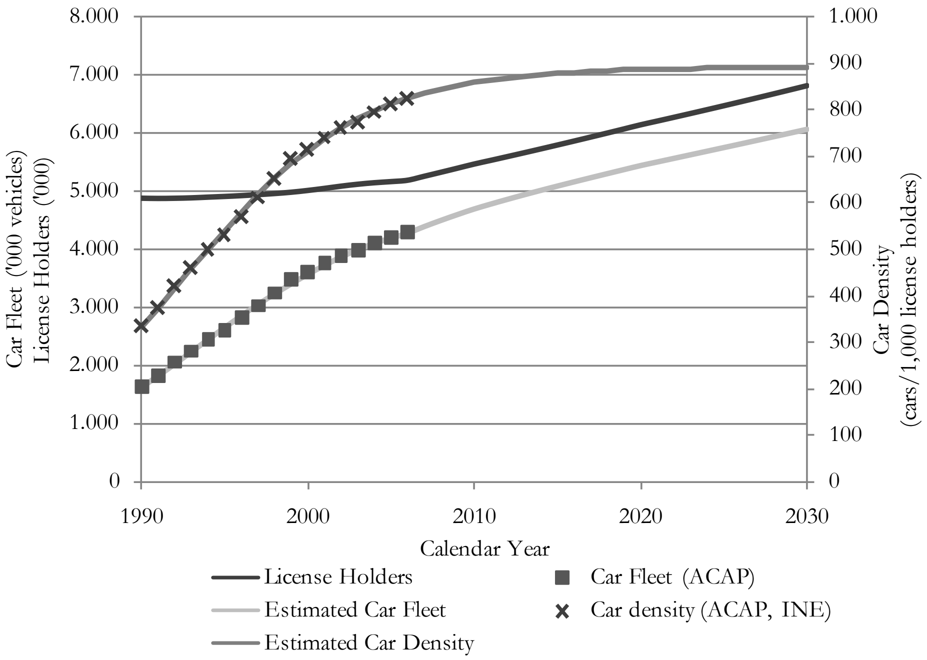


Figure 94. Estimated evolution of the Portuguese car stock from 2007 to 2030 (source: author)

Finally, we present the expected evolution of new car sales. The following figure compares our estimates with the real new car sales (published by ACAP) from 1995 to 2006. It also presents our estimated sales until 2030, which we calculated with the methodology described previously. Interestingly, while the car fleet is experiencing the booming stage of a standard car fleet evolution (refer to Figure 86, p.207), the variation of new car sales is more irregular than in a maturing stage where those sales tend to stabilize. We recall that our simulation exercise is expected to be an approximation of the real world (at best) and does not incorporate any analyses of potential external factors that would impact the demand of cars in Portugal in the future (for instance, macro-economic changes that would hinder or boost private consumption).

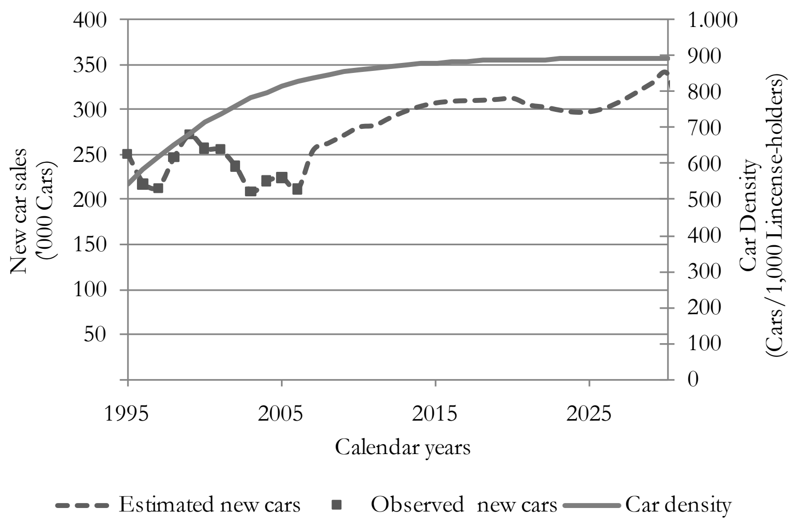


Figure 95. Estimated evolution of new car sales from 1995 to 2030, in Portugal (source: author)

The following sections present the car fleet evolution in the "Baseline" scenario, including its technological and age characterization for the car types considered here and considering the assumptions presented before.

7.3.3 Characterization of the baseline car fleet distribution and evolution

The full matrices of the car fleet distribution obtained for both "Baseline" and "Technological Transplant" scenarios are available in at the end of this dissertation. We reiterate that it is not aimed in our research to accurately reproduce and forecast the evolution of the Portuguese car fleet, but instead to have a reasonable approximation of reality. Therefore, we compare our results to surveys performed elsewhere.

The following figures illustrate the "Baseline" car fleet distribution that we estimated (a) and compare it with the car fleet forecasts calculated in the TREMOVE project (b) by Ceuster et al. (2007a). Ultimately, the major difference between the forecast by TREMOVE (Ceuster *et al.*, 2007b) and ours is the vehicle stock evolution and lower estimates of older vehicles (age cohort over 9 years) by Ceuster *et al.* (2007b). While their estimates reach a maximum of nearly 4.5 million vehicles with 5-year stagnation in the stock's growth between 2005 and 2010, we estimate a continuous smooth growth that reaches 5.7 million vehicles (i.e., 27% more by 2030). This difference is necessarily related to the methodology used in both cases. While our approach is based on the total license holders – as explained before, Ceuster et al. (2007a) calculations are based on the national demand of passenger.km estimated for each vehicle type and vintage and divided by the average annual mileage of those vehicles (i.e., vehicle.km).

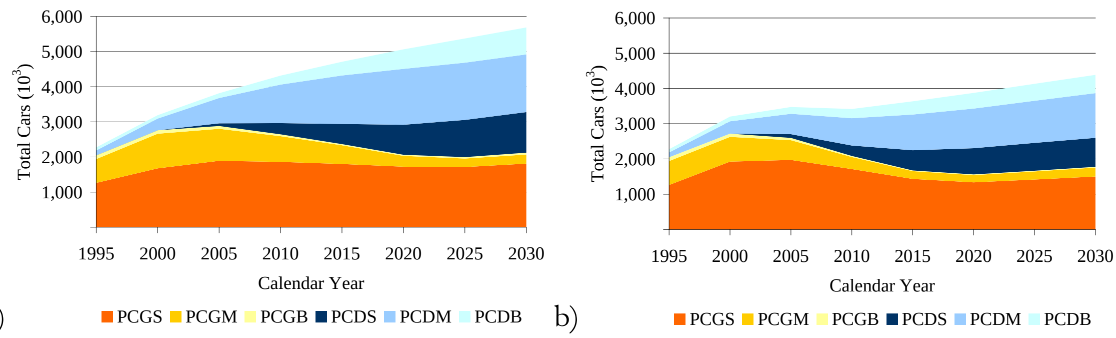


Figure 96. Car Fleet vehicle type distribution: a) Baseline scenario (source: author), b) Ceuster *et al.* (2007a)

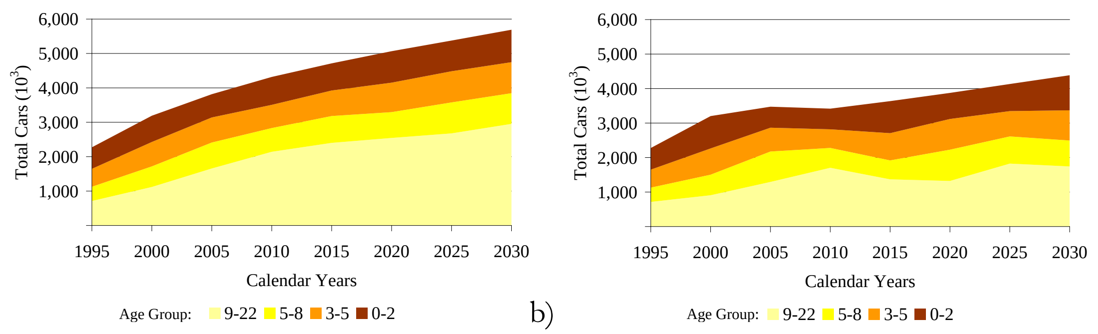


Figure 97. Car fleet age cohort distribution: a) Baseline scenario (source: author), b) Ceuster *et al.* (2007a)

If we calculate the car density (on the basis of the Portuguese population and not solely on the license holders) in 2005, we obtain 400 cars/1,000 inhabitants, in our case, and 215 cars/1,000 inhabitants, in TREMOVE's results. According to the ACAP statistics (2007), our result is closer than the TREMOVE project. Still, both methodological approaches result in similar vehicle type distributions, where we can observe a transition from a majority of gasoline-powered vehicles to some equilibrium between both fuel type vehicles. The increase of diesel-powered vehicles is mainly due to the spectacular growth of small and medium cars powered by this fuel since 2005.

With respect to the age structure, there are significant differences, where Ceuster *et al.* (2007b) calculations forecast a younger overall car fleet that reflects a higher average rate of turnover (see Figure 98), which in turn reflects shorter lifetimes of vehicles, although new car sales estimates are quite similar (as illustrated in Figure 98). In the case of our estimates, as the car fleet reaches its maturity and the car density stabilizes (900 cars/1,000 license holders), the demographic structure also stabilizes: gasoline-powered cars get older from an average of 6 years, in 1995, to an average of 11 years, in 2010, and then stabilize at 9 years; diesel-powered cars get younger from an average of 6 years, in 1995, to an average of 5 years, in 2010, and then stabilize at 9 years, too.

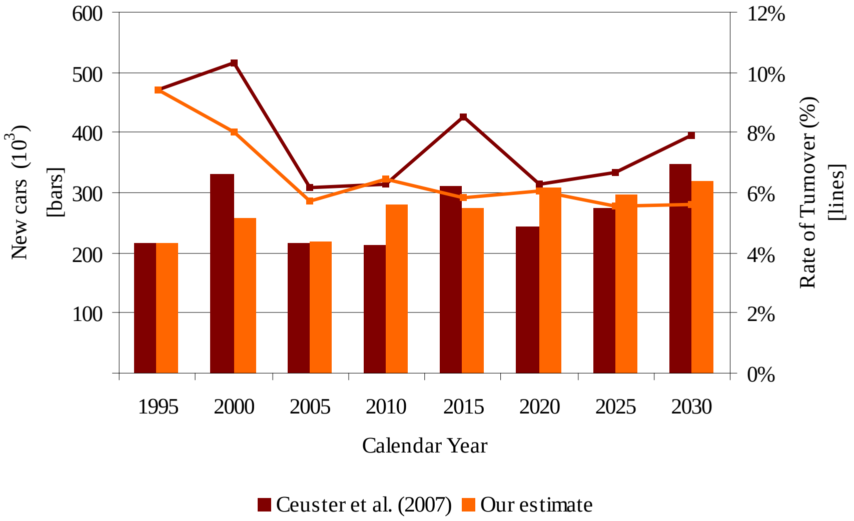


Figure 98. Comparison between new car volumes and turnover rates (source: author and Ceuster *et al.*, 2007b)

Finally, we conclude that according to our assumptions and modeling results (see Figure 99) nearly 25% of the stock is equipped with technologies complying with pre-EURO standards, in 2005. We recall that significant reductions (up to 90%) occurred after the introduction of this regulation in the EU. Refer to section 2.2 (p.21) for a discussion on the importance of regulation in the improvement of air quality in industrialized countries. In addition, our estimates indicate that these vehicles will correspond to 5% of the stock, by 2010, while 60% will comply with post-EURO 3 standards. Importantly, 70% of cars will be fitted with post-EURO 5 technologies, by 2020 (according to our assumptions).

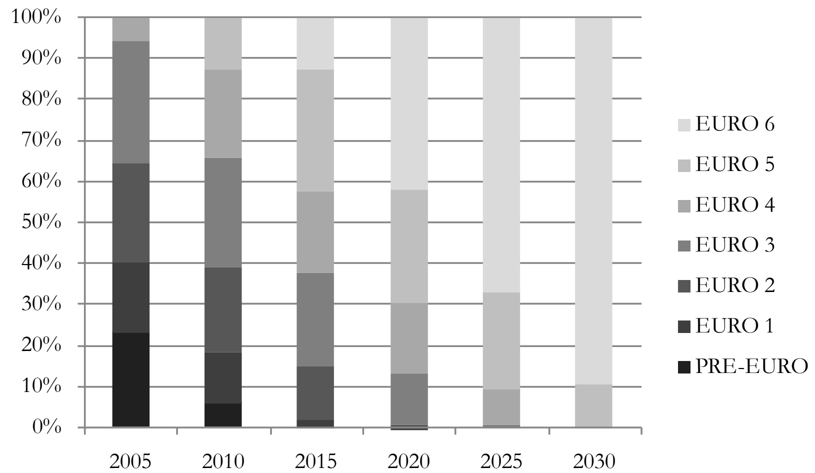


Figure 99. Car stock technological structure according to EURO standards (Source: author)

The statistics presented by ACAP (2007) for 2005 reinforce the accuracy of our model (see Figure 100). There is a high level of similarity between the number and the age structure of both car fleet characterizations. Therefore, we consider that our model reproduces well the dynamics of the Portuguese car fleet and we consider that it is a good basis for our simulation exercise.

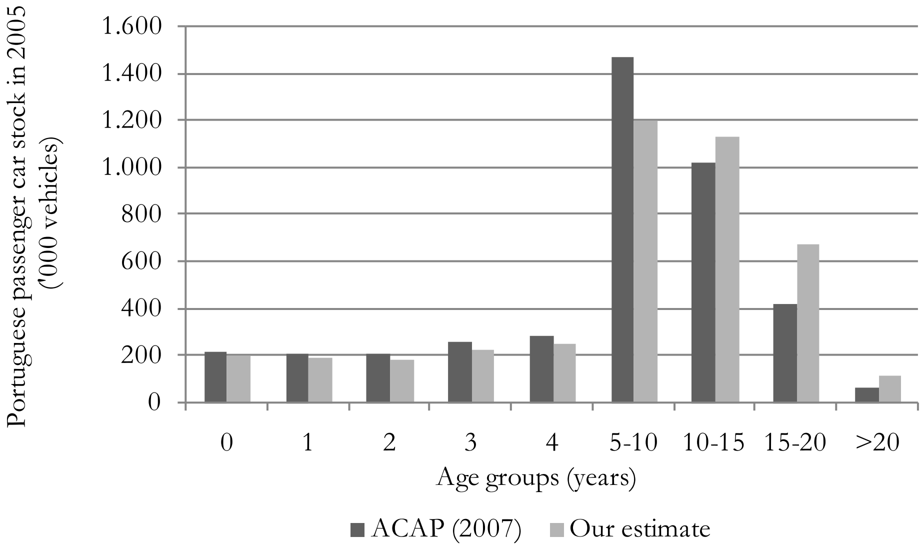


Figure 100. Comparison between car fleet demographic structures, in 2005: our estimate and ACAP (2007)

7.4. Summary and conclusions

As presented in the introductory chapters of Part C, we approach the concept of organ transplant in cars on a fleet basis. In this sense, we developed models to extrapolate the results obtained in Part B for a single car ownership and extend the car organ transplant concept to an entire car fleet. In this sense, we explore the choices of car owners on whether they keep their cars, buy new and used cars or if they transplant (or buy transplanted) cars in an aggregate and systemic way, until 2030. We used the Portuguese car stock as our case study.

In this sense, we developed in this chapter (and in the forthcoming Chapter 8) a combined model of *aggregate time series* to estimate the car demand (the running stock) over time with a *static disaggregate car-type discrete choice* model to build a reasonable approximation of the Portuguese car fleet, where policy sensitive variables are included to explore different policy scenario analyses. In the present chapter, we presented the aggregate time series car demand model.

The first step was to estimate the evolution of total car density of the Portuguese fleet using a logistic curve. The car density was based on the population of license holders (and not based on the total population, as is usually used to calculate motorization of countries) to set our maximum K to 1 car per license holder (i.e., K=1,000). After calibration, we obtained the following parameters: K=900; a=-0.189; b=378; and correlation was R^2=0.99. Our results indicate that car density will reach 890 cars/1,000 license holders (which is equivalent to 600 cars/1,000 inhabitants) by 2030 and that it will stabilize thereafter.

After estimating the annual global stock of cars and knowing how many vehicles are scrapped yearly, we calculate the number of new vehicles entering the car stock each consecutive year. With respect to the scrappage of cars, we used a probabilistic approach using a Weibull s-shaped curve to estimate the probability of a car's lifetime being greater or equal to age cohort. We calibrated the scrappage curve parameters on a 5 years basis to approximate our fleet technological composition and volume to the figures presented by ACAP. As such, the parameters (shape and scale) vary but, generically, we estimate that 20% of cars would be retired after they are approximately 15 years old (results should be viewed taking into account that they result from modeling calibration). This is equivalent to 150,000 scrapped cars yearly. We note that our model does not include migratory movements of used cars. Although they exist, they correspond to less than 2% of the total car stock or less than 13% of total annual cars sales, in Portugal. As a result, our estimates indicate that in the longer term annual sales will stabilize at approximately 350 thousand passenger cars a year (although fluctuations can occur due to economic and market circumstances that our aggregate modeling approach does not capture).

The technological structure of the car fleet is categorized according to the age of each vehicle type (annually) because the diffusion of cleaner technologies in cars has been driven principally by regulation rather than by the automotive industry. As such, we started our simulation of the fleet's technological turnover on the basis of TREMOVE's characterization of the vehicle age structure in 1995 (Ceuster *et al.*, 2007b). The technological structure of new car sales from 1996 to 2006 was obtained from ACAP statistics (ACAP/AUTO INFORMA, 2007) while, from 2007 onwards, we used the technological distribution estimated by Ceuster *et al.* (2007b). Based on our assumptions and modeling results, we conclude that as the car fleet reaches maturity (i.e., car density stabilizing at 900 cars/1,000 license holders), the technological structure also stabilizes. Results indicate that the gasoline stock is 6 years old, in 1995. By 2010, it gets older (11 years) and stabilizes at 9 years of age, as from 2010. Differently, the diesel stock gets younger from 6 to 5 years, from 1995 to 2010 (probably due to the dieselization of the Portuguese car stock), and then it stabilize at 9 years of age (although later that the gasoline stock).

Accordingly, we conclude that in 2005 nearly 25% of the stock is equipped with technologies complying with pre-EURO standards (model years older than 1991). Likewise, our estimates indicate that these vehicles will correspond to 5% of the stock, by 2010, while 60% will comply with post-EURO 2 standards. 70% of cars will be fitted with post EURO 4 technologies, by 2020 (according to our assumptions). Importantly, significant reductions in emission factors (up to 90%) occur after the introduction of EURO 1 technologies. As such, much reductions can be achieved through a faster technological turnover of the fleet. We will explore this issue in Chapter 8 and Chapter 9.

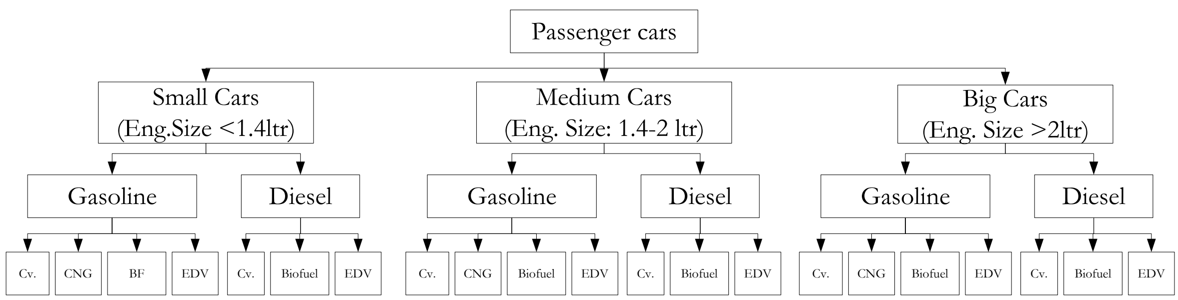
Differently to the technological structure of new car sales that was taken from Ceuster *et al.* (2007b), we develop a discrete choice model to simulate the options of consumers when facing a finite set of remarketed car alternatives in order to include the option of transplanted cars and analyze the potential diffusion of such technologies in the future. We describe the development of the remarketed car discrete choice model in Chapter 8.

Chapter 8. Discrete choice model of remarketed cars

8.1. Introduction

We pointed out before that car type choice predictions must be structured according to the fuel type, technology (EURO standard), engine size and age of each vehicle. For this reason, aggregate models are not sufficient and, thus, a discrete car type choice model is explored to deliver a more detailed structure of the fleet. This qualitative choice problem can be modeled through micro-econometric analysis of choice behavior of consumers when facing discrete alternatives. More particularly, we use here discrete choice modeling based on the random utility maximization theory and the utility functions to compare alternatives (in this case, cars available in the market). As explained in section 9.2.1 (p.259), we assume that customers who decide to buy new cars do not take into consideration used-cars or transplanted cars in their set of alternatives. This is why we did not need to have a discrete choice model for new cars and we used data from Ceuster *et al.* (2007b). Differently, we have to model the discrete choice of remarketed cars only (which obey to different purchasing factors than the new car market).

However, there is a very large number of alternatives in the car markets and it is unrealistic to expect the decision maker to compare the many attributes of all available alternatives before choosing. For example, in Portugal there are over 4,000 makes and models (by vintage) of cars available in the used car market. Although discrete choice models are getting more and more sophisticated and we can use higher computational capacity, it is too cumbersome to treat each as an available alternative to each individual and to develop a model to explain the choice between 4,000 alternatives. As described by Hensher *et al.* (2005), one strategy to circumvent this problem is to define each individual's choice set as their chosen alternative plus a randomly selected set from the remaining 3,999. On our case, we used the set of alternatives (which, in simple terms, we call "*aggregate cars*" that represent broad car type categories), instead of the more than 4,000 unrealistic alternatives. As discussed in Chapter 3 (section 3.2.1), the *car taxonomy* adopted here is determined by the methodologies used to calculate energy consumption and emissions that we mentioned before (EMEP/CORINAIR-EEA, 2002, TREMOVE - Ceuster *et al.*, 2006a, ARTEMIS - Keller and Kljun, 2007): small gasoline-powered (*PCGS*) or Diesel (*PCDS*) passenger cars, medium gasoline-powered (*PCGM*) or Diesel (*PCDM*) passenger cars, big gasoline-powered (*PCGB*) or Diesel (*PCDB*) passenger cars. The following diagram (Figure 101) illustrates this classification.



Legend: Cv. – Conventional; CNG – Compressed Natural Gas; EDV – Electric Drive Vehicles

Figure 101. Passenger car types (source: EEA, 2007a)

CNG, biofuel-powered cars and EDV[62] are considered as technological variants to the conventional gasoline and diesel-powered car types and are added at the lowest level of the structure under the corresponding fuel nests. As referred in earlier chapters, biofuels and EDV are promising technological breakthroughs in the automotive industry although the latter will slowly enter the car market since they suffer to different degrees from a lack of market experience and high costs. Still, we do not rule out such possibility in the longer term. In a *drive-by-wire* paradigm of the automotive industry, '*plug-out & plug-in*' interchangeable systems appear even more attractive than current thermal ICE where thermodynamic and mechanical barriers can become harder to overcome (refer to Box 3). Larger technological gaps in ICE solutions can lead to more difficult (eventually rule out) bridging of newer components in much older vehicles, indeed (refer to section 3.3, p. 81, where we discuss the possible mechanical hurdles to car organ transplant).

Box 3. Transplanting standard vehicles with disruptive technological innovations

To illustrate the idea that transplanting current vehicles with disruptive technological solutions is conceivable, we present one of the recent advances in biotechnology to solve the hydrogen storage in EDVs powered by fuel cells. Zhang et al. (2007) are using a combination of 13 enzymes to completely convert starch and water into hydrogen when and where that form of energy is needed (e.g., in the car). Over the years, many substances have been proposed as "hydrogen carriers" such as methanol, ethanol, hydrocarbons, or ammonia, all of which require special storage and distribution. Also, the thermo chemical reforming systems require high temperatures and are complicated and bulky. The vision is for the ingredients to be mixed in the fuel tank of a normal car. A car with a 50 liters tank could hold 27 kg of starch, which is the equivalent of 4 kg of hydrogen. 1 kg of starch will produce the same energy output as 0.85 liters of gasoline. Considering a 4.58 km/kWh fuel economy of an average fuel cell EDV, the range would be more than 480 km, autonomously. This compared to today's 650 km of an average gasoline ICE vehicle is a viable alternative. Considering the above, transplanting this technology into older vehicles is apparently an acceptable hypothesis, since fuel cell stacks and electric engine can fit into the hood of a standard passenger car.

We review now the theoretical background of discrete choice modeling. This review includes also an explanation of how discrete choice modeling helped us to solve our problem. This is why we did not include this theoretical insight in annex such as we did for the mathematical expressions used in some of our calculations.

[62] Electric Drive Vehicles (EDV) can be full electric (large battery), hybrid (smaller battery combined with an Internal Combustion Engine – ICE) or hydrogen-fuelled cars.

8.2. Background of discrete-choice modeling

8.2.1 Standard logit models

The roots of *discrete choice analysis* lie in classical economic theory that postulates that consumers seek to maximize their self-interest but also in psychology studies when analyzing the process of choice decision-making from the psychophysical discrimination perspective ("Law of Comparative Judgment" by L.L. Thurnstone (1927) as cited by McFadden, 2001). In his Nobel lecture, McFadden (2001) explains how discrete choice modeling has evolved and, more particularly, how the initial theoretical developments by Jacob Marschak (1960) and R. Duncan Luce (1959) led to more complex formulations of the (today's) extensive list of discrete choice models (starting with the original and simpler binomial logit to more sophisticated models, such as mixed-logits or latent class choice models).

As put by Train (2003), the major discrete choice models are: logit, generalized extreme value (including nested and cross-nested logits), probit, and mixed logit, plus a variety of specifications that build on these basics. We recommend the reading of Ben-Akiva and Lerman (1985), Train (1986, 2003) or Louviere *et al.* (2000) for comprehensive and in-depth reviews of discrete choice modeling. Ortúzar and Willumsen (2002), Hensher and Button (2000) and Hensher *et al* (2005) also make reviews on discrete choice theory but in the context of transport studies only (the latter includes very clear user's guidelines for the LIMDEP/NLOGIT software). For more advanced discrete choice modeling, Ben-Akiva *et al.* (1997) present a review of the more sophisticated modeling techniques such as latent class choice models, multinomial probit, hybrid logit (or logit kernel, or mixed-logit), and non-parametric methods.

As stated by Train (1986), "a qualitative choice situation (…) is defined as one in which a decision maker faces a choice among a set $C_n=\{1,2,3,\ldots,n; n \in N\}$ of J_n alternatives meeting the following criteria: (1) the number of alternatives in the set is <u>finite</u>; (2) the alternatives are <u>mutually exclusive</u>: that is, the person's choosing one alternative in the set necessarily implies that the person does not choose another alternative; and (3) the set of alternatives is <u>exhaustive</u>: that is, all possible alternatives are included, and so the person necessarily chooses one alternative from the set".

The decision of an individual based on some rule (e.g., self-interest, dominance, satisfaction, utility, etc.) can be modeled by discrete choice models that calculate the probability of that decision given the data observed by the researcher. Such models postulate that "the probability of individuals choosing a given option is a function of their socioeconomic and demographic characteristics and the relative attractiveness of the alternative" (Ortúzar and Willumsen, 2002). There are factors that collectively determine the attractiveness of the alternatives and the concept of *utility* ("what the individual seeks to maximize") is used to measure it. Some of these factors are observed by the researcher and some are not.

The utility function $U_{j,q}$ of an alternative j as perceived by an individual q can be represented by the two components:

$$U_{j,q} = V_{j,q} + \varepsilon_{j,q} \qquad 8\text{-}1$$

, where $V_{j,q}$ is a function of the observable attributes z (quantifiable and systematic term of the function), and $\varepsilon_{j,q}$ is the random term (unobserved factors), which reflects the idiosyncrasies and particular tastes of each individual, together with any measurement or observational errors made by the modeler.

The deterministic (or systematic) term of the utility $V_{j,q}$ is usually defined as a linear-in-parameters function of the attributes z (although other formulations can also be considered):

$$V_{j,q} = \sum_m \theta_{m,j} z_{m,j,q} \qquad 8\text{-}2$$

where the parameters θ are assumed to be constant for all individuals q (although they may vary across alternatives) and m is the number of attributes considered (that may also be different across alternatives). These attributes can be divided into technical or socioeconomic and demographic: the 1st characterize the alternative (e.g., age and size of the car) and the 2nd characterize the socioeconomic and demographic profile of the decision maker (e.g., gender and income). As will be discussed after, our discrete choice model does not include socio-economic and demographic attributes since these are a limitation of our database.

Since ε is not observed, the agent's choice is not deterministic and cannot be predicted exactly. Instead, the probability of any particular outcome is derived. The probability that the consumer chooses alternative i is the probability that the corresponding utility $i_{j,q}$ is larger than the utility of all other existing alternatives.

$$P(i \mid CSET) = P\left(U_{i,q} \geq U_{j,q}, \forall j \in CSET, j \geq 2\right) \qquad 8\text{-}3$$

Again, since ε is not observed, they are considered random with some pdf (probability density function) $f(\varepsilon)$. The probability that the agent chooses a particular outcome from the set of all possible outcomes is simply the probability that the unobserved factors are such that the behavioral process results in that outcome. We include the utility functions (as formulated in Eq.8-2) in the former equation and obtain:

$$\begin{aligned} P(i \mid CSET) &= P\left(V_{i,q} + \varepsilon_{i,q} \geq V_{j,q} + \varepsilon_{j,q}, \forall j \in CSET\right) \\ &= P\left(V_{i,q} + \varepsilon_{i,q} = \max_{j \in CSET} (V_{j,q} + \varepsilon_{j,q})\right) \qquad 8\text{-}4 \\ &= P\left(V_{i,q} - V_{j,q} \geq \varepsilon_{j,q} - \varepsilon_{i,q}, \forall j \in CSET\right) \end{aligned}$$

As ε follows some pdf $f(\varepsilon)$, the option of whether to choose the alternative i over whatever remaining alternative j, depends on the values that the error term can take. Eq.8-4 can be re-written as follows:

$$P(i\,|\,CSET) = P\left(V_{i,q} - V_{j,q} \geq \varepsilon_{j,q} - \varepsilon_{i,q}, \forall j \in CSET\right) \\ = \int I\left[h(x_i, \varepsilon_i) = y\right].f(\varepsilon)d\varepsilon \qquad \text{8-5}$$

where the indicator function *I* $[h(x, \varepsilon) = y]$ indicates that the statement in brackets is true when it takes the value of 1 and 0 when the statement is false. In simpler terms, what the previous equation estimates is the final probability of choosing alternative *i* that results from the integration of all probabilities of choosing alternative *i* over all possible values of the unobserved terms. To calculate this probability, the integral must be evaluated.

For instance, the simplest logit model formulation (Binary Logit model – BL) can be calculated with a complete closed-form. In the BL, the agent will decide upon two alternatives and will choose the alternative that provides him with a net benefit. The logit model is obtained by assuming that each $\varepsilon_{j,q}$ is *identically and independently distributed (IID)* extreme value, i.e. the error term of each alternative follows a Type I Extreme Value cdf (cumulative distribution function), a.k.a. Gumbel distribution, such as:

$$F_\varepsilon\left(\varepsilon_{i,q}\right) = e^{-e^{-\mu\varepsilon_{i,q}}} \text{ and } F_\varepsilon\left(\varepsilon_{j,q}\right) = e^{-e^{-\mu\varepsilon_{j,q}}} \qquad \text{8-6}$$

Under IID assumption, the error for one alternative provides no information to the researcher about the error for another alternative. Stated equivalently, the researcher has specified V_j sufficiently that the remaining, unobserved portion of utility is essentially not significant.

The mathematical implication of the error terms $\varepsilon_{j,q}$ being *IID* is that the variance-covariance matrix of the parameter estimates (of the set of attributes of the utility functions) is *(nxn) squared symmetrical and positive*, where *n* is the number of attributes of the utility function.

Parameters and ε term are identically distributed (variances are equal).

$$COV(U) = \begin{bmatrix} \sigma^2 & 0 & 0 & 0 \\ 0 & \sigma^2 & 0 & 0 \\ 0 & 0 & \sigma^2 & 0 \\ 0 & 0 & 0 & \sigma^2 \end{bmatrix}$$

Symmetrical and independent (covariances of parameters and ε terms are zero)

Figure 102. Error variance-covariance matrix of a Logit model (Ben-Akiva, 2007)

In the cases where the unobserved portion of utility is correlated over alternatives given the specification of representative utility (i.e. the IID assumption is violated) then there are three optional ways out of it: (1) use a different model that allows for correlated errors, such as a Probit model, (2) specify a new representative utility so that the source of the correlation is captured explicitly and thus the remaining errors are independent, or (3) use the logit model under the current specification of representative utility, considering the model to be an approximation. As referred by Train (2003), "violations of the logit assumptions seem to have less effect when estimating average preferences than when forecasting substitution patterns". This statement is important in the context of our research since we are estimating the diffusion potential of a new alternative (i.e., transplanted vehicles) and conventional alternatives will necessarily experience substitution patterns.

Coming back to the formulation of choice probability, Eq.8-4 can be expressed as follows:

$$\begin{aligned} P_{i,q} &= P\left(V_{i,q} - V_{j,q} > \varepsilon_{j,q} - \varepsilon_{i,q}, \forall j \in CSET, \forall j \neq i\right) \\ &= P(\varepsilon_{j,q} \geq V_{i,q} - V_{j,q} + \varepsilon_{i,q}, \forall j \in CSET, \forall j \neq i) \end{aligned} \qquad \text{8-7}$$

Assuming that the ε's are IID, they follow a Gumbel cdf such as

$$F_{\varepsilon}\left(\varepsilon_{j,q}\right) = e^{-e^{-\mu\left(V_{i,q} - V_{j,q} + \varepsilon_{i,q}\right)}} \qquad \text{8-8}$$

and, the choice probability is the following integral:

$$P_{i,q} = \int \left(\prod_{j \neq i} e^{-e^{-\mu\left(V_{i,q} - V_{j,n} + \varepsilon_{i,q}\right)}} \right) e^{-\varepsilon_{i,q}} e^{-e^{-i,q}} d\varepsilon_{i,q} \qquad \text{8-9}$$

Some algebraic manipulation of Eq.8-9 results in a succinct, closed-form expression:

$$P_{i,q} = \frac{e^{\mu V_{i,q}}}{\sum_{j} e^{\mu V_{j,q}}} \qquad \text{8-10}$$

With this closed-form formulation, logit models are calibrated taking into consideration the systematic component of the utility function only. The scale parameter μ is present in both numerator and, usually, it is set equal to 1. The challenge is to calibrate the parameters θ of the utility function in order to reproduce the consumers' choice. The calibration of these parameters is performed through standard Maximum Likelihood (ML) techniques.

As referred previously, if $j = 2$ then the model is a binary logit model (BL). Otherwise, it is a multinomial logit model (MNL). In the case, a closed-form expression also applies to calibrate Generalized Extreme Value models (GEV), such as nested and cross-nested logits. For more complex models (such as probit, mixed logit and others), the calibration of parameters has to be performed through simulation techniques, since there are no closed-form expressions (refer to Train (2003) for further explanations in such cases).

In addition to the IID assumption, there is an equivalent behavioral association with another constraint when using multinomial logit models, known as the *independence of irrelevant alternatives – IIA* assumption. This assumption refers that the ratio between any two alternatives of the choice set is necessarily the same no matter what other alternatives are in that choice set or what the characteristics of other alternatives are. In simple terms, this amounts to assuming that all the information in the error term is identical in quantity and affects only marginally the relationship between pairs of alternatives and hence across all alternatives. As referred by Train (1986), such properties have a series of very interesting practical uses, among which the possibility for the researcher to predict demand for alternatives that do not currently exist, such as the demand for a new make of car, a new technology (e.g. transplanted-cars), a new mode, and so on, provided that these alternatives can be adequately characterized by the same attributes (i.e., the unobserved effects of the new alternatives are equally influenced by the attributes of the utility function).

The appropriateness of this procedure is conceptually related to the consistency of estimation on a subset of alternatives (the Hausman-test that we will describe hereafter). If the full set of alternatives is considered to be all the currently available makes and models plus the soon-to-be-introduced technology, then estimation on currently available makes and models is equivalent to estimating on a subset of alternatives, which provides consistent estimates of the model parameters. Both assumptions have, of course, to be verified. Hausman and McFadden (Hausman and McFadden, 1984, cited in Hensher *et al.*, 2005, p.519) proposed a specification test for the IIA assumption (see Box 4).

Box 4. The Haussman-test

This test is conducted in two stages. Firstly, the analyst estimates a complete and unrestricted model with the full set of alternatives. Then, he/she estimates a model synonymous with the alternative hypothesis using a subset of restricted alternatives. When specifying the 2nd "restricted" model, the same specification in terms of the attributes, should be used. The test-statistic is calculated with the following equation.

$$q = [b_u - b_r]' [V_r - V_u]^{-1} [b_u - b_r] \qquad 8\text{-}11$$

where b_u (b_r) is a column vector of parameter estimates for the unrestricted (restricted) model and V_r (V_u) is the variance-covariance matrix for the restricted (unrestricted) model (note: the (') sign refers to the transposed matrix of its original).

The test-statistic, q, follows a χ^2 distribution (with n degrees of freedom – number of attributes of the utility function) and if the obtained value is lower than the χ^2 value, then we reject the IIA assumption (null hypothesis). This result would suggest that a more complex model which relaxes the IIA assumption (e.g., Nested Logit model – NL) should be considered.

In our research, provided that the IID/IIA assumptions are verified, we can estimate a multinomial model describing the choice of car-type by using currently available makes and models, and then use the calibrated model to calculate the probability that a consumer would choose a transplanted car or would choose to transplant his current vehicle.

8.2.2 Generalized extreme value logit models

As referred in the previous section, the Hausman test's objective is to check whether the IIA assumption is violated. In the case where it is violated, the IIA assumption must be relaxed. As explained by Train (2003), the IIA property can be seen either as a restriction imposed by the model or as the natural outcome of a well specified model that captures all sources of correlation explicitly, so that the unobserved portions of utility are correlated and IIA does not hold. In such cases, other models have to be estimated such as Generalized Extreme Value (GEV) models. The unifying characteristic of GEV models is that the error terms of the utilities for all alternatives are jointly distributed as generalized extreme value (see Eq.8-12). While in standard logit models the error terms ε are Type I extreme value (see Eq.8-6, p.231), the GEV models are obtained by assuming that ε_n follow a GEV cumulative distribution such as:

$$F(\varepsilon_{j,q}) = exp\left[-\sum_{k=1}^{K}\left(\sum_{j\in B_k} e^{-\frac{\varepsilon_{j,q}}{\lambda_k}}\right)^{\lambda_k}\right] \quad 8\text{-}12$$

where q is the number of individuals, j is the number of alternatives and K is the number of nests. The parameter λ_k is a measure of the degree of independence in unobserved utility among the alternatives in nest k. The closer λ_k gets to 1, the more independent two nests are and their correlation is low. When $\lambda_k=1$ for all k there is independence among all the alternatives in all nests and the GEV distribution becomes the product of independent extreme value terms, i.e. the GEV model reduces to the standard logit model (MNL).

This distribution allows for correlations over alternatives and is a generalization of the univariate extreme value distribution that is used for standard logit models. The most widely used member of the GEV family is called nested logit (NL). The following figure illustrates a NL Logit (inverted) tree for the car-type alternatives considered in our study.

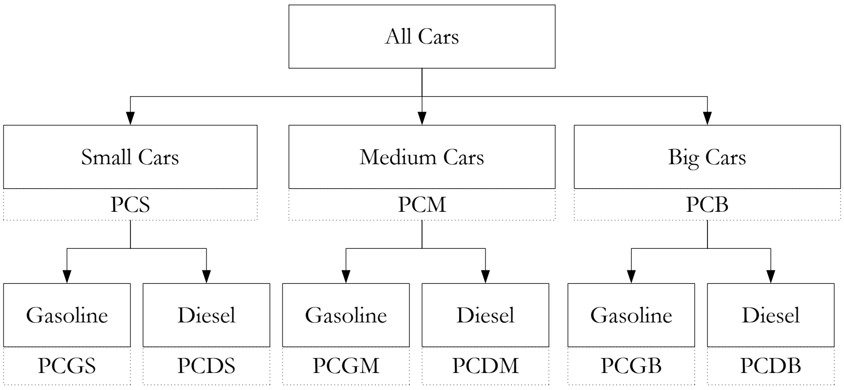


Figure 103. Simple NL Logit structure (source: author)

As reviewed by Carrasco and Ortúzar (2002), many authors (Ben-Akiva, 1973, Domencich and McFadden, 1975, Williams (1997), among others) contributed to the actual theoretical formulation of the NL models. A NL model is appropriate when the set of alternatives faced by a decision maker can be partitioned into subsets, called nests that group the alternatives that are more correlated (as referred above), in such a way that the following properties hold:

1. For any two alternatives that are in the same nest, the ratio of probabilities is independent of the attributes or existence of all other alternatives. That is, IIA holds within each nest.

2. For any two alternatives in different nests, the ratio of probabilities can depend on the attributes of other alternatives in the two nests. IIA does not hold in general for alternatives in different nests.

As put by Hensher *et al.* (2005), a NL model can be envisaged as a set of linked MNL models and its tree structures can be divided in:

- Trunks, which are the highest-level nests (tree structures with one trunk are known as three level NL models, which corresponds to our final NL – section 8.3.2),
- Limbs and branches, which are intermediate-level nests, and

- Leafs that are the elemental alternatives and correspond to the lowest-level of the tree structure.

In the example presented in Figure 103 (in the previous page), the two-level NL tree structure has one *trunk* (all cars), three *branches* (small, medium or big used cars) and two elemental alternatives for each branch (gasoline or diesel), which amount to six *leaves*.

As stated by Hensher *et al* (2005), behaviorally intuitive NL tree structures represent an excellent starting point in exploring alternative models to MNL. Still, NL tree structures are not (*necessarily*) a reproduction of the decision-making process, i.e. we could have counter-intuitive NL tree structures (refer to section 8.3.2 for the description of how we defined our NL model). Ben-Akiva (1973) analyzed in his doctoral thesis different structures of transport demand models, among which *recursive* and *simultaneous structures*. Both are a decomposition of complex MNL models (especially when there are a great number of alternatives) with difficult mathematical computation. In the first case, *recursive structures* could be viewed as a simplifying assumption of the decision-making process (with possible sensible deviations from reality) or as truly representing a conditional decision-making process. In the second case, it is assumed that the individuals make *simultaneous decisions*, rather than *recursive* (or sequential) *decisions*. The author concluded that when comparing both structures, simultaneous models would deliver more interesting results. In the case of Figure 103 (p.234), choosing a car following a recursive structure implies the assumption of a sequential decision making process: for example, people would choose the car size and afterwards opt for the type fuel (or inversely). The problem with car-choice decisions is that we cannot find a unique "natural" sequence of partitions (or nests) that will be generally applicable. Instead, we assume that the car buyer will normally consider all decisions simultaneously (although in a NL tree structure they might look like being sequential). This is a reasonable assumption and required to model a NL.

The estimation of alternatives in a NL model is more complex that in a MNL model, since the probability of choosing an elemental alternative (*leafs*) is dependent (or conditional) upon the upper-level nests (*branches*, *limbs* and *trunks*, sequentially) of the NL tree structure. Assuming a two-level NL, the probability of choosing alternative i belonging to the j alternatives of nest B_l (which is one of the K nests) corresponds to the joint probability of choosing the nest B_l (i.e., $P(B_l)$) and choosing the alternative i (i.e., $P(i|\ B_l)$):

$$P_{i:B_l} = P(B_l) \times P(i|B_l) \tag{8-13}$$

where we assume that choosing i and choosing B_l are interdependent (otherwise: $P_{i:B_l} = P(B_l) \times P(i)$).

Hensher *et al.* (2005) refer to $P(B_l)$ as a composite (or *weighted*) alternative that is interdependent on the probabilities of the elemental j alternatives, in a way that the expectation of utility when choosing the nest B_l is dependent on the expected maximum utilities (EMU) of the elemental utilities.

The utility (V_j) of each elemental alternative j is characterized by its systematic attributes and $V_j = \Sigma\mu_j.\theta_j.z_j$ (such as in Eq.8-2, p.230, where (we recall) parameters are normalized on the scale parameter μ that is set equal to 1). If the attributes of the elemental alternatives, which are linked to a composite alternative (i.e., nest), influence the choice between all nests (due to simultaneous decision-making), then this information from the lower-level nest must be included in the upper-level nest. We present the mathematical formulation of this linkage below, which was referred above as *Expected Maximum Utility* but is commonly referred to as the *Inclusive Value* (IV). It is also possible to find references to it as the *composite value* (linked to the idea that its utility is directly dependent on the utility of lower levels) or *log-sum term* since the formula of the *IV* corresponds to the natural logarithm of the denominator of the MNL model associated with the elemental alternatives of that nest (refer to Eq.8-16, below). Figure 104 presents schematically the relationship between the two-levels of a simple NL tree structure and the corresponding scale parameters.

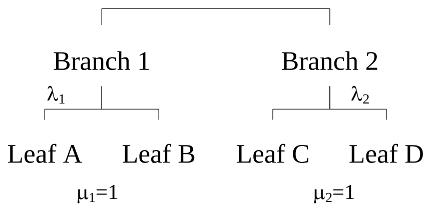


Figure 104. Two-levels NL tree structure and corresponding scale parameters (Hensher *et al.*, 2005)

As presented in Eq.8-2 (p.230), the utility function of the elemental alternatives is $V_j = \Sigma\mu_j.\theta_j.z_j$. For the Branch 1 (*B1*) and Branch 2 (*B2*), the utility may be expressed as:

$$V_{B1} = \lambda_1 \times \left[\left(\sum_{n=1}^{N} \alpha_{nB1}.w_{nB1} \right) + \frac{1}{\mu_1} IV_{B1} \right] \text{ and } V_{B2} = \lambda_2 \times \left[\left(\sum_{n=1}^{N} \alpha_{nB2}.w_{nB2} \right) + \frac{1}{\mu_2} IV_{B2} \right] \qquad \text{8-14}$$

where N is the number of w nest-specific attributes (for example, common attributes to all diesel cars) and a, the respective coefficients. If no nest-specific attributes are considered, the term $\left(\sum_{n=1}^{N} \alpha_{nB2}.w_{nB2} \right)$ is zero.

IV_{B1} and IV_{B2} are calculated as follows:

$$IV_{B1} = ln\left(e^{\mu_1(V_{LA})} + e^{\mu_1(V_{LB})}\right) \text{ and } IV_{B2} = ln\left(e^{\mu_2(V_{LC})} + e^{(\mu_2 V_{LD})}\right) \qquad \text{8-15}$$

, where V_{nLA}, V_{nLB}, V_{nLC}, V_{nLD} are the respective utilities of elemental alternative in Leaf A, B, C, and D, and $\mu_1 = \mu_2 = 1$ (normalized) are the scale parameter of the elemental alternatives.

More generically, the IV can be formulated with the following expression,

$$IV_k = ln \sum_{j=1}^{J} \left[e^{\mu_j \left(V_{j,q} \right)} \right] \qquad \text{8-16}$$

, where j is the number of elemental alternatives and k the nest, and the level-two utility is expressed as follows:

$$V_k = \lambda_k \times \left[\left(\sum_{n=1}^{N} \alpha_{n,k} w_{n,k} \right) + \frac{1}{\mu_{j,k}} \times IV_k \right], \text{ where the IV parameter is } \frac{\lambda_k}{\mu_{j,k}}. \qquad \text{8-17}$$

The same reasoning applies in NL tree structures with more than two levels, i.e. the information included in the utility function at the branch level must be "transported" to the upper-level, and so forth until the uppermost level. The consistency of NL models with microeconomic concept (i.e., utility maximizing theory) was first verified by Williams (Williams, 1977, cited by Carrasco and Ortúzar, 2002) by introducing structural conditions associated with its IV parameters[63]. The restriction to the IV parameter determines that it is bounded between 0 (exclusive) and 1 (inclusive), in order to ensure the model's internal consistency with the utility maximization principle. Ortúzar and Willumsen (2002, p.220) gives an intuitive explanation why this condition must hold:

1. If $(\lambda_k / \mu_{j,k})<0$ then an increase in the utility of one of the alternatives in the nest would actually reduce the probability of selecting the nest, which is counter-intuitive.

2. If $(\lambda_k / \mu_{j,k})=0$, such an increase would not affect the nest's probability of being chosen, which again is not intuitive.

3. If $(\lambda k / \mu j,k)>1$, an increase in the utility of an alternative in the nest would tend to increase not only its selection probability but also those of the rest of the options in the nest (this restriction is disputed as we briefly discuss hereafter).

4. If$(\lambda k / \mu j,k)=0$, for all nests, then the NL becomes mathematically equivalent to a MNL and calibrating a MNL model is more efficient than a NL.

In our modeling exercise, we will respect this restriction, although the upper-bound limit (i.e., ≤ 1) is somehow controversial as referred by Borsch-Supan (1990) and Herriges and Kling (1996) (cited by Carrasco and Ortúzar, 2002). These authors argue that in certain conditions, the upper-limit of the scale parameters can be higher than 1, depending on the probability values obtained for the nest. Referring to the tree structure of Figure 104, if Prob(B1)$\approx$ 0.5, then the value of the corresponding IV parameter could reach nearly 2 without compromising the utility maximization consistency – refer to Herriges and Kling (1996) for more details.

As stated by Carrasco and Ortúzar (2002), "it is important to note here that a NL model that does not meet this condition is, nonetheless, a valid probabilistic discrete choice model in the sense that it is a statistical description of a sample of choice data". If we face such a situation in our modeling exercise, we could use the calibrated model, in terms of its statistical validity. Still, theoretically and empirically speaking, we could not argue that our model reproduces the decision-makers behavior, since it is not consistent with the utility maximization theory.

Finally the calculation of probabilities in a two-level NL model is given by:

[63] His work on the restriction of the IV parameter (*aka* the Daly-Zachary-Williams proof) was further developed by Daly and Zachary (Hensher et al., 2005).

$$P(B_1)=\frac{\lambda_1\left(\frac{1}{\mu_{j,1}}\times IV_1\right)}{\sum_{k=1}^{K}\lambda_k\left(\frac{1}{\mu_{j,k}}\times IV_k\right)}$$, at the 2nd level of the NL model 8-18

, and

$$P(L_1\mid B_1)=\frac{e^{\mu_1\times\sum_{m=1}^{M}\theta_{m,1}z_{m,1}}}{\sum_{j=1}^{J}e^{\mu_1\times\sum_{m=1}^{M}\theta_{m,j}z_{m,j}}}$$, at the 1st level of the NL model 8-19

Therefore the marginal probability of the elemental alternative is calculated as follows:

$$P(L_1)=\frac{e^{\mu_1\times\sum_{m=1}^{M}\theta_{m,1}z_{m,1}}}{\sum_{j=1}^{J}e^{\mu_1\times\sum_{m=1}^{M}\theta_{m,j}z_{m,j}}}\times\frac{\lambda_1\left(\frac{1}{\mu_{j,1}}\times IV_1\right)}{\sum_{k=1}^{K}\lambda_k\left(\frac{1}{\mu_{j,k}}\times IV_k\right)}$$, where $IV_k=ln\left(\sum_{j=1}^{J}e^{\mu_1\times\sum_{m=1}^{M}\theta_{m,j}z_{m,j}}\right)$ 8-20

The final specifications of the NL we modeled in our study are presented in detail in annex A.14 (p.384).

8.3. Base model of remarketed cars discrete choice

8.3.1 Base data

Estimation of discrete choice models relies strongly on the data availability and its quality. Discrete choice models can be based either on revealed or stated preferences:

- Revealed preferences (RP) data represents data collected on choices that are made in an actual market. As such, RP data represents events that have been observed to have actually occurred and to which it is possible to relate socio-economic attributes of the decision makers (or of the real context) and technical attributes of the alternatives.
- Stated preferences (SP) data represents data collected by asking decision makers operating within the market being analyzed to chose among a set of alternatives and the decision is to be based on the attributes the analyst presents to the interviewee.

In both cases, the analyst must be able to collect information on either the choices made (left hand side of the equation) and the attributes of the alternatives be chosen (right hand side for the equation). RP data can be collected from available statistics although the analyst can be sometimes limited to the type and number of attributes associated to the choices she wishes to evaluate and she is bound to the alternatives existing in the market being studied. With this respect, SP data is more versatile in the sense that the analyst can obtain the information on choices by collecting (socio-economic attributes of the decision-maker) and presenting the technical attributes of the alternatives (existing or new entrants) she wishes to analyze. However, subjectivity and 'cleanness' of data can become an issue when estimating discrete choice models based on SP. Importantly, the experimental design is a fundamental step before formulating the questionnaires used to enquire the decision makers. For a discussion on the advantages and disadvantages of RP and ST approaches, refer to Hensher *et al.* (2005).

Due to time and budget limitations, we could not perform a SP survey. As such, we decided to base our estimation on RP data of remarketed cars and corresponding attributes (technical and few socio-demographic). The Portuguese national authority IRN (Instituto dos Registos e do Notariado, I.P.; http://www.dgrn.mj.pt/) holds this data that include registers of the used-cars traded annually, their technical attributes and basic attributes of the decision makers (age, gender and location). However, we could not have access to this information due to time and confidentiality barriers. Therefore, our model is based on data emulated from the used-car sales database provided by Auto Basic Motor S.A. (2007). Auto Basic Motor is a Portuguese consultant that provides used car market information and services (http://www.abmotor.pt). Since all prices are solely suggestions by sellers, they do not represent the equilibrium price but rather an upper limit of the market value and, as such, these do not represent market equilibrium data. Nevertheless, we can assume them to be a fairly good approximation and, therefore, an adequate proxy variable for the market equilibrium price. This constitutes a limitation in our modeling exercise and the database we use is (at best) an approximation of market equilibrium prices[64].

After cleaning the original database, we ended with 11,768 valid entries of used cars with the following attributes:

1. Make, Model and Version that identify the vehicle in detail (this was important in order to search for missing attributes, such as fuel economy);

2. Used-car price announced by the seller for each car (expressed in 2006 Euros);

3. Horsepower and Engine size are indicators of the size of the vehicle (hp and c.c., respectively);

4. Model Year is the indicator to calculate the age of the car and corresponding energy consumption and emission factors; and

5. Cumulative kilometrage gives an indication of the use of the vehicle over its lifetime (km).

Based on the previous details, we could search for fuel economy (*FE*) (fuel mix as published by the automakers) of each vehicle in order to calculate the operation costs of each car. As we will present later, these include fuel consumption (liters/100 km) and circulation taxes based on

[64] Demand and supply of used cars can experience seasonality and, as such, its price structure can vary along the year. Our sample is a snapshot of April 2007.

the CO_2 emission factor. The fuel economy factors were obtained from the Parker's website (Parker's - EMAP automotive, 2007) and we recall here the ultimate-CO_2-emissions formulae presented in Chapter 3 (EEA, 2007a):

$$EF_{CO_2,i} = 44.011 \times \frac{FE_{im}}{12.011 + 1.008 r_{H:C,m}} \qquad \text{8-21}$$

where $EF_{CO2,i}$ is the emission factor of CO_2 of the car type *i* and $r_{H:C,\,m}$ is the ratio of hydrogen to carbon atoms in the fuel *m* (~1.8 for gasoline and ~2.0 for diesel).

Fuel prices were obtained from the Portuguese National energy authority (Direcção Geral de Energia e Geologia, 2007, www.dgeg.pt). The following figure illustrates the variations of diesel and gasoline prices, in Portugal. We can observe that the variation of prices has been different between gasoline and diesel by which diesel price has been catching up with gasoline but the ratio gasoline-to-diesel is stabilizing at approximately 1.3. For forecasting purposes, we used the indexed progression (index 100 = 2006) of fuel prices used in the TREMOVE project (Ceuster *et al.*, 2007b). According to the forecasted data, the ratio between fuel prices is expected to be constant over time[65]. In section 5.2.3 (p. 155 in Chapter 5), we analyze the effect of fuel price on the behavior of car ownership. We were testing if facing much higher fuel prices, car owners would replace their older cars sooner to benefit from more efficient powertrains and, therefore, lower operation costs. As pointed out then, only under extreme conditions, such as the doubling of fuel prices (compared to 2007 reference price), did the change in fuel price have a noticeable effect on the replacement optimization. In the present part, we are analyzing the problem in a different perspective in that choice is to be made between six different car types over different vintages. As such, discrete choice models capture differences between costs and not absolute values. As such, if we assume that the difference between gasoline and diesel prices is not expected to vary significantly in the future, overall fuel costs differences between car types is determined by fuel efficiency and not fuel price. In this sense, we used Ceuster *et al.* (2007b) price forecast consistent with the EU's Directorate-General Energy and Transport Energy Outlook (DGTREN, 2006), i.e. a longterm stability of fuel price (in nominal terms) although some annual fluctuation (<1%) may occur.

[65] We note that the present research and this modeling exercise (more particularly) were performed prior to the strong fuel price increase from late 2007 to mid 2008, when oil prices grew from approximately US$80 to nearly US$140 *per* barrel (almost a doubling of price). As such, this variation was not considered in our study.

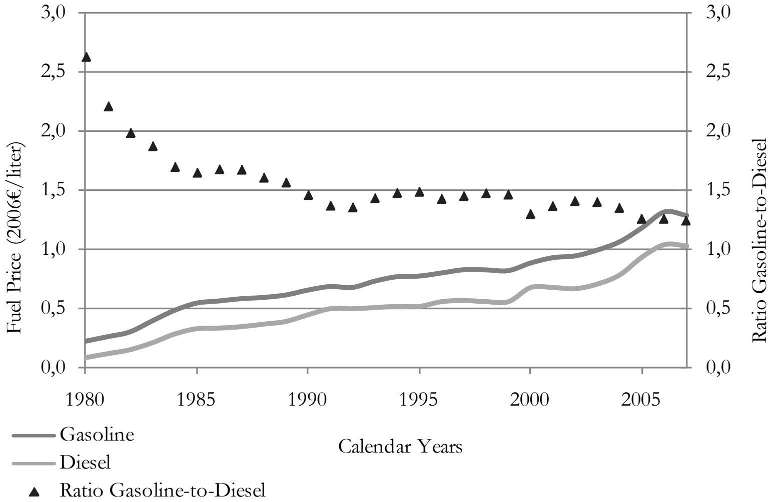


Figure 105. Fuel price variation (source: author based on DGEG, 2007)

As we explained before, our methodological approach reduces the diversity of car makes and models to six "aggregate" car-types, classified according to their engine size (<1,400c.c., 1,400-2,000c.c. and ≥ 2,000c.c.) and fuel type (gasoline and diesel). We aggregated the database into these six types of vehicles and calculated some basic descriptive statistics that we present in Table 37 and Table 38.

Table 37. Summary statistics of the transformed Auto Basic Motors database (source: author)

Vehicle type	Age Class (years)				Total	%
	0-2	3-5	6-8	>9		
PCGS	128	622	529	589	1,868	16%
PCDS	55	222	61	16	354	3%
PCGM	49	403	680	821	1,953	17%
PCDM	223	1,579	950	588	3,340	28%
PCGB	55	305	250	313	923	8%
PCDB	315	1,607	894	514	3,330	28%
Total	825	4,738	3,364	2,841	11,768	
%	7%	21%	19%	44%		
Gasoline	232	1,330	1,459	1,723	4744	40%
Diesel	593	3,408	1,905	1,118	7024	60%

From the Table 37, we build Figure 106 that illustrates the aggregate distribution of used cars according to the typology of cars we defined for our study. We observe that 81% of used cars traded are medium (45%) or big (36%), according to our assumptions and based on the database we use here. The smallest share goes for small diesel-powered (3%), which is due to the early stage of diffusion of this type of car since its large scale distribution started in early 2000's. It is expectable that these vehicles get larger shares of the used car market soon attending to their competitive prices and performances. Again, according to our sample, 60% of the traded used cars are diesel-powered (see Table 37). The majority of used cars are aged between 3 and 5 years (11% for gasoline and 29% for diesel).

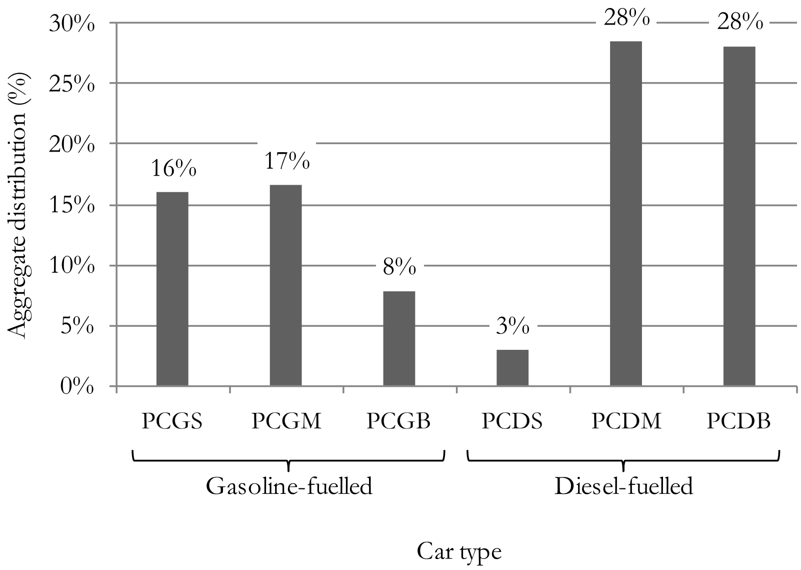


Figure 106. Aggregate Distribution of Used cars (source: author)

Regarding the technical attributes of our sample (Table 38, below), we observe that the median and average values are approximate and that the standard deviation for the engine size, horsepower and fuel economy are low ($\sigma/\mu < 0.2$). This value indicates low variability within each car type, regarding those attributes, and increases our confidence in approaching our problem with this segmentation of the car fleet.

The price of used cars and cumulative kilometrage show a higher variability ($\sigma/\mu \approx 0.4$), namely in the segment of bigger vehicles, which is not surprising. The latter two attributes being correlated with the attribute "Age" of used cars is not surprising (also) since, on one hand, used car prices are determined by their age and use, and on the other, the older they get, the more they are used and cumulative kilometrage increases. We calculated the following correlation intervals where all car types fit: $CORR_{AGE/PRICE} \in]-0.7;-0.3[$, $CORR_{AGE/CUM.KM} \in]0.4;0.8[$, and $CORR_{PRICE/CUM.KM} \in]-0.7;-0.4[$. These statistics are important when deciding which attributes should be included in the utility function of our model. We must avoid colinearity between explanatory variables in order to maximize the capture of decision makers' behavior when choosing a car. We will return to this point later in this section.

We mentioned that one important limitation of the RP data is the lack of socio-economic characteristics (SEC) of decision makers. Having this in mind and accepting that the data we hold is a reasonable emulation of real life choices we could say that they correspond to *proxy*-revealed preferences (RP) data. RP are bound by the real constraints confronted by those same decision makers. Still, we are limited to collecting data only on the chosen alternatives within those markets, i.e. we fail to collect information directly from the market or from respondents operating within the market on the non-chosen alternatives. We describe now our strategy to overcome this problem.

Table 38. Summary statistics of the attributes of used cars (source: author)

	Used car Price (2007€)				Cumulative Kilometrage (km)				Engine Size (c.c.)	Horsepower (hp)	Fuel Economy (l/100km)
Age Class (years)	0-2	3-5	6-8	>9	0-2	3-5	6-8	>9	All	All	All
Small Gasoline-powered car (PCGS)											
Median	12,900	10,825	7,250	3,500	65,000	37,000	74,000	102,000	1,200	65	5.9
μ	13,603	10,824	7,217	3,755	69,315	40,079	75,182	107,110	1,176	67	5.9
σ	2,426	2,250	1,622	2,172	7,348	20,025	28,022	41,056	97	11	0.6
Min	7,900	4,500	2,500	250	1	346	1,800	61	500	39	4.1
Max	22,350	21,500	16,830	26,750	30,039	140,000	278,000	324,000	1,300	163	8.2
Small diesel-powered car (PCDS)											
Median	19,450	12,275	8,500	2,850	45,950	45,450	68,000	127,882	1,300	41	3.4
μ	18,319	12,540	8,371	3,637	51,380	48,368	75,770	123,454	1,157	56	4.1
σ	3,008	3,921	1,652	1,953	10,475	23,840	80,905	32,705	224	20	0.9
Min	8,250	6,800	2,500	1,200	263	2,600	32,512	58,000	500	41	3.4
Max	24,000	48,602	11,750	7,000	59,000	131,234	680,000	178,000	1,300	177	7.0
Medium Gasoline-powered car (PCGM)											
Median	19,900	16,500	9,990	5,900	88,000	41,000	85,000	111,163	1,400	95	6.8
μ	21,747	17,018	10,849	6,359	89,471	47,277	87,735	116,293	1,521	103	6.9
σ	6,576	5,032	3,852	3,652	8,258	29,607	45,708	47,795	151	25	0.9
Min	6,000	5,250	6	500	20	83	7,205	2	1,400	45	4.5
Max	41,000	37,000	27,500	22,500	34,889	225,000	960,001	880,000	1,900	265	16.0
Medium diesel-powered car (PCDM)											
Median	22,800	19,500	15,500	6,900	88,000	63,000	109,350	145,000	1,800	105	5.3
μ	23,896	19,465	15,004	7,861	91,269	66,606	110,259	153,855	1,725	100	5.3
σ	6,486	8,677	5,731	4,098	13,236	35,258	36,636	54,719	197	23	0.8
Min	8,500	5,000	3,500	900	38	28	7,500	6,283	1,400	45	4.3
Max	44,990	266,854	45,000	27,250	87,988	210,000	260,000	400,000	1,900	250	9.4
Big Gasoline-powered car (PCGB)											
Median	57,800	39,980	24,925	19,800	70,000	39,500	82,050	98,000	2,000	224	9.6
μ	67,392	51,808	32,114	25,988	75,837	46,550	86,406	106,408	2,118	232	10.3
σ	31,408	34,799	20,018	20,730	12,886	33,918	37,172	56,090	181	89	2.8
Min	25,000	10,750	10	1,400	500	1,000	7,600	900	2,000	54	6.0
Max	159,500	475,000	142,500	150,000	57,000	207,000	191,000	437,000	3,200	612	27.0
Big Diesel-powered car (PCDB)											
Median	43,500	33,900	23,500	11,725	83,219	62,000	114,000	155,000	2,200	143	6.3
μ	48,671	35,363	23,526	12,260	89,902	65,814	116,638	161,522	2,343	155	6.8
σ	16,189	11,300	8,939	5,488	11,020	36,820	43,202	55,125	418	38	1.5
Min	13,900	7,000	21	1	10	5	140	10,000	2,000	73	4.9
Max	111,111	91,000	72,500	35,000	67,610	225,000	450,000	375,000	6,500	525	15.6

Hensher *et al.* (2005) suggest three options to overcome lack of data on the non-chosen alternatives, assuming that, in the aggregate, information on the attribute levels for all alternatives within the choice set are available. The first approach involves taking the average of the attribute levels (or median for qualitative attributes) for each chosen alternative. These are then substituted for the attributes of the non-chosen alternatives. Thus for each individual, while we retain the information on the individual's chosen alternative, we generate data on the non-chosen alternatives. This approach has two drawbacks: the risk of promoting a better set of attributes than the one that exists in reality; and the risk of reducing the variability of the attribute level distribution in the sampled population. Consequently, by reducing the variability of attributes, there is an increased risk of non-convergence of the logit model.

In the second approach, instead of taking attribute level averages, we generate the attributes of the non-chosen alternatives randomly across the observed attributes of the chosen alternatives. If we had the SEC attributes of the decision makers, we could attempt to match the non-chosen alternatives attribute levels to specific decision makers based on their SEC. The benefit of this approach is the conservation of variability of our sample.

The third approach is to generate data for the non-chosen alternatives from synthetic data obtained from the chosen alternatives. Synthetic data is generated from probability density distributions (pdf) that are calibrated from the observed attribute-levels of chosen alternatives.

We tried the second and third approaches in order to obtain a more favorable data set for model calibration (i.e., preserve variability of attribute levels). Our logit models could not converge with the second approach. Conversely, we obtained remarkable results with the data set generated with the third approach, using the following pdf:

1. Age follows different beta distributions [*Age~ BETA(a, β, min, max)*] depending on the vehicle type;

2. Horsepower follows different trimodal normal distributions [$HP \sim N(\mu_1, \sigma_1; \mu_2, \sigma_2; \mu_3, \sigma_3)$] depending on the vehicle type;

3. Price of used-cars normal distributions [$CP \sim N(\mu, \sigma)$] are bound to each vehicle but also to age classes (refer to in annex).

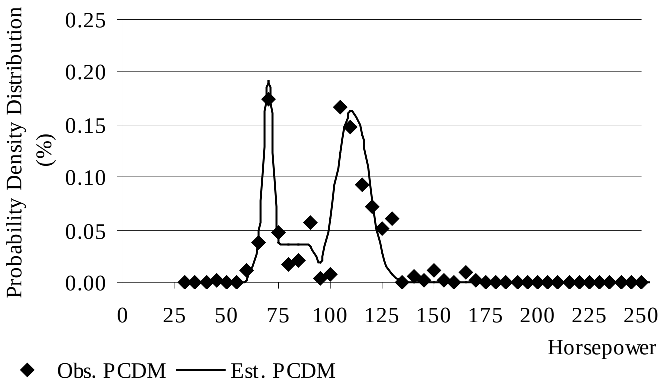


Figure 107. Example (PCDM) of horsepower distribution (observed and estimated) (source: author)

Based on our sample, we detected a linear relationship between the horsepower and engine size for each type of vehicle (although some variability occurs). We generated the engine size of the non-chosen alternatives based on regressions between those two attributes. Again, we refer that we are inducing colinearity when generating an attribute based on another attribute of the same sample.

Finally, fuel economy was estimated based on a multi-linear regression of engine size, horsepower and age. We note that this relationship is purely statistical and we do not make any mechanical interpretation out of it, although it is known that there is a mechanical relationship between fuel consumption and combinations of horsepower and engine volume. In addition to the previous variables, the generation of fuel economy factors accounted for a random term ε. As such, it allowed us to keep some variability for the attribute "fuel economy" and reduce colinearity with the other explanatory variables (see Figure 108d). Eq. 8-22 shows the equation in the case of PCGS car type.

$$FE = 0.006 \times Horsepower + 4.542 \times Engine\ Size + 0.034 \times Age + \varepsilon \qquad 8\text{-}22$$

, where $\varepsilon \sim \text{Normal}(\mu=0; \sigma=0.653)$ and all coefficients are statistically significant (i.e., $t_{(df=3,\alpha=0.05)} > 1.96$).

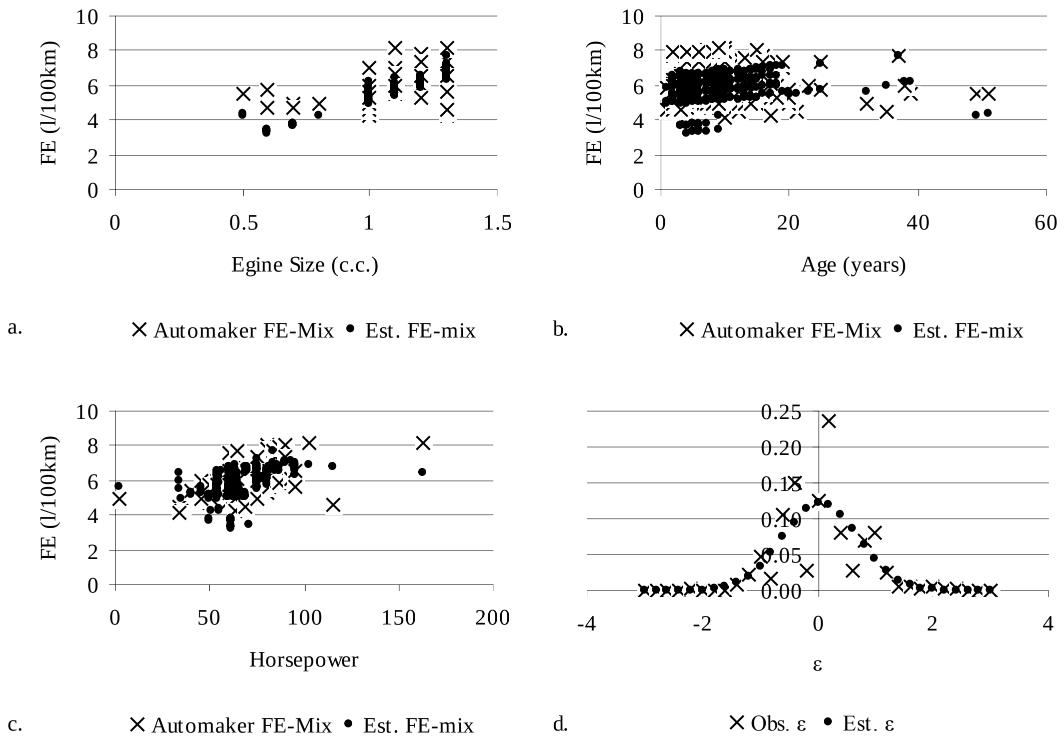


Figure 108. Fuel economy multi-linear regression in the case of PCGS (source: author)

As referred previously, "age" and "cumulative kilometrage" are correlated (which is not surprising!). In this sense, we estimated logarithmic curves for each type of vehicle (refer to chapter 3). These curves were compared with the average cumulative kilometrage used in the TREMOVE project (Ceuster et al., 2006b) and proved to be similar (comparison is not presented here). The parameters for each pdf or regression curves are presented in the annex A.10 (p.379).

When generating synthetic attribute-levels for the non-chosen alternatives, we faced the problem of obtaining unrealistic attribute values, in some cases. The problem resides in the tailed-distributions (e.g., normal distribution) that are symmetrical to the mean attribute value. When probability approaches zero, the attribute levels tend to negative (or positive) infinite and eventually become unrealistic (and meaningless). For example, used cars cannot have negative residual prices. Therefore, we truncated those distributions in order to obtain realistic and usable datasets. We followed an iterative procedure to truncate the distributions and the last iteration was determined when the logit model could converge to some solution. In this sense, we used the normal probability distribution curves calibrated for remarketed-car prices and presented in Table 38 (p.243).

After describing how we handled the sample data to build the final dataset of the chosen and non-chosen alternatives, we now present the remarketed-car discrete choice model specifications.

8.3.2 Model specifications

Based on the theory, data limitations and arguments, presented in previous sections, we made the following assumptions to pursue our modeling exercise:

1. The consumer who considers the purchase of a vehicle faces a discrete choice situation and must choose amongst a set of mutually exclusive alternatives.[66]

2. In face of the characteristics/attributes of each alternative, the consumer behaves rationally and seeks to maximize the utility of his final choice.[67]

3. We assume that all used-cars are bought for private use.[68]

We ran an extensive number of MNL and NL models. For the MNL, we tested several configurations of the utility function by including (or excluding) attributes (and combinations of attributes) and the structure of the alternatives is presented in Figure 109 (for more details on the setting up of alternatives refer to section 8.1, p.227).

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[66] He/she will not buy several cars at the same time.

[67] One drawback of this assumption is that pure rationality is hardly acceptable in real life, especially when referring to buying cars that is much influenced by emotional factors (which are not captured by the systematic attributes we choose). We could capture emotional influences in the car-type choice making with latent variable logit models. Here again, we would need to have SP data to calibrate such model. This will certainly be included in our further research to further explore the concept presented in the present thesis.

[68] We rule out used car purchases by companies.

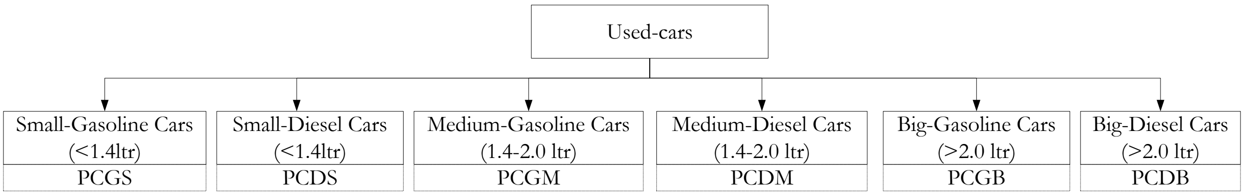

Figure 109. Simple MNL Logit structure (source: author)

The utility function and respective systematic attributes are expressed in the following equation:

$$V_j = \mu_j (\theta_1 \times AGE + \theta_2 \times CP + \theta_3 \times TC + \theta_4 \times CIRCT + \theta_5 \times ES + \theta_6 \times NBRMODS) \qquad \text{8-23}$$

where, V_j is the utility function of each alternative.

AGE is the variable that captures the impact of the age of the substitution vehicle on the utility perception of used-car consumers.

CP is the variable that captures the impact of the capital investment cost, which corresponds to the substitution car price (final consumer price including VAT) after subtraction of the replaced car price.

TC captures the impact of fuel costs (*€/km*) on the consumer's choice and these are estimated by multiplying the fuel economy factor (*liter/km*) by the fuel price (*€/liter*, which final consumer price including national taxes and VAT) and by the average annual kilometers of the vehicle (*cumulative km/age*).

CIRCT captures the impact of circulation taxes on the consumer's choice (calculations were based on the Portuguese law – Lei n.º 22-A/2007 de 29/06 - Série I nº 124 – refer to annex A.12, p.382)[69].

ES is the engine size (c.c.) that captures the impact of the car size on the consumer's choice.

NBRMODS is the number of Makes and Models available for each type of "aggregate" vehicle considered in our model. It is intended to capture the impact of the diversity of some technology on the final choice of the consumer. The greater the diversity is, the more he/she will choose that type of vehicle.

$\theta_{1,\dots,5}$ are the attributes' coefficients that were calibrated using LIMDEP v7.0.

μ_j is the scale parameter (which we normalize and, thus, set equal to 1).

---

[69] As mentioned in the annex, the law that determines the circulation taxes for passenger cars suffered a structural modification in 2007. According to the older version of this regulation, the circulation tax decreased for older vehicles, although bigger vehicles paid higher taxes for the same registration year. The logic behind this law was that older vehicles circulate less than younger vehicles and therefore imposed less deterioration on roads. Starting with vehicles registered in 2007, the new regulation includes a carbon component and the tax depends on the engine size and the CO_2 emission factor of the vehicle. The bigger the vehicle is and the more CO_2 it emits, the higher the tax is, independent of its model year. The logic now is to somehow internalize part of the externalities induced by the use of vehicles. One expected effect of this new version of the law is that it progressively induces the car consumers to choose more efficient vehicles.

We referred previously (and recall now) that we could not collect data on the socio-economic (SEC) attributes of the decision makers. Without better (or viable) options, we decided to continue and build a model that is an approximation of what we could get with a complete dataset including those SEC attributes.

We did not include the attributes "cumulative kilometrage" and "horsepower" referred in the previous section because they were too correlated with other attributes: firstly, "cumulative kilometrage" with "age" [0.8] and "engine size" [0.82]; secondly, "horsepower" with "fuel costs" [0.78]. Still, we tried to calibrate our MNL including these attributes, but the results were totally unsatisfactory (i.e., attributes with wrong signs and low statistic significance).

Although the attribute "engine size" is quite correlated with "fuel costs" [0.54] and "circulation taxes" [0.60] (and the latter two are also correlated between them [0.77]), we decided to keep them since they are important pieces for future tests of policy scenarios. The correlation between the remaining attributes is always below 0.3, which we considered sufficiently small to allow a correct calibration of our model.

Additionally, a large number of nested structures were assessed arriving at the two preferred structures in Figure 111 (a, b). Our starting tree structure is presented in Figure 110, where we assumed that used-car buyers would follow a logical sequence for making their choice, i.e. first looking at the car price (thus explaining the limbs of the following tree structure), then the size of the vehicle (the branches of the same tree) and finally, deciding upon which fuel to choose (leafs or elemental alternatives).

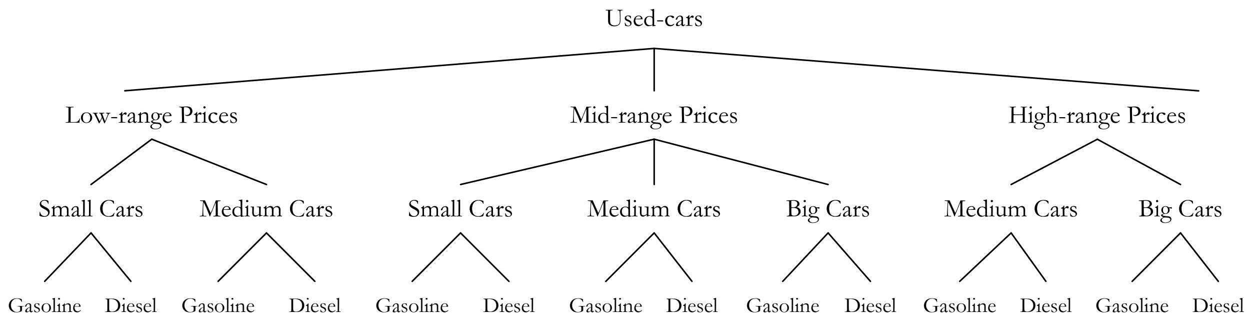

Figure 110. Initial tree structure for the NL model (source: author)

After analyzing our database, we concluded that, for the car price ranges we defined, (almost) no big cars fit into the range of low prices (see Table 39). Conversely, there were no small cars (and very few medium cars) fitting in the high range prices (although luxury models of small cars do exist, but they remain a smaller portion of existing small cars).

Table 39. Used car distribution according to price and size classes (source: author)

			Range of used-car price (2007€)			
			Low	Mid	High	Total
Car Type	Gasoline	Small	12%	4%	0%	16%
		Medium	9%	7%	0%	17%
		Big	1%	2%	5%	8%
		Total	21%	14%	5%	40%
	Diesel	Small	2%	2%	0%	3%
		Medium	7%	19%	3%	28%
		Big	1%	9%	17%	28%
		Total	10%	30%	20%	60%
	Total		31%	43%	25%	100%

Note: Used-car Price bands: Low ≤ 10,000€; 10,000€ < Medium ≤ 25,000€; High > 25,000€. This traditional stratified segmentation of car types by price band is likely to erode and follow the more horizontal segmentation that is now emerging for new cars (Nieuwenhuis and Wells, 2003, p.183). For example, it will soon be possible to choose from among a group of different car types, such a large saloon or estate (bigger cars), a small executive, a well specified compact MPV, a small SUV, etc., within the same price band (e.g., from 25,000€ to 35,000€).

However, the model could not converge and, hence, we evolved to other tree structures. The final structures are presented in the following figures. As referred previously, we attempted to model the used-car market only. The new vehicles entering the Portuguese fleet are exogenous to our discrete choice model.

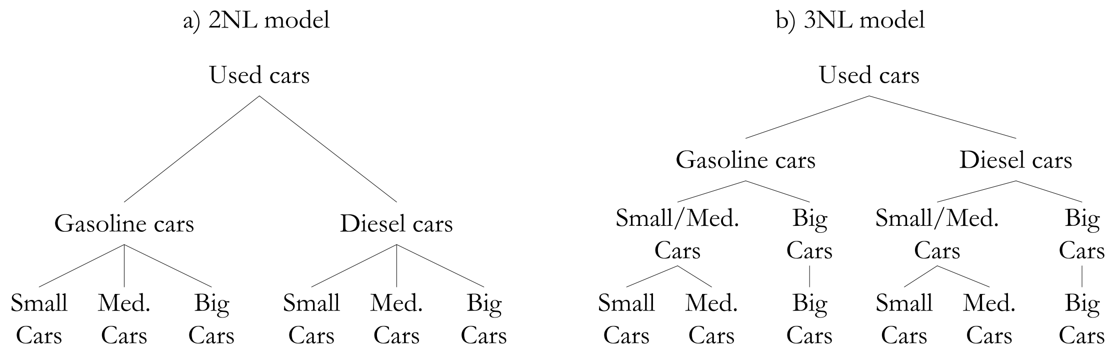

Figure 111. Final tree structures for the (a) 2-level NL (2NL) and (b) 3-level NL (3NL) (source: author)

The final results obtained for the models[70] we calibrated are presented in Table 40 (next page). Intuitively, the utility perceived by the decision maker is expected to increase ("+" sign) as the "engine size" (which captures the size of the car) or the "number of car makes and models" of that vehicle type (which captures the diffusion extent and "*maturity*" of that technology) increase. Conversely, utility should decrease ("-" sign) while costs (whether fuel costs or taxes) and age increase. For all three selected models, all signs of the attributes are correct and the Wald-statistics for all parameters are higher than 1.96 (for a level of significance α = 0.05),

[70] The models were calibrated using the software LIMDEP v.7.0 with standard Maximum Likelihood techniques, since MNL and NL models have closed-form probability expressions.

which means that they are statistically significant and, therefore, the corresponding attributes should be considered in the utility function.

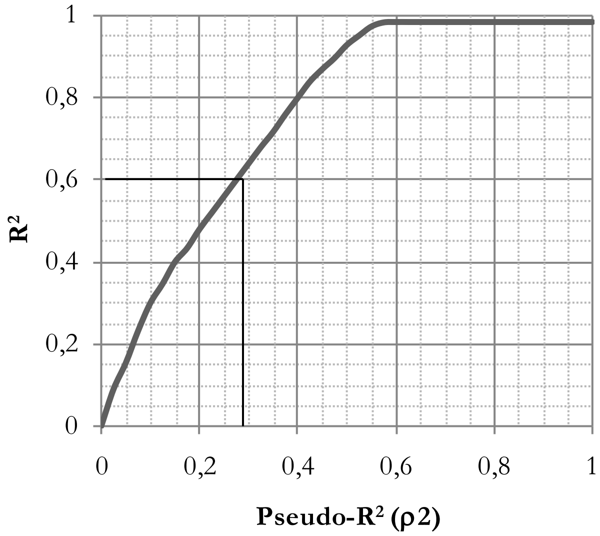

Figure 112. Mapping the *pseudo-R^2* to the corresponding linear R^2 (Domencich and McFadden, 1975, cited by Hensher et al. ,2005)

Similarly to the R^2 statistic for linear regressions, the coefficient of determination ϱ^2 (or *pseudo*-R^2) gives an indication of the model's goodness-of-fit. Therefore, the interpretation of the ϱ^2 values is similar. However, since the underlying choice analysis for a MNL model is non-linear, $\varrho^2 = 0.3$ is different than $R^2 = 0.3$ (which would denote a poor model fit). Domencich and McFadden (1975, cited by Hensher et al. ,2005) proposed an empirical relationship between the two statistics that is illustrated in Figure 112 (above). Therefore, a *pseudo*-$R^2 = 0.30$ is equivalent to a $R^2 = 0.60$, which would be a good linear model fit.

The overall goodness-of-fit obtained for all models is fine with ϱ^2 of 0.298, 0.320 and 0.483, for the MNL, 2NL and 3NL models, respectively. On one hand, models based on RP data are easier to estimate than those based on SP data, since data derives from real choices from decision makers that are bound to real (and not hypothetical) constraints. However, we recall that the RP data refers to the chosen alternatives and, therefore, we had to generate synthetically the attributes of the non-chosen alternatives and imposed some criteria so that the models could converge. Consequently, the coefficients of determination we obtained are not very surprising. The likelihood ratio test of differences between the three models (for 1 degree of freedom (*df*) for the comparison between MNL and 2NL, 3 *df* between MNL and 3NL, and 2 *df* between 2NL and 3NL) at 95% level of confidence rejects the hypothesis of no differences, leading us *a priori* to select the 3NL model as the preferred final model (highest ϱ^2). However, there are some assumptions and restrictions to verify before accepting a model for further analyses and simulations.

Table 40. Summary of calibration results for the MNL, 2NL and 3NL models (source: author)

Attribute	Acronyms	MNL	2NL	3NL
Engine Size	ES	0.00178 (19.58)	0.00159 (12.96)	0.00293 (12.96)
Car Age	AGE	-0.17316 (-16.45)	-0.19714 (-18.34)	-0.12018 (-18.34)
Car Price	CP	-0.00011 (-27.681)	-0.00013 (-28.96)	-0.00008 (-28.96)
Annual Fuel Costs	TC	-0.00002 (-27.98)	-0.00002 (-33.15)	-0.00002 (-33.15)
Annual Circulation Taxes	CIRCT	-0.01263 (-14.01)	-0.00536 (-4.36)	-0.01409 (-4.36)
Number of car makes and models	NBRMODS	0.00722 (13.56)	0.00932 (14.93)	0.00088 (14.93)
IV parameters for 2NL				
Gasoline Cars	G		1 (fixed)	
Diesel Cars	D		0.47355 (16.29)	
IV parameters for 3NL				
Branch				
Small/Medium (Gas.) Cars	GSM			2.53763 (15.75)
Big (Gas.) Cars	GB			1 (fixed)
Small/Medium (Dies.) Cars	DSM			10.0051 (23.01)
Big (Dies.) Cars	DB			1 (fixed)
Limb				
Gasoline Cars	G			1 (fixed)
Diesel Cars	D			0.55434 (13.48)
Log Likelihood for the base model		-4199.88	-4199.88	-4199.88
Log Likelihood at convergence		-2949.35	-2854.39	-2170.52
ϱ^2		0.298	0.320	0.483
Sample size		2345	2345	2345

a) Numbers in parenthesis are the Wald-statistics of the attributes' parameters.

b) We recall that the first level scale parameters μ were normalized to 1 (also referred in the literature as RU1, for random utility model specification 1).

c) In both cases of the 2NL and 3NL, we normalized the "gasoline cars" IV parameter to 1.

d) In the case of the 3NL, since the μ parameters are also equal to 1, the scale parameters at the branch level (or level 2) were also, by logical deduction, normalized to 1, in order for the IV parameter be equal to 1. As referred by Hensher (2005, p.488), the variance is an inverse function of the scale parameter (since it is demonstrated that $\sigma^2 = \pi^2/6\lambda^2$). Therefore, if a limb (level 3) has only one branch (level 2), then the variance should remain the same (provided that there are no branch-specific attributes), such as the corresponding scale parameters. If $\sigma^2 = \pi^2/6\lambda^2$ then the variance of the gasoline cars is σ^2=1.645.

In the case of the MNL, we tested the IIA (Independence of Irrelevant Alternatives) assumption (Hausman test as described in section 8.2), to evaluate if the model reproduces correct substitution patterns and, hence, if we could assess the potential diffusion of new technologies (e.g., transplanted technologies) in the used car population. In this sense, we calculated one unrestricted model with all alternatives presented in Figure 109 and six restricted models, where we excluded each alternative at a time, maintaining all the others[71]. The values of

[71] Other restricted models could have been tested. We decided to test these configurations to evaluate the potential impact of the absence/presence of each alternative in the choice set.

the parameters obtained for the each model are presented in Table 41, together with the Hausman q-test statistic.

Table 41. Parameter values for unrestricted and restricted MNL models and q-test statistics (source: author)

		Restricted					
Attributes	Unrestricted	PCGS	PCGM	PCGB	PCDS	PCDM	PCDB
Engine Size	0.00178	0.00182	0.00115	0.00243	0.00174	0.00067	0.00500
Age	-0.17316	-0.18788	-0.17646	-0.27450	-0.15938	-0.04366	-0.20174
Car Price	-0.00010	-0.00009	-0.00010	-0.00014	-0.00008	-0.00004	-0.00012
Annual fuel costs	-0.00002	-0.00002	-0.00001	-0.00002	-0.00002	-0.00002	-0.00003
Running Taxes	-0.01263	-0.01297	-0.01425	-0.03278	-0.01309	-0.00231	-0.02809
Number of car makes and models	0.00722	0.00629	0.01266	0.01027	0.00163	0.00918	0.00617
q-test statistics	n.a.	649	318	253	3689	421	624

Note: There is a high variability in the parameters from model to model, indicating that the presence/absence of one alternative is not negligible. This is also reflected in the variability of the covariance matrixes obtained (refer to one example of the Hausman test presented in annex A.13, p.383).

For all configurations of the restricted models, we found that the *q* test-statistic is higher than the $\chi^2_{(df=6;a=0.05)}=12.597$ (see Table 41). Therefore, the IIA assumption is violated and substitution patterns between alternatives are expected to be dependent on the remaining alternatives. Hence, this model cannot be used to test the substitution of existing alternatives by any new alternative to be introduced in the choice set (such as transplanted vehicles). This is why we did not consider this model to analyze the potential diffusion of transplanted technologies in the Portuguese car fleet.

As referred in section 8.2.2, the IV parameters are bounded to the interval]0, 1] (DZW restriction) in order to ensure the model's internal consistency regarding the utility maximization theory. In the case of the 2NL model, the IV parameter of 0.4736 for the diesel cars is statistically significant and different from 1 assigned to the gasoline cars and complies with DZW restriction. What we see is that the amount of the variance of the unobserved variables is higher for diesel cars (inverse of the scale) than for gasoline cars. The scale parameter can be used to derive the correlation of the unobserved portion of the utility for alternatives in the nest, which is quite high (i.e. 1-0.4732 = 0.776) and suggests that this nest is consistent with respect to the error terms of the alternatives. The Wald-test value for the "Diesel cars" IV parameter is >1.96 (for a 95% level of confidence), suggesting that it is significantly different than zero. The same can be tested for the upper-bound, i.e. if it is significantly different than one (otherwise, the 2NL should be collapsed into a MNL). We performed the Wald-test and obtained a value of (-18.11). Thus, we kept this NL tree structure.

Regarding the 3NL model, there are three free scale parameters: firstly, the IV of the limb that groups all "diesel cars" (D = 0.554; $\sigma^2_{\text{Unobs. Utility}}$ = 0.69, that is again quite high), and branches with "Diesel, small and medium cars" (DSM = 10.001) and "Gasoline, small and medium cars" (GSM = 2.538). Although the scale parameter of the diesel cars does not violate the DZW restriction, the other IV parameters do exceed by far the upper-bound 1. Therefore, although the 3NL model is statistically correct and reproduces our sample's choices quite well, we cannot perform further analysis since the utility maximization principle is not verified and simulation results would not be trustful.

Therefore, the final model we selected is the 2-level nested logit (2NL). The utility and probability functions are presented in the annex A.14 (p.384). The contingency table presented hereafter is another way of analyzing how well our model is performing. In the rows, the table presents the choices observed in our sample data, whereas in the columns are the choices estimated based on our model. One way of analyzing the results of the following table is to say that the probability of choosing PCGB is 11% while PCGS was the observed choice from our sample choice set. The grey cells in the table contain the matching rate between the observed and estimated choices. We observe that the model performs rather well for PCDS, PCGM, PCDB, and PCDM (43%, 47%, 48%, 52%, respectively), not so well for PCGS (34%), and badly for PCGB (10%, although in this case the sample is quite small – 69 events).

Table 42. Contingency table of the 2NL model (source: author)

		Choices estimated by the model (highest probability)						
		PCGS	PCGM	PCGB	PCDS	PCDM	PCDB	Total
Choices observed in the sample	PCGS	34%	16%	11%	9%	1%	30%	16%
	PCGM	7%	47%	10%	9%	1%	26%	17%
	PCGB	11%	22%	10%	14%	2%	40%	8%
	PCDS	9%	16%	10%	43%	0%	22%	3%
	PCDM	7%	13%	8%	4%	52%	16%	28%
	PCDB	10%	19%	12%	10%	1%	48%	28%
	Total	12%	22%	10%	9%	16%	31%	100%

The following section compares the estimated technological distribution of remarketed cars using our estimated choice model with the observed distribution we presented in previous sections.

8.3.3 Estimated technological distribution of remarketed cars

The following figure illustrates the aggregate car-choice distribution, by comparing the observed choices (total in rows in the previous table) and estimated choices (total in columns in the previous table). Again we can verify that the model performs quite well, except in the cases of small diesel-powered cars (PCDS) that are over-estimated by the model (+6% probability of being chosen) and of medium diesel-powered cars (PCDM) that are under-estimated by the model (-12% probability of being chosen). It is expectable that the share of PCDS increases in the near future since this vehicle type is in an early stage of diffusion. Therefore, we expect that our model will not introduce much bias in our forecasting analysis (except for PCDM vehicles).

As referred by Train (2003), one popular variable aggregation approach is sample enumeration, by which the choice probabilities of each decision maker in a sample are averaged over decision makers. A consistent estimate of the total proportion of decision makers of the population who choose alternative *i* is the weighted sum of the individual probabilities. In our case, since all individuals are considered similar (we recall that we could not include discriminatory variables for socio-economic attributes in the utility function) we calculated simply the average probability.

Aggregate probabilities $\bar{p}_i$ are calculated for each car type as follows:

$$\bar{p}_i = \frac{\sum_{n=1}^{N} p_{i,n}}{N} \quad \text{8-24}$$

, where $p_{i,n}$ is the individual probability of choosing alternative I by the decision maker n

N is the sample size (in our case N = 2,345 individuals)

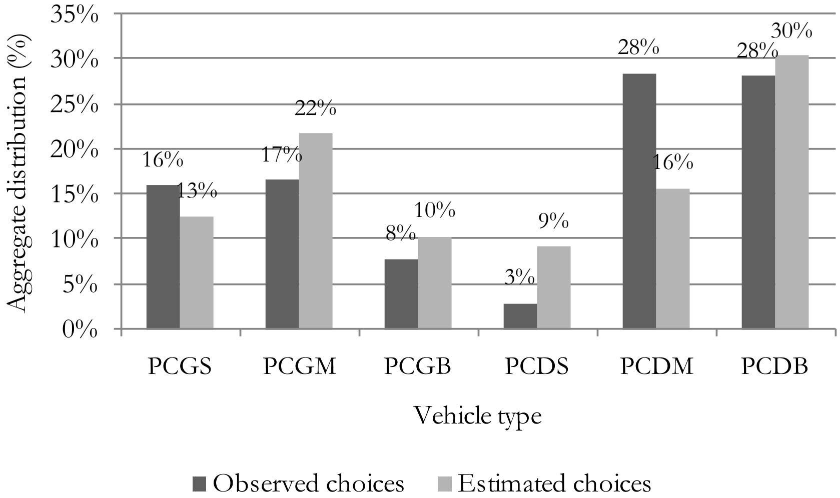

Figure 113. Aggregate car-choice distribution (observed and estimated) (source: author)

Intuitively, the age of a car is an important aspect when considering the alternative of buying a remarketed car. Hence, we compared the distribution of remarketed cars' age in our sample with the one estimated by our model, for each vehicle type and in aggregate terms. The following figure refers to the aggregate age distribution (age distributions per car type are presented in annex A.15, p.385).

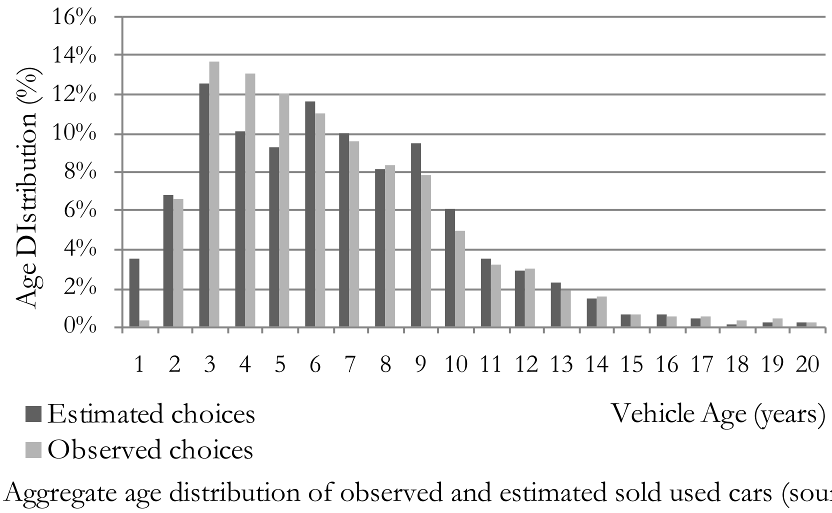

Figure 114. Aggregate age distribution of observed and estimated sold used cars (source: author)

The figure above suggests that, globally, the model reproduces well the sample's age distribution. However, Figure 148 (annex A.15, p. 385) suggests that the model chooses older vehicles in the case of bigger used cars. This bias will also be considered when analyzing our simulation results in Chapter 9. Finally, the results of choice probability are to be applied to universe of annual remarketed cars (RC_{Sales}) in Portugal (our case-study).

We will now explore the final parametric specifications of the selected NL model.

8.3.4 Parametric analysis

The analysis of our selected parameters provides important insights to the structure of demand of used cars in the Portuguese used car market. Table 43 presents the elasticity of demand with respect to car price, fuel costs and circulation taxes, for each vehicle type considered in our study. Table 44 presents the willingness-to-pay for younger cars. The formula of elasticity is $E_{z_{i,q,m}}^{P_{i,q}} = \frac{\delta P_{i,q}}{\delta z_{i,q,m}} \times \frac{z_{i,q,m}}{P_{i,q}}$ that calculates the elasticity of the probability of alternative i for decision maker q with respect to the marginal change in the m^{th} attribute of the i^{th} alternative ($z_{i,q,m}$). As advised by Hensher *et al.* (2005, p.385), we used the probability-weighted sample enumeration technique to calculate the aggregate elasticity: $E_{z_{j,q,m}}^{\bar{P}_i} = \left(\sum_{q=1}^{Q} \hat{P}_{i,q} . E_{z_{j,q,m}}^{P_{i,q}} \right) / \sum_{q=1}^{Q} \hat{P}_{i,q}$, where $\bar{P}$ is the aggregated probability and $\hat{P}$ is the estimated probability for the q^{th} decision maker.

Table 43. Vehicle elasticity with respect to the attributes: car price, fuel cost and circulation taxes (source: author)

	Car price elasticity	Annual Fuel Cost	Annual Circulation Taxes
PCGS	-1.173	-2.53	-0.147
PCGM	-1.146	-2.994	-0.218
PCGB	-2.396	-3.338	-0.621
PCDS	-3.206	-1.292	-0.075
PCDM	-7.547	-1.383	-0.141
PCDB	-3.378	-1.553	-0.174

Goldberg and Verboven (2001) estimated the new car demand elasticity with respect to price, for five EU countries (Belgium, France, Greece, Italy, and UK). The average elasticity found was ε = *-5*, meaning that for a 10% increase of the price of a new car, demand decreases 50%. The results presented by the authors are aggregate over all car types and, therefore, do not provide elasticity values for all car types considered. Since, our results were obtained for the used car market, we should be cautious when comparing our results to theirs. Still, we obtained elasticity values with the same order of magnitude (ranging from -7.547 to -1,146) although the elasticity of buying a used car is slightly lower, in average, ε = *-3.5*. One reason for such difference is that the range of used-car prices is lower than that for new cars (in absolute terms) and therefore we can argue that the corresponding elasticity is also naturally lower. In other words, relative increases of used-car prices (which are much lower in absolute terms) induce lower reductions of used-car demand than for new-cars, since the corresponding reduction in absolute terms is lower as well. However, in both cases, demand is quite elastic (|ε|>1) indicating that buyers are sensitive and shift between car types with smaller variations in price. We observe that in face of a variation in the price of gasoline-fuelled cars, demand is shifted in equal proportion to the other car types. Differently, if the price of diesel-fuelled cars increases, demand is shifted towards to the other diesel-cars, at to a much lower extent to gasoline-cars. Generically, the shift is higher towards diesel-powered vehicles. Within each fuel nest, changes are in proportion among alternatives. In fact, these conclusions are bound to the nested logit structure by which alternatives dispute proportionally its share with the remaining alternatives of the same nest, but any variation in the choice set of one nest implies an equal variation in all the alternatives of the other nests, although that variation can be different than that of the other nest. After comparing our elasticity results to the ones presented in the literature brings additional confidence to the consistency of our model.

Regarding the remaining elasticity calculations, we did not find any references in the literature comparable to our results. The demand of diesel-powered cars is more elastic with respect to fuel costs than gasoline-powered cars. Demand of remarketed cars with respect to fuel costs is elastic (|ε|>1) and elasticity is higher in the case of gasoline-powered vehicles, i.e. variation of fuel prices or fuel efficiency will be reflected in a shift of gasoline towards diesel-fuelled cars, confirming the tendency from previous observations. Additionally, elasticity of demand of smaller cars with respect to fuel costs is less elastic than for bigger cars (for both fuel types). The same analysis can be performed for the elasticity with respect to circulation taxes (which is not surprising since these two attributes are correlated, as mentioned previously). Still, the demand for used cars is inelastic ($|\varepsilon|<1$) with respect to circulation taxes. For example, 1% change in PCGS circulation taxes induces a 0.15% reduction in the probability of choosing PCGS vehicles. This confirms our perception from the used-car consumers' behavior regarding circulation taxes, in Portugal, i.e. they do not weight much the circulation taxes in their decision making process. This is probably due to the fact that these values are still low (comparatively with the investment and overall annual mobility budget). The situation is about to change since it is now mandatory to publish the car's fuel economy rates when advertising new cars and the automakers are also presenting the CO_2 emission factors. This also has an important policy implication. If the national authorities wish to influence used-car consumers through taxes, then the changes have to be significant. Otherwise, the impacts from their interventions will be low. The regulation that forces the automakers to present the fuel economy rates of the new cars should also be mandatory for used-car sellers although in this case a large share of trades is performed directly between individuals.

Table 44. Willingness-to-pay for a younger car (source: author)

Attribute	Coefficient	Unit
Age	-0.19714	1/years
Car price	-0.00013	1/€
WTP age	1,494	€/year

In Table 44, the calculation of the willingness-to-pay (WTP) for younger used cars (unit: *€/years*) corresponds to ratio between the age parameter (unit: $years^{-1}$) and the car price parameter (unit: $€^{-1}$). The WTP indicates that to buy a 1-year younger used car, consumers are willing to pay for an additional 1,500€. This corroborates with the fact that, according to our depreciation curves we presented (refer to section 5.2.1, p.151), the average annual depreciation of a 2000 midsize gasoline-fueled car is 1,900€, during its first eight years of use. We highlight that the value obtained is an "average" WTP for all vehicle types. In fact, we consider that it is too high for the smaller cars (i.e., PCGS and PCDS). We could not estimate WTP values for different car types, since our utility function does not include alternative-specific parameters.

8.4. Summary and conclusions

As pointed out before, the present part of the dissertation explores car organ transplant on a fleet basis. After presenting our model of the car fleet evolution in Chapter 7, the present chapter described the approach to characterize the technological structure of remarketed cars. As explained later in section 9.2.1 (p.259), we assumed in our research that customers who decide to buy new cars do not include remarketed cars or transplanted cars in their set of alternatives. As such, we modeled the discrete choice of remarketed cars only (as these obey to different purchasing factors compared to new car), in order to subsequently include the option of transplanted cars and analyze the potential diffusion of such technologies in the future.

We began by presenting the theoretical background of discrete choice modeling. Importantly, discrete choice modeling holds on the following basic criteria: the number of alternatives in the set is finite, the alternatives are mutually exclusive, and the set of alternatives is exhaustive (i.e., all possible alternatives are included). It is assumed that the choice is based on the utility of each alternative perceived by the consumer compared to all other options. As such, the probability of one customer choosing a particular car from the set of all possible makes, models and vintages is calculated by the utility of that car over the sum of utilities of all other alternatives. Perceived utility is calculated through the utility function that comprises a set of observables attributes, which due to data limitation included technical attributes only, i.e., we did not include socio-demographic attributes of the decision maker. Those attributes were: <u>age</u>, <u>car price</u>, <u>engine size</u>, total <u>fuel costs</u> (over one year), <u>circulation taxes</u>, and <u>number of models</u> available for each car type considered here.

In order to estimate the discrete choice models, we used revealed preferences (RP) emulated from the remarketed car sales database provided by Auto Basic Motor S.A. (2007) since we could not obtain the official statistics of traded used cars hold by the IRN (Instituto de Registos e Notariado). We could collect a data set with 11,768 valid entries of remarketed cars with the attributes presented in the previous paragraph plus horsepower and cumulative kilometrage (that were discarded in the calibration process since they were much correlated with other attributes like age, engine size and fuel costs). According to the classification of car types we used, 81% of remarketed cars are midsized (45%) or bigger (36%) and 60% of total cars are diesel-powered. The smallest share goes for small diesel-powered (3%) as these have been introduced in the new car retail market no sooner then 2000, in Portugal. The majority of remarketed cars are aged between 3 and 5 years (11% for gasoline and 29% for diesel). In the case of gasoline-powered cars, the distribution is quite uniform for cohorts over 5 years of age.

We estimated a nested logit with an acceptable goodness of fit, i.e. $\rho^2=0.3$. The iterative modeling process began with multinomial logits for which we tried different attribute combinations but could not guaranty the IIA assumption. In order to release the IIA assumption we modeled several configuration of nested logit and ended up with a final two-level tree structure. We did not include mixed logit modeling mainly because we could obtain satisfactory results with nested logit, but also because the base data for model estimation is an emulation of real data and, hence, there is some degree of uncertainty associated to it. For a matter of fact, the model we obtained did reproduce reasonably the observed structure of remarketed cars and suited well for the purpose of the present research, i.e. estimate the potential diffusion of car organ transplants.

The parametric analysis of our results indicates that elasticity of remarketed car demand (*-3.5*) with respect to price is lower than new cars (*-5* as estimated by Goldberg and Verboven, 2001). This result confirms that used-car buyers are less reactive to price changes than new cars buyers as new cars are pricier and any percent-variation is reflected in higher absolute price variation than cheaper remarketed-cars. However, in both cases, demand is quite elastic indicating that buyers are sensitive and shift between car types with smaller variations in price. In the case of the model we calibrate, car buyers tend to shift towards diesel-powered vehicles.

Demand of remarketed cars with respect to fuel costs is elastic ($|\varepsilon|>1$) and elasticity is higher in the case of gasoline-powered vehicles, i.e. variation of fuel prices or fuel efficiency will be reflected in a shift of gasoline towards diesel-fuelled cars, confirming the tendency from previous observations. Conversely, elasticity with respect to circulation taxes is rather low ($|\varepsilon|<1$), confirm our perception of the behavior of car owners in a general sense, regarding circulation taxes, in Portugal. In reality, circulation taxes are low comparatively to the investment and overall annual mobility budget. Importantly, these taxes won't be very effective if authorities want to influence the choice of remarketed cars. Either circulation taxes are reviewed or acquisition of remarketed cars should also be taxed. Finally, the regulation that forces automakers to present the fuel economy rates of the new cars should also be mandatory for used-car sellers although in this case a large share of trades is performed directly between individuals. Interestingly, our results also indicate that consumers are willing to pay for an additional 1,500€ to buy a 1-year younger used car. This corroborates with the fact that the average annual depreciation of a 2000 midsize gasoline-fueled car is 1,900€, during its first eight years of use. Besides the depreciation savings, car consumers also save operating costs (particularly, fuel costs over the lifecycle of the car) although to a much lesser extent (refer to Chapter 5 for a deeper discussion on car ownership lifecycle costs).

The next chapter, we present the methodology used to calculate energy and emissions from the entire fleet, considering all lifecycle stages. We present also the details for including the new transplanted alternatives and how we characterized the corresponding attributes required to run the nested logit model. Finally, we describe the results obtained for the estimation of the potential diffusion of transplanted cars, such as the corresponding impacts on the efficiency of the overall car fleet in terms of natural resources consumption (including raw energy), emissions and solid waste.

Chapter 9. Impact of transplant technologies on the car fleet

9.1. Introduction

This chapter presents our evaluation of the potential impacts of transplant technologies in the Portuguese car fleet, from 2007 to 2030. Impacts are analyzed in terms of the technological distribution of the car fleet (and related effects in terms of the quantity of scrapped cars and the impact on the amount of new cars sold, annually), energy and environmental burdens (including emissions, raw materials consumption and solid waste production).

We describe firstly the additional model specifications for transplanted alternatives in both the car fleet and the discrete choice models (section 9.2). Then, we present our estimates of the potential annual market shares of transplanted cars over time (section 9.3). In section 9.4, we describe how the diffusion of transplanted technologies might impact the technological turnover of the fleet over our period of analysis and we analyze the corresponding impacts on the overall energy consumption and air emissions. In this sense, we begin by characterizing the energy and environmental burdens for the baseline evolution of the car fleet (characterized in section 7.3.3, p.223). Then, we calculate the same energy and environmental burdens considering the diffusion of transplant technologies and compare this scenario with the baseline. Finally, we perform a sensitivity analysis to critical variables of our model (section 9.5) to assess the robustness of our results and give support to some policy implications presented later in the conclusions (section 9.6).

9.2. Additional model specifications for transplanted car alternatives

9.2.1 Discrete choice model

When assessing the potential diffusion of transplant technologies, we are analyzing the possibility of new entrants coupled with the possibility of innovative behavior from consumers, since this is a new alternative compared to the conventional new or remarketed-cars. As referred by Hensher *et al.* (2005), "innovation, whether from existing competitors or new entrants, suggests new attribute levels and possibly even new attributes being introduced to the market that may potentially impact upon choice behavior". An indicator deciding whether or not an alternative is new is to evaluate if the attribute profile (i.e., price, circulation costs, size, technology, etc.) differs significantly from that of an existing alternative, i.e., if the estimated levels of the potentially new alternative stretch outside the range observed in real markets for the existing alternatives.

When we presented the concept of organ transplant in cars in Chapter 3, we referred that similar approaches exist currently in the automotive aftermarket, for instance, car retrofitting (e.g., from gasoline to LPG powertrains) and car tuning. As such, we argued that the concept is not fully new although it involves smaller segments of the car aftermarket. Additionally, these approaches are not necessarily aiming to environmental improvements. On the contrary, they rather strive for fuel cost saving or horsepower increase, respectively. Our case is to upgrade the vehicle's powertrain, exhaust systems and other equipments for better energy and environmental performance, extending (potentially) this approach to a larger segment of the car market. As such, we considered the technological transplant of vehicles a new alternative in the remarketed car market choice set although the utility profile does not vary significantly from that observed for the conventional alternatives.

Concerning the possibility of innovative behavior from consumers that could hinder our modeling exercise, we argue that no radical changes in car consumer's attitudinal behavior should be expected. Although transplanted, the vehicle maintains its conventional look, it is operated like any other conventional car and servicing should not be much different for car owners than currently handled. Therefore, we assume that the perception of utility of transplanted cars can be captured with the same set of attributes and respective estimated parameters of remarketed-car discrete choice model, except possibly for some variable that would capture some initial resistance due to strangeness of the concept. In this sense, we considered the attribute "number of available makes and models" for each car type. The logic behind this attribute is that the more there are makes and models of the same car-type the more the consumers are acquainted to that car type and the corresponding attractiveness should become similar to other market competitors. This issue was explored before in section 8.3.2.

Therefore, we can argue that testing the potential diffusion of transplanted cars using the remarketed-car discrete choice model is acceptable, and to a large extent, adequate. However, conclusions and policy implications deriving from our modeling exercise will be made cautiously and always disclaiming this particular methodological assumption. We present hereafter the assumptions of the present analysis:

1. Transplanted vehicles compete with remarketed cars and choices are essentially influenced by the characteristics of cars[72], for instance, type of vehicle (e.g., fuel type and vehicle size), investment cost (used-car price and/or technological-transplant cost), age, operation costs, taxes, and the number of makes and models with transplanting kits available in the market.

2. If a vehicle is transplanted with a newer propulsion system, its performance in terms of energy consumption and emissions is that of a new system[73].

3. A used-car is transplantable once during its lifetime[74].

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[72] These characteristics are the attributes of the utility function that is calibrated for the discrete choice model (refer to forthcoming sections).
[73] This assumption might strongly condition the results of our exercise. However, there is no available data on the potential losses of efficiency by adapting a new propulsion system to an older model, compared to its performance in a new car. This is certainly an interesting topic for further research in cooperation with mechanical engineers.
[74] We recall that in Part B of this dissertation, we did not consider this limitation to car organ transplant. However, we decided conservatively to consider this limitation.

There is an underlying assumption striving from the 1st assumption: new-car buyers do not become *transplanters*. Alternatively, what we are assuming is that the attitude of potential transplanters is similar to the attitude of used-car buyers when facing a discrete choice. And, both are different from the attitude of a new car buyer. Indirectly, we are assuming that the consumer who wishes to buy a new car will value differently the criteria for decision-making (e.g., novelty/fashion[75], wear of the car/maintenance costs, etc.). In terms of discrete choice modeling, this attitudinal difference would be reflected both in the set of variables of the utility function and on the parameters of the variables. Moreover, the unobserved errors of each alternative would be influenced differently and, thus, the IID/IIA assumptions would have to be verified accordingly. Therefore, the alternative to buy a new car cannot be addressed with the model we calibrated. A different Logit model would have to be modeled. Still, we consider that our methodological approach is sufficient to demonstrate the potential pervasiveness of transplanted cars and make our case.

Furthermore this assumption has an important methodological implication. If the transplanted alternatives compete with remarketed cars, we have to estimate how many used-cars are remarketed every year. In this sense, we adopted a simple approximation of the reality by assuming the moving-average ratio of used-to-new cars ($r_{U:N}$), with a time window of the previous 5 years (refer to the next section for more details). Therefore, the cars that are potentially transplanted belong to this universe. By adopting this methodology, we make sure that transplanted vehicles do not compete directly within the new car market (our assumption). As we will analyze in the forthcoming sections, the diffusion of transplanted cars in the used-car market affects indirectly the quantity of new cars sold yearly.

Regarding our second assumption, we present the following example to make it clearer. If a 1.4 liter gasoline car from 1990 (<EURO I) is transplanted with a propulsion system of 2005, the vehicle is assumed to be a car from 2005 that was homologated according to the enforceable EURO standards at that time, i.e. EURO IV. For simulation purposes of the car fleet, we consider that transplanting a car aged k years, in calendar year t, corresponds to abating that car that is substituted by its transplanted version. This transplanted version becomes aged 0 years (i.e., it becomes new with respect to its powertrain, exhaust control systems and other energy-intensive equipments) and therefore it is reclassified into the EURO standard of year t. Although we determine that it corresponds to a new car in terms of energy consumption and emissions, for discrete choice modeling purposes the car maintains its age and residual price. We opted to do so because the remaining components of the car are wear out when the vehicle is transplanted. The car consumer will certainly consider these aspects when making his choice. The following figure illustrates this assumption where used-cars that are transplanted are added to the bar of new cars. Besides the benefits of having a cleaner fleet, our assumption potentially

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[75] These qualitative attributes dealing with attitudes and perceptions (e.g., fashion, comfort, safety, etc.) are difficult to capture through simpler Logit models. However, more advanced modeling alternatives, such as latent variable logit models, have been developed to overcome such difficulties with success (Ben-Akiva et al., 1999). This modeling approach is challenging for further development after the present work. However, it requires Stated Preference interviews to be made for its application, which is out of the scope of the present research.

reduces the quantity of material consumption and solid waste generation, since the demand for new cars is reduced.

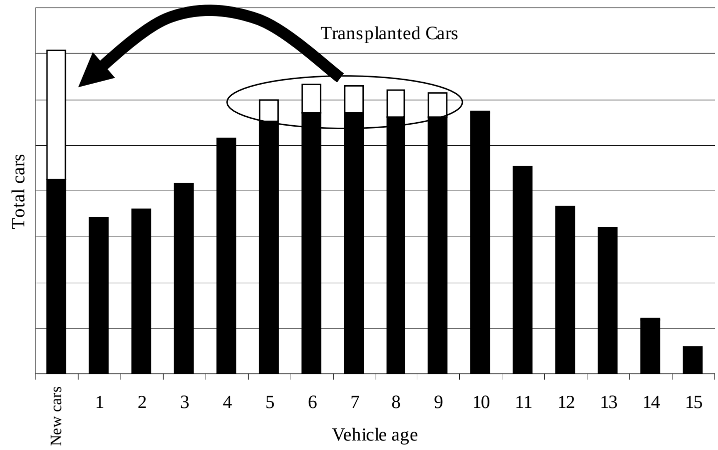


Figure 115. Illustration of the impact of the technological-transplant concept in the car fleet age structure (source: author)

To estimate the probability of transplanted used cars being chosen we add new alternatives to the two-level nested structure presented in Figure 111a (p.249). The structure presented then is transformed into the following one.

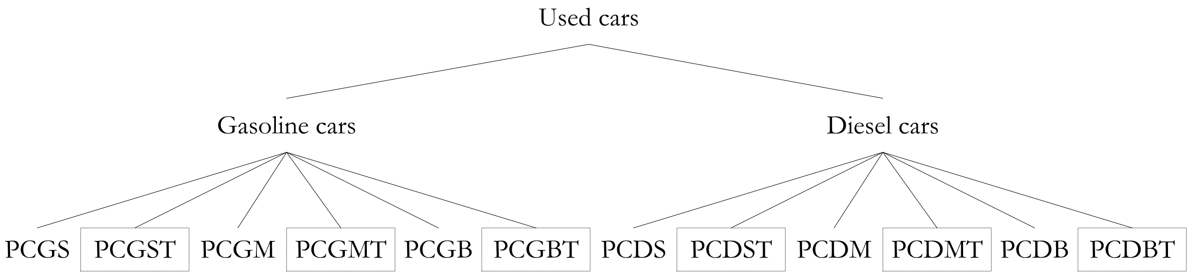


Figure 116. 2-level NL structure including the new transplanted alternatives (PC_ _T) (source: author)

We note that each dotted-box corresponds to a group of 4 transplanted alternatives. The alternative 'T1' belongs to the same age cohort and the others belong to different age cohorts: [0-4] for T2, [5-8] for T3 and [>9] for T4, where ages are determined randomly within each interval (refer to p.266 for details on each of these cohorts). In the first case, the residual value of the used-car is equal to the conventional car whereas, in the others, vehicles have different residual values since we determine that they have different ages.

Firstly, it is implicit in this tree structure that each transplanted alternative will dispute directly its share with the remaining alternatives of the same fuel nest, but any variation in the choice set of one nest implies an equal variation in all the alternatives of the other nest. We consider this conceptually acceptable when addressing our problem. Secondly, when using the same utility function to assess the diffusion of new alternatives, we accept that consumers of remarketed-cars will face the transplanted-alternatives with the same rationale. As discussed in section 8.2, we are assuming that the unobserved attributes equally influence the decision of choosing a transplanted or a conventional alternative. This assumption might be disputable.

The next step in using the remarketed car discrete choice model is to determine the attribute levels of the utility function, in order to re-compute the choice probability of each option (including conventional and transplanted alternatives). The attribute engine size was considered to keep the values of conventional used cars. Fuel costs are lower because we assume that transplanted cars are equivalent to new cars in terms of fuel economy and emission factors (Assumption 2, section 9.2.1, p.259). Therefore, CO_2 emissions are also lower (since they vary linearly with the fuel economy of cars), which implies that the attribute circulation taxes is also recalculated in that these depend on the vehicle's carbon intensity, also. The levels of the previous attributes were calculated with the equations presented in section 8.3.2 (p.246).

The attribute car price of transplanted cars includes the costs involved in organ transplant that are added the residual value of the used car. The transplant base costs are presented in the Table 45 and include all the costs involved in the manufacturing and mounting of all the parts and components used in the transplanting process. The estimation procedure of these costs is described in detail in Chapter 5 (section 5.3, p.161). We recall that used-car residual values are estimated with the p.d.f. that we calibrated using the AB motors database (refer to the Table 69 in annex A.10, p.379).

Table 45. Organ transplant costs (source: author)

	PCGS	PCGM	PCGB	PCDS	PCDM	PCDB
Transplant costs (€)	4,300	4,400	4,650	4,350	4,450	4,700

Although the transplanted cars are considered new in terms of their energy and air emission performances, we did not assume the same for the attribute age (i.e., age = 0 years), as we mentioned earlier. Accordingly, we consider that there are a number of additional ageing aspects that influence the decision maker's choice in the sense that they have a negative impact on the vehicle's utility, which would be hidden if age was reset to 0 years. The remaining car parts are not renewed because they are still in good condition, still they are not new; the design of the car might become old-fashioned; the car body might get worn out; among other ageing aspects.

Finally, the attribute "number of car makes and models" (NBRMODS) was included to capture the resistance of the consumer to novelty, or degree of innovativeness as referred by Rogers (2003), when facing each alternative. Recalling the logic behind this attribute, NBRMODS increases when the corresponding car type (and technological characteristics) gets more diffused and is measured by counting the number of makes and models that are available for that specific car type. Hence, the consumer's resistance to choose this alternative is expected to decrease as NBRMODS increases. The difficulty here is to determine the levels of the attribute for a new alternative. We know that it is expected to evolve over time following an s-shaped curve like any common process of diffusion of innovations (Rogers, 2003). Although innovativeness is a continuous variable, partitioning the corresponding curve into classes aids to the understanding of human behavior. As referred in section 2.6.3 (p.48), Rogers (2003) proposed a generalization of the diffusion process based on the innovativeness of typical groups of individuals: innovators, early adopters, early majority, late majority and laggards.

In our case, the question is what is the shape of such curves for transplanting kits? Although they constitute an innovation (as such), the concept is not entirely new for the automotive industry and some segments of car consumers (as discussed in chapter 2 and in the present chapter). Therefore it might not have the same degree of innovativeness as completely new (and barely available) alternatives like, for instance, fuel-cell hydrogen-powered vehicles.

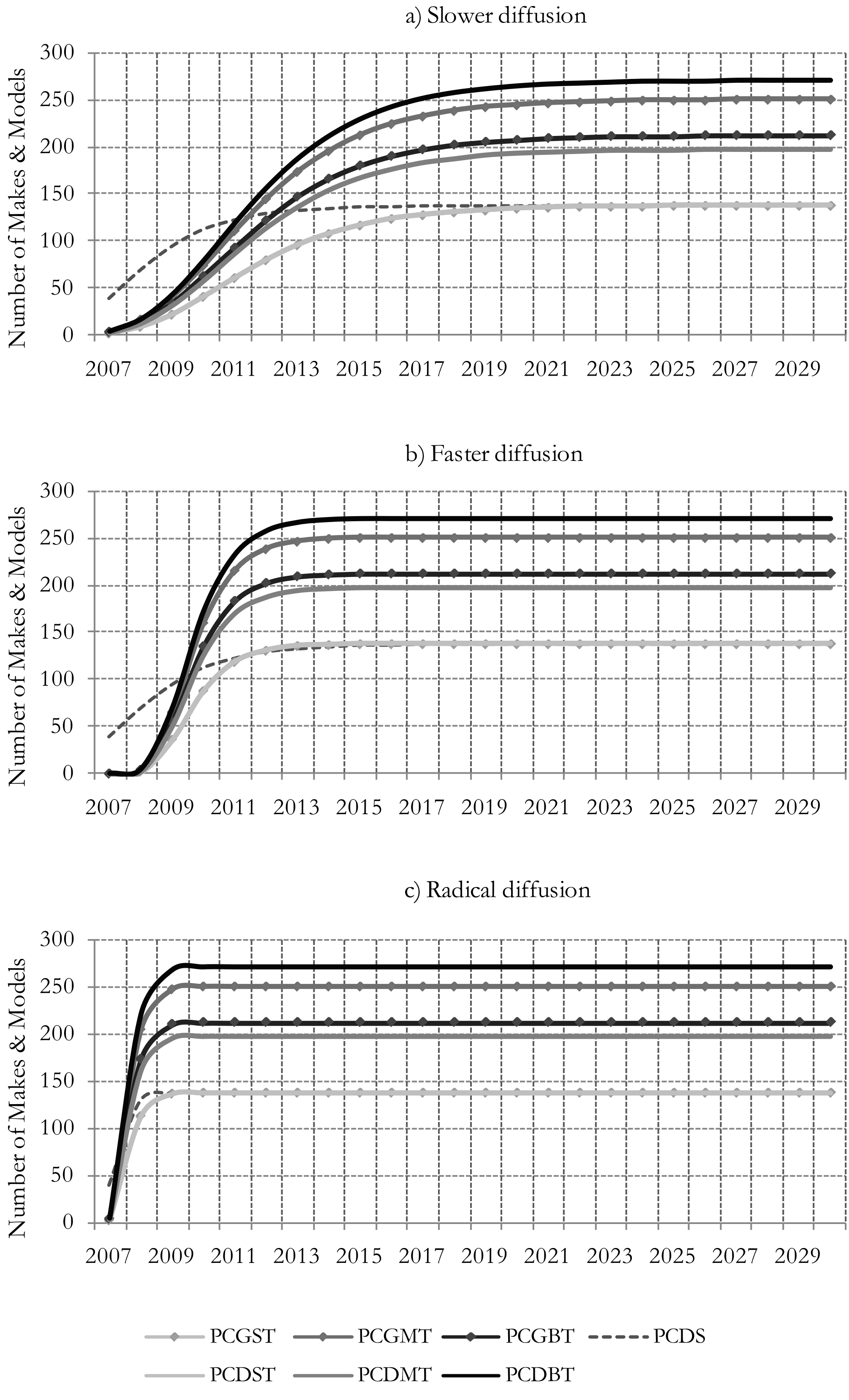


Figure 117. Diffusion curves of transplanting kits (source: author)

Not having better ways of calibrating the diffusion pattern of transplanting kits, we opted to use one of three scenarios. The other two will be used to perform a sensitivity analysis in section 9.5:

1. a scenario of slow diffusion of transplant kits, by which these would be available for 100% of makes and models by 2025 (Figure 117a);

2. a scenario of faster diffusion of transplant kits, by which these would be available for 100% of makes and models by 2015 (Figure 117b); and

3. a scenario of radical diffusion of transplant kits, by which these would be available for 100% of makes and models in 2009 (Figure 117c).

All curves ensure a full diffusion of transplanting kits over a 20-years time period. As a reference of diffusion time scales of technologies in the US automotive industry (Jutila and Jutila, 1986 cited in Grübler, 1990), we may refer the use of air conditioning in cars that reached its full diffusion after 30 years. Conversely, electronic ignition experienced a faster diffusion reaching a full-market share after 10 years (refer to Chapter 2). We consider that the time-scales adopted for our simulation purposes are reasonable. The results presented from now on refer to the faster pattern of diffusion of transplant technologies (our base case).

As referred previously, small diesel-powered cars (PCDS) are not as widely diffused as small gasoline-powered cars (PCGS). This is reflected in the smaller number of makes and models available for the former. According to our sample, there are 40 models for the PCDS car type whereas for the PCGS we counted 138. For simulation purposes, we assumed that PCDS will reach maturity by 2015, i.e. there will be 138 models available also (solid line in Figure 117, above). Again, this assumption is open to debate, but we consider it acceptable for our simulation purposes and important since the attribute NBRMODS influences positively the attractiveness of this car type (i.e., PCDS).

Although other attributes evolve over time (e.g., car and fuel prices), for simplification purposes, we assumed that the evolution index would remain unchanged. For example, as shown in Figure 105 (p.241), diesel and gasoline prices varied in the same proportion over the last decades and we assumed that they will follow the same pattern in the forthcoming years.

In the end, the adapted discrete choice model is used to estimate the share of potential "*transplanters*" among the existing used-cars (whether they are transplanted by the vehicle owner or they are bought used transplanted).

Going back to Eq.8-20 (p.238), the probability of a transplanted car of type i, with age k, in year t, being chosen over the remaining used and transplanted cars is calculated using the used car discrete choice formulation. As an example, we present the formula used to estimate the marginal probability of a PCGST1 (i.e., of the same age of the conventional remarketed car) being chosen:

$$P_{PCGST1} = \left[\frac{e^{V_{PCGST1}}}{\left(e^{V_{PCGS}} + e^{V_{PCGST1,...,4}} + e^{V_{PCGM}} + e^{V_{PCGMT1,...,4}} + e^{V_{PCGB}} + e^{V_{PCGBT1,...,4}}\right)} \right] \times \left[\frac{e^{V_G}}{\left(e^{V_G} + e^{V_D}\right)} \right] \qquad 9\text{-}1$$

where we include all transplanted and conventional used-cars in the model denominator (transplanted and conventional used cars compete under the same market circumstances).

We note that we consider four alternatives of transplanted cars that are symbolically expressed as (*PC_ _T1,…,4*) in the formula. These alternatives are different in that cars are transplanted with different ages:

- The transplanted car (*T1*) has the same transplant age as the used-car alternative and is different than the remaining transplanted cars. Here the difference lies in the transplanting costs, since the residual price of the used-cars is the same. In this case, transplanting our car or buying a remarketed- transplanted car is equal for modeling purposes.
- The transplanted car (*T2*) has a different age than the remaining transplanted cars and the remarketed-car, and the age is determined randomly between 1 and 4 years (inclusive). Here, the transplanted car has a different residual price than the used-car, besides the transplanting costs.
- Similarly to the previous case, the age of transplanted car (*T3*) is determined randomly between 5 and 8 years (inclusive).
- Again, the transplanted car (*T4*) is determined randomly between 9 and 30 years (inclusive).

This issue is relevant since the final transplanted car price is obtained by summing its residual value with the transplanting costs. Obviously, older vehicles are more competitive with respect to the investment cost. On the other hand, since they are older, the remaining car parts and components are more worn out and the consumer will consider this in her decision about the purchase or the transplanting operation. These trade-offs are captured by our modeling approach.

We describe in the next section the complementary methodological procedure we used to incorporate the transplanted car alternatives in the choice set, at the car fleet level.

9.2.2 Car fleet model

The diagram next page illustrates our methodological approach to estimate the potential amount of transplanted cars in year *t*. The forthcoming paragraphs present the mathematical formulation sustaining this methodology.

Eq. 7-6 (p.210) can be replaced by the following expression to incorporate used and transplanted cars in the simulation of the car fleet's turnover:

$$C_i(t) = UC_i(t) - ST_i(t) + N_i(t) + T_i(t) - T'_i(t) \qquad 9\text{-}2$$

where

$UC_i(t)$ are used cars in year t and is equal to $UC_i(t) = C_i(t-1) - S_i(t)$.

$T_i(t)$ $(=T'_i(t))$ is the number of transplanted cars with their technological components equivalent to a car of type i and age $k=0$.

$T'_i(t)$ is the equivalent numbers of used cars of type i that were transplanted in year t and are discounted from the total stock. Ultimately, transplanted cars correspond to used-cars that are transformed. Therefore, the total stock of used-cars does not vary because they are transplanted, but because their lifetime increases (according to our assumptions explained hereafter). This is reflected in the following years after the transplant is performed and not during the same year t.

$ST_i(t)$ is the numbers of transplanted cars of type i that are retired, in year t. Their expected lifetime is estimated differently than conventional vehicles, as explained later in this section.

By determining the technological composition of the new, retired and transplanted cars for each year, we can simulate the technological turnover of the total car fleet, considering the new alternative transplanted cars.

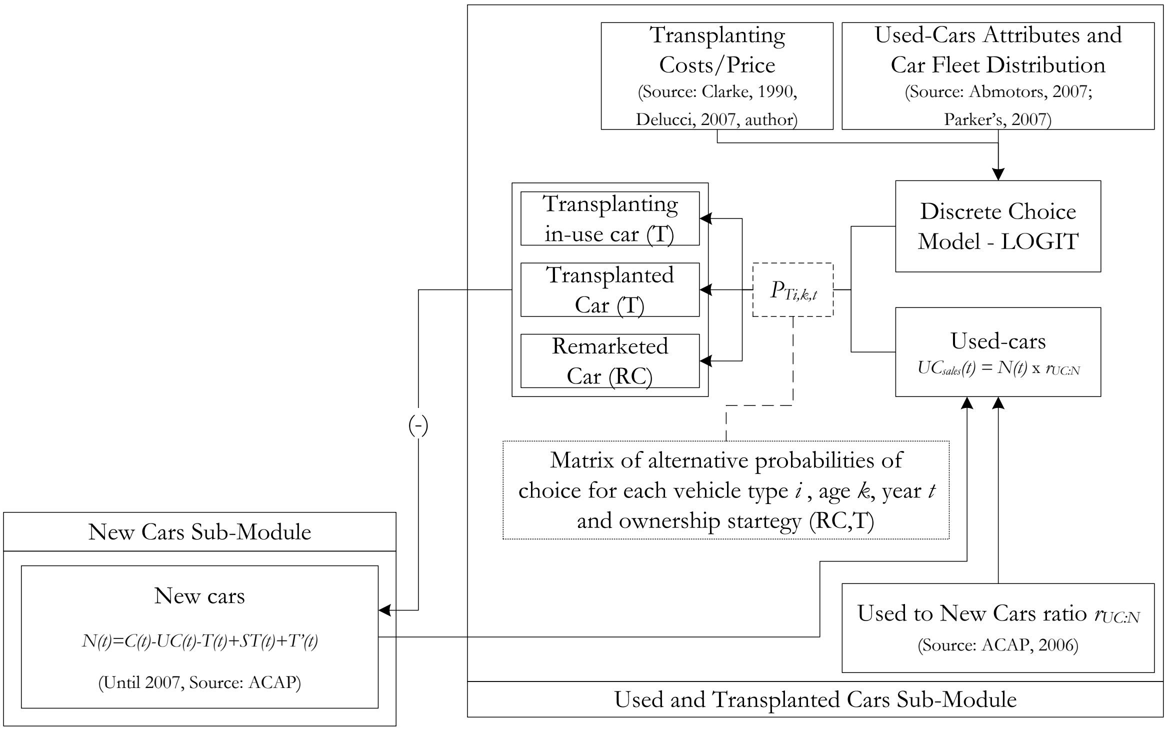


Figure 118. Methodology to estimate the potential number of transplanted cars (source: author)

As referred in section 8.3.3, the technological distribution of remarketed-cars we estimate is to be applied to the total universe of annual remarketed-cars (RC_{Sales}) in Portugal. We estimate the universe of remarketed vehicles, in year t, by assuming the moving average of the ratio of used-to-new car sales ($r_{U:N}$), during the previous 5 years. According to data provided by the Portuguese National authorities (DGV, 2006) and ACAP (2007), the $r_{U:N}$ has evolved over time, but tends to stabilize around 2.5 remarketed-cars for one new car sold, every year (see Figure

119). In our simulation, we will use this figure to estimate the diffusion of transplanted technologies.

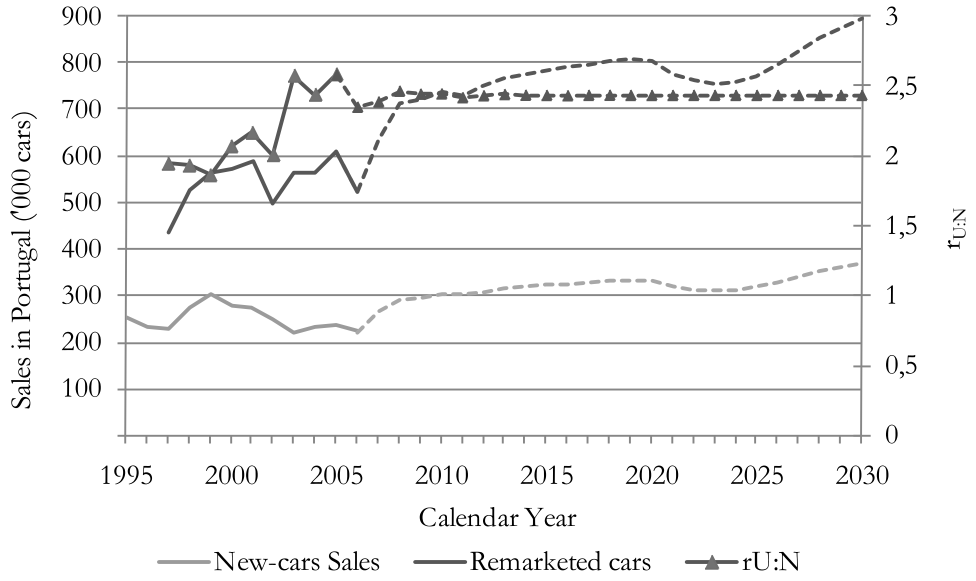


Figure 119. Ratio between used and new cars traded in Portugal, between 1997 and 2030 (source: author)

Therefore, the number of transplanted cars of type *i*, transplant age k_t, in year *t*, is calculated with the following formula:

$$T_{i,k,t} = P_{T_{i,k,t}} \times N(t) \times \frac{\sum_{m=1}^{5} r_{U:N}(t-m)}{5} = P_{T_{i,k,t}} \times RC_{sales}(t) \qquad 9\text{-}3$$

And the technological matrix of transplanted vehicles in some year *t* is calculated with the following expression:

$$\begin{bmatrix} t_{1PCGS} & t_{1PCGM} & t_{1PCGB} & t_{1PCDS} & t_{1PCDM} & t_{1PCDB} \\ t_{2PCGS} & t_{2PCGS} & t_{2PCGS} & t_{2PCDS} & t_{2PCDM} & t_{2PCDB} \\ t_{3PCGS} & t_{3PCGM} & t_{3PCGB} & t_{3PCDS} & t_{3PCDM} & t_{3PCDB} \\ t_{4PCGS} & t_{4PCGM} & t_{4PCGB} & t_{4PCDS} & t_{4PCDM} & t_{4PCDB} \end{bmatrix}. = RC_{Sales}(t) \times \begin{bmatrix} p_{PCGST1} & p_{PCGMT1} & p_{PCGBT1} & p_{PCDST1} & p_{PCDMT1} & p_{PCDBT1} \\ p_{PCGST2} & p_{PCGMT2} & p_{PCGBT2} & p_{PCDST2} & p_{PCDMT2} & p_{PCDBT2} \\ p_{PCGST3} & p_{PCGMT3} & p_{PCGBT3} & p_{PCDST3} & p_{PCDMT3} & p_{PCDBT3} \\ p_{PCGST4} & p_{PCGMT4} & p_{PCGBT4} & p_{PCDST4} & p_{PCDMT4} & p_{PCDBT4} \end{bmatrix}. \qquad 9\text{-}4$$

where

$t_{k,i}$ is the number of transplanted cars of type i at age k, where k belongs to age cohorts 1, 2, 3 and 4,

$p_{k,i}$ is the fraction of car type *i* with age *k* that is calculated using Eq.9-1, and

$RC_{sales}(t)$ are all used cars traded in year *t*, calculated with Eq. 9-3.

We referred previously that it is assumed here that transplanted cars last longer than conventional cars. We recall the function we used to calculate the survival probability of conventional cars, in section 7.2.3 (Eq.7-16, p.213): $s_{i,k}(t) = c_{i,k-1}(t-1) \times \left\{ 1 - e^{\left[-\left(\frac{k+\lambda}{\beta} \right)^{\lambda} \right]} \right\}$. In section 5.3 (p.161), we considered that several components and car parts would probably have to be substituted apart from the components strictly related to the propulsion system (e.g., air condition and exhaust systems), when we estimated the potential costs of organ transplants in cars. However, the car (as a whole) remains a used car and the non-transplanted parts of the vehicle are originals. These car parts have their own typical lifetime that is usually greater than the car's lifetime (as a whole). Therefore, it is expectable that the lifetime of a car is extended a few years after being transplanted, although it wouldn't be reasonable to consider that it (its age) would be reset as it was new. This is why we define a new survival curve for the transplanted-cars.

For simulation purposes, we consider that the maximum lifetime of a conventional car is 30 years. In the case of transplanted cars, we extended this maximum to 35 years. For example, if the used-car is transplanted after 10 years, we consider that its maximum surviving age is 25 years, after transplant. Or, if it is transplanted at the age of 16, it will last another 19 years at the most. Since the lifetime extension is arbitrary, we will test the impact of different values for sensitivity analysis. The mathematical formulation of scrapped transplanted-cars ($st_{i,k,kt}$) is:

$$st_{i,k,k_t}(t) = c_{i,k-1}(t-1) \times \left\{ 1 - \left(e^{\left[-\left(\frac{k_t + \lambda_i}{\beta_i} \right)^{\lambda_i} \right]} e^{\left[-\left(\frac{k - k_t + \lambda_i}{\beta t_i} \right)^{\lambda_i} \right]} \right) \right\} \qquad 9\text{-}5$$

for $k_t > k$, with $\beta t_{i,kt} = \beta_i - k_t + w$.

where k is the age of the used-car, k_t is the age after transplanting, β_i, βt_i (scale), and λ_i (shape) are parameters of the modified Weibull function, and w is a calibration constant (where $w = 5$ that affects the scale parameter of the scrappage curve of the transplanted vehicles).

The probability of a transplanted car being scrapped is conditional to the probability of a used-car being retired after having survived until the transplanting age k_t. Intuitively, we would say that an older vehicle that is transplanted will potentially survive longer, but the average lifetime is extended to a lesser extent. The following figure illustrates the scrappage curves for three situations: no transplant, transplant at the age of 10 and transplant at the age of 15.

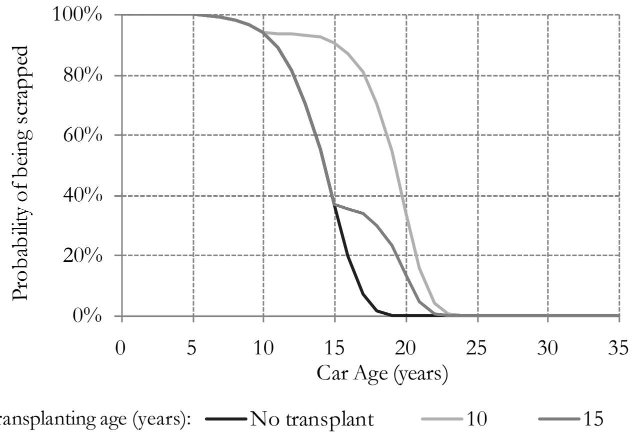


Figure 120. Scrappage curves for three vehicles-types: normal vehicle (no transplant), transplanted at the age of 10 and 15 years (source: author)

The previous figure shows that, in average, the probability of a used car being retired is postponed (5 years in the case of a transplant after 10 years car and 2 years in the case of a 15 years transplant) and that the cumulative amount of cars that survive increases accordingly. This has another consequence on the technological turnover dynamics, apart from extending the transplanted cars lifetime comparatively to its conventional counterpart: the number of used-cars across the overall fleet (conventional and transplanted) increases comparatively to the scenario where there are no transplanted alternatives. Recalling the Eq. 7-17 (p.215), we can say that in the "Baseline" scenario (without transplanted cars) new cars are estimated with the following equation: $N(t)=C(t)-UC(t)$ where $C(t)$ is the total stock, $UC(t)$ $[=C(t-1)-S(t)]$ are the used cars and $S(t)$ are the scrapped cars. In the "Transplant" scenario (with conventional and transplanted used cars), new cars are estimated as follows: $N^*(t)=C(t)-UC^*(t)$, where $UC^*(t)=C(t-1)-S^*(t)-ST(t)+T(t)-T'(t)$ and ST(t) are the scrapped vehicles that were transplanted and T(t) the transplanted vehicles. The mark (*) is used here to differentiate the used or scrapped cars in the "Transplant" scenario from those in the "Baseline" scenario, since they are different. Since $T(t) = T'(t)$ (refer to Eq. 9-2, above), we can deduct the following expression from the two equations:

$$N(t)-N^*(t)= [C(t)-UC(t)]-[C(t)-UC^*(t)]=UC^*(t)-UC(t) \quad \text{, which can be expanded}$$

to

$$\begin{aligned} &= [C(t-1)-S^*(t)-ST(t)+T(t)-T'(t)]-[C(t-1)-S(t)] \quad \text{, or} \\ &= S(t)-(S^*(t)+ST(t)-T(t)+T'(t)) \\ &= S(t)-[S^*(t)+ST(t)] \quad \text{, since } T(t)=T'(t). \end{aligned} \qquad 9\text{-}6$$

Assuming that $S(t)-[S^*(t)+ST(t)]=a$, we can draw three conclusions[76] from Eq. 9-6:

[76] Note: We assume also that the total stock of vehicles *(C)* remains constant in both scenarios and for year *t* and *t-1*.

- If $a=0$, then $N(t)=N^*(t)$ and the existence of transplanted alternatives does not influence the demand for new cars.
- If $a>0$, then $N(t)>N^*(t)$ since $N(t)=N^*(t)+a$. Here, by providing transplanted alternatives to conventional used-cars, there is a reduction of new cars sold in year t, since the total stock remains equal in both scenarios. On the one hand, this has a positive environmental impact since there would be a reduction of natural resources consumption (by reducing the production of new cars), besides the reduction of energy consumption and emissions during the operation phase (since transplanted cars are expected to be more efficient than their conventional counterparts). On the other hand, this might have a negative economic impact on the automotive industry since the demand for new cars decreases, although there would be an increase of the production of car parts and components (for transplanting purposes). We will analyze both aspects later.
- If $a<0$, then $N(t)<N^*(t)$ since $N(t)=N^*(t)+a$. However, this does not occur since we assumed that transplanted cars last longer than conventional cars.

Finally, we propose a general reformulation of Eq. 9-2 (p.266) with a detailed mathematical specification of all variables needed:

$$\begin{cases} C_i(t,k)=UC_i(t,k)+N_i(t,k=0)+T_i(t,k)-T'_i(t,k)-ST_i(t,k) \\ \textit{where,} \\ N_i(t,k=0)=p_{N_{i,k,t}}\times N(t,k=0) \\ UC_i(t,k)=Ci(t-1,k)-S_i(t,k-1), \textit{with } S_i(t,k)=\sum_{k=0}^{30} C_i(t-1,k-1)\times\left\{1-e^{\left[-\left(\frac{k+b_i}{T_i}\right)^{b_i}\right]}\right\} \\ ST_{i,k,k_t}(t,k,k_t)=\sum_{k=0}^{30} C_i(t-1,k-1)\times\left\{1-\left(e^{\left[-\left(\frac{k+b_i}{T_i}\right)^{b_i}\right]}e^{\left[-\left(\frac{k+b_{i,k_t}}{T_i}\right)^{b_{i,k_t}}\right]}\right)\right\}, \textit{for } k\geq k_t, \textit{ with } b_{i,k_t}=\frac{T_i+5-k_t}{c} \\ T_i(t,k)=\sum_{k=1}^{30} p_{T_{i,k,t}}\times RC_{sales}(t), \textit{if }(\textit{and only if}), T_i(t,k)\leq UC_i(t,k), \textit{else } T_i(t,k)=UC_i(t,k) \\ RC_{Sales}(t)=N(t)\times\frac{\sum_{m=1}^{5} r_{U:N}(t-m)}{5} \\ T'_i(t,k)=T'_i(t,k) \end{cases} \quad 9\text{-}7$$

where $p_{Ni,k,t}$ (Eq.8-20) and $p_{Ti,k,t}$ (Eq.9-1) are the fractions of new and transplanted vehicles (respectively) of type i, age k[77], that use the standard technology of year t (in short, the technological distribution of new and used-cars).

Interestingly, we note that although $T_i(t)$ and $T'_i(t)$ are equal, we made the distinction because all transplanted cars $T_i(t)$ are considered new for the purpose of energy consumption and emissions estimation and for that purpose $k=0$. Finally, we refer that our model imposes our third assumption referred in the beginning of this section, where we said that a car is transplantable only once during its lifetime. Furthermore, the model restricts the number of

[77] Transplanted in age k, in the case of $P_{Ti,k,t}$.

transplanted cars to those available in the same car category, thus avoiding illogical results, such as an ever-increasing number of used-cars in the fleet (4th equation in the set presented here above).

We present in the next section the results we obtained with the application of the previous methodology to the Portuguese car fleet.

9.3. Diffusion of transplant technologies in the Portuguese car fleet

9.3.1 Estimates of future market share of transplanted cars

After caculating the attributes of transplanted cars, we could estimate the probability of choosing each alternative of the choice set. The following figure presents the shares of conventional and transplanted remarketed-cars in a scenario of full availability of transplanting services for all makes and models, in 2030. These results were obtained by recalculating the aggregate choice probabilities for each decision-maker after including the new set of transplanted alternatives in the choice set. The aggregation procedure was the same as the one used in section 8.3.2 (refer to Eq. 8-24, p.254). The share of each transplanted car type includes all age cohorts mentioned above.

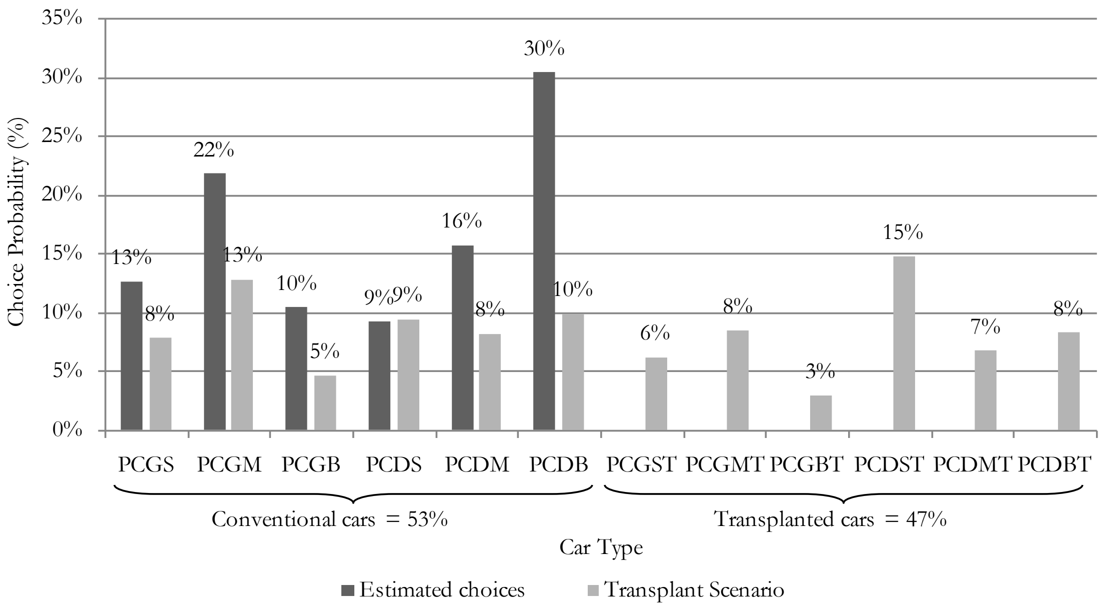


Figure 121. Share of conventional and transplanted used-cars (includes transplant-base costs) (source: author)

A priori, we could say that, under the assumptions presented before, the potential diffusion rate of the transplanted technologies is approximately 47%, every year, i.e. half of the consumers of remarketed cars would prefer to buy transplanted cars (2%, 5% and 8% for used cars aged 1 to 4, 5 to 8 or more than 9 years, respectively – *not shown in the graph*) or to transplant their own cars (32% – *not shown in the graph*), every year. In this case, gasoline-powered cars would lose 2% of their market share in favor of diesel-powered cars when comparing the baseline and the transplant scenarios. Thus, there would be 26% of conventional gasoline-powered cars and 27%

of diesel-powered vehicles, while 17% of transplanted vehicles would be gasoline-fuelled against 30% for diesel.

In short, it seems there would be a shift from gasoline to diesel-powered vehicles, in general terms, while more diesel-fuelled cars would be transplanted. This is certainly due to the more attractive options of diesel cars that would be transplanted with more efficient powertrains (plus new environmental control equipment) and, consequently, would have lower annual fuel costs. The bigger reductions in the fuel costs and circulation taxes would compensate the increase of capital costs of diesel-fuelled vehicles (car price plus transplant costs) to a larger extent than for gasoline-fuelled cars. Within the diesel-powered fleet, older and midsize or smaller cars are preferable for transplanting than larger and younger vehicles. Regarding gasoline-powered cars, smaller and midsize vehicles make a larger share of the transplanted cars than bigger vehicles, since they take up a larger share of the market and are generically cheaper. In these cases, the gains of fuel efficiency and CO_2 emissions compensate more the increase of capital costs than medium and bigger cars. Again, the balance between the reductions in the fuel costs together with circulation taxes, and the increase of capital costs of larger vehicles (car price plus transplant costs), is larger (and positive) for smaller and midsize gasoline-powered cars than for bigger cars.

Analyzing now these results from an economic point of view, these market shares would occur only if any supplier of transplanting services was willing to perform such operations at transplant prices equal to the base transplant costs (as estimated in the previous chapter). The base cost for organ transplant is how much the transplanter pays for the service. As mentioned before, this cost includes purchase of materials and labor costs and are called marginal (or variable) costs, in economic terms. In addition, we included here the production overheads as suggested in Delucchi's cost breakdown methodology (Delucchi *et al.*, 2000). Overheads include rent, salaries, among others. The difference between customer price and the business's total cost is equal to the Net Benefit (what the transplanter earns at the end of the day that indicates the value added from his work). If the sales revenues are lower than all production costs, then transplanters would obviously lose money.

Complementarily, car organ transplant only takes place if consumers are willing to pay for the market price offered or if they get their value for money. In economics, value can be defined in simple terms as how much a good or a service are worth to the consumer (refer, for example, to Samuelson *et al.*, 1992). Each consumer will consider transplanting his car to be worth a different value depending on how much they desire it, the necessity of this option (when compared to other options, for example, buying a remarketed-car), and the amount of money the customer has to spend. The value to the customer may be above or below the price set for the transplanted alternative. If the price is below the value, then the consumer will consider that option. If the price is higher than the value, he will not consider it.

This said, we need the demand curve of each transplanted alternative (which varies with the car type), and a starting point for organ transplant price, to estimate what would be the profit-maximization price for transplanters. This profit-maximizing price is calculated by multiplying the profit per transplant by the quantity of transplanted cars (which we express in relative terms, as a percent-market share). In this sense, we calculated the probability-weighted demand curve of each vehicle type using the above approach and we estimated what would be the profit-maximizing organ transplant price for transplanters, considering overall profits.

We calculated the choice probability of each alternative for different transplant base costs, ranging from 0€ to 50,000€. Thereafter, these probabilities were aggregated ($\overline{P}$) and the total-profit curve (see Figure 124) was obtained for each vehicle type by plotting the potential transplant price (*TP*) on the *x-axis* and the corresponding potential revenues for the set of transplanters on the *y-axis*, where (*Revenues* = $\overline{P}$ × *TP*). The following figure presents the aggregate probability-weighted demand curve (for all transplanted vehicles).

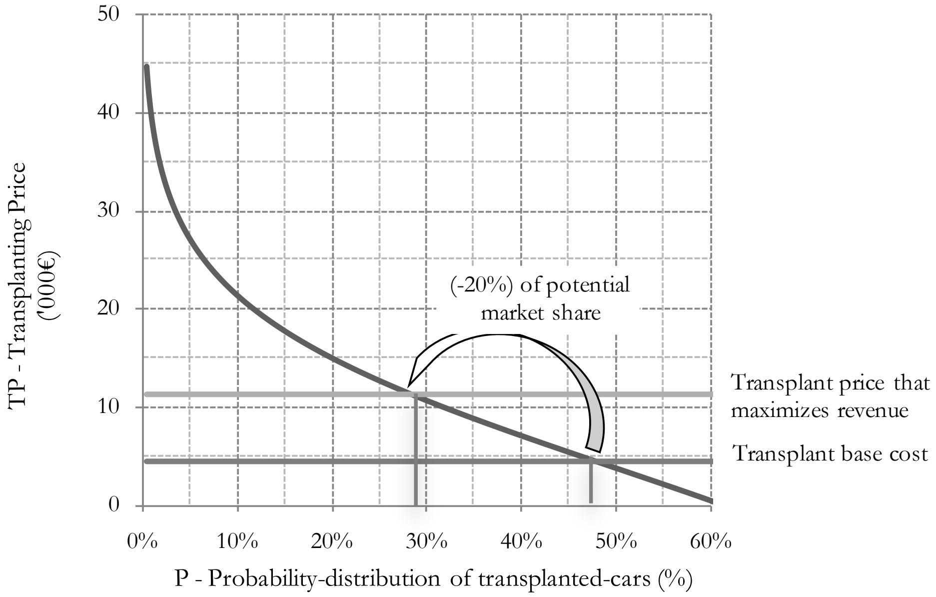


Figure 122. Probability-weighted demand curve of transplanted cars (source: author)

The previous figure illustrates the shift from the average transplant base cost (~4,400€/vehicle) to the average transplant price (~11,000€/vehicle) that would maximize the transplant suppliers' benefits. Under the assumptions used here, this shift would induce a reduction of approximately 20% of the potential market share of transplanted cars from 48% to 27%, as illustrated in the figure above. We emphasize that this approach for determining the optimal price is indicative since we did not include potential competitors, no economies of scale (due to lower material costs), and no benefits of a learning curve (due to gaining expertise in manufacturing and operating). The shifts of market shares were estimated as if there was only one transplanter for each car type and therefore he would behave monopolistically in his own market. Under such circumstances, the optimal price obtained here is higher than the one that would be practiced under perfect competition conditions. Accordingly, the transplanter would have to increase the quantity of organ transplants for profit-maximization. We conclude that the share of transplanted vehicles would lie somewhere between 30% and 50% of remarketed cars. In Chapter 6, we concluded that the payback period for a car transplanted at the age of 6 years, would correspond to 7 years, if transplant prices were 50% above base costs, i.e. roughly 7,000€. In this case, the overall market share for transplanted vehicles we round to 40% of remarketed cars.

Figure 123 presents the new distribution of market shares by car-type after maximizing the potential revenues of transplant suppliers. Interestingly, transplanted diesel-powered vehicles are more penalized (13%, in terms of share losses, whereas gasoline-powered cars lose 4%) due to the higher increase of transplant prices for diesel-fuelled cars (more than 160% in average, whereas gasoline-powered cars suffer an average-increase of 120%).

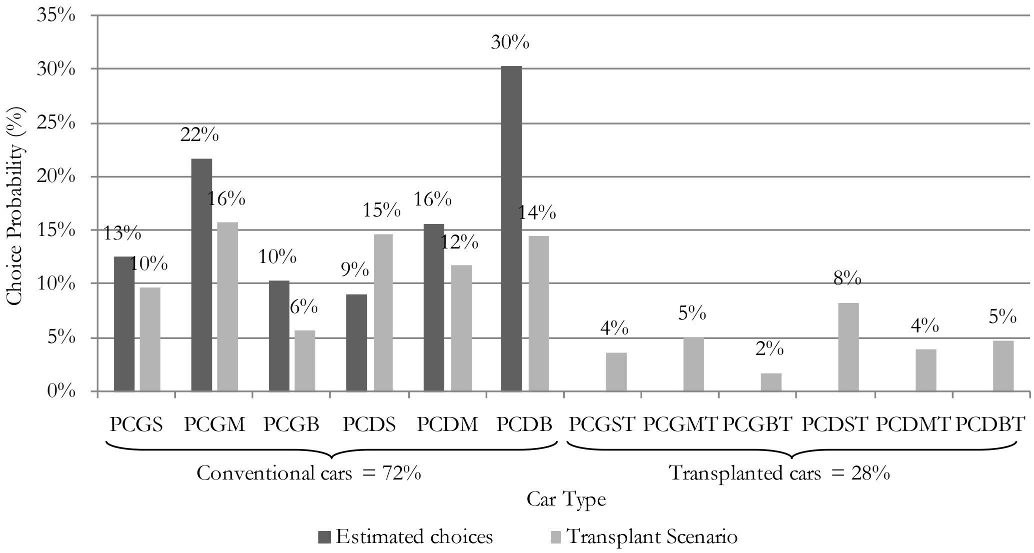


Figure 123. Conventional and transplanted used-cars distribution (with optimal transplant prices) (source: author)

The following figure shows the total-profit curves estimated for each vehicle type that were used to calculate the profit maximization prices of organ transplant. The bell shaped curves are due to the decrease of demand (Q, expressed here in terms of their percent probability-distribution) while the price of transplanting increases.

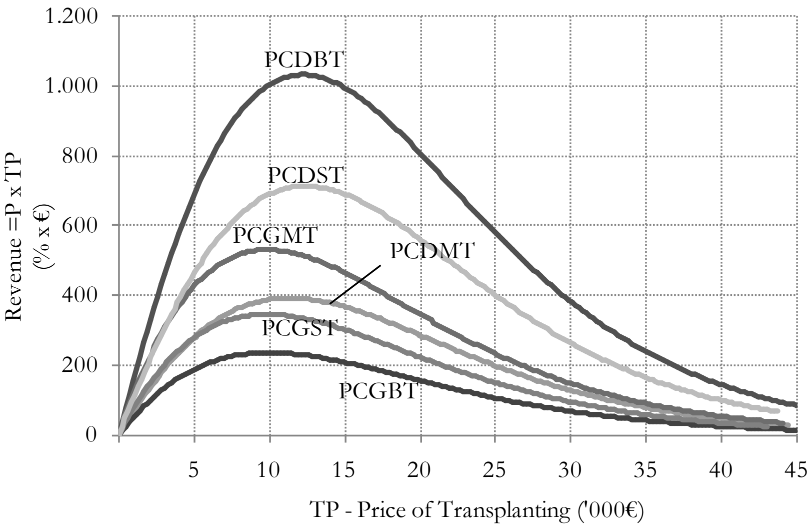


Figure 124. Total-profit curves of transplanted cars and optimal transplanting prices (source: author)

The following table shows the potential unit revenues for *transplant suppliers*. Based on our assumptions, they could earn 7,000€ *per* transplanted car, in average. We recall that the price of transplant services must be added to the residual value of the remarketed car to obtain the final transplanted car price for the final consumer. For example, a 7-years old, medium-sized gasoline-powered car (PCGM) would cost approximately 21,400€ (with a cumulative mileage of 120,000 km) after being transplanted (11,500€ for residual value + 9,900€ for transplant price). This is the price that is included in the utility function of this vehicle to estimate the probability of being chosen after confronted with the remaining alternatives (whether they are conventional or transplanted). These are good grounds for an economically sound business model for the transplant technologies since the gross benefit (~20%) would allow several stakeholders to participate in the value chain of transplanting services.

Table 46. Costs and profit-maximization prices of transplant services (source: author)

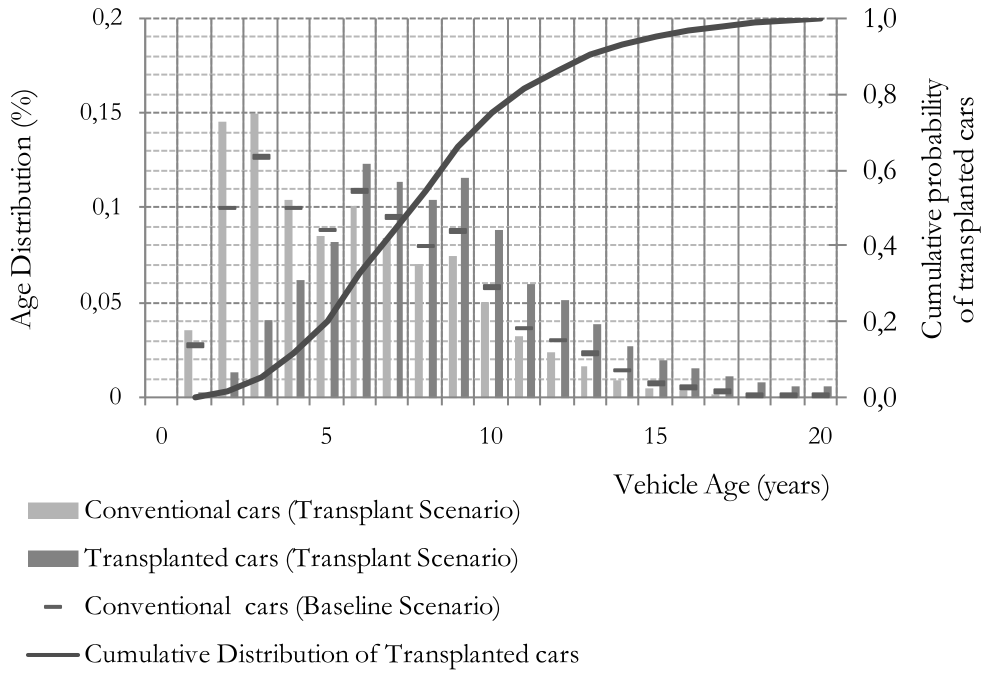
	PCGST	PCGMT	PCGBT	PCDST	PCDMT	PCDBT
Used-car residual value (€) [a)]	8,500	11,500	16,000	16,000	34,500	40,500
Transplant base costs (€) – TC	4,300	4,400	4,650	4,350	4,450	4,700
Transplant optimal Price (€) – TO [b)]	9,900	9,900	10,000	12,250	11,350	12,150
Retail price (Residual value + TO)	18,400	21,400	26,000	28,250	45,850	52,650
Potential unit revenue (€ - *% gains*)	5,600	5,500	5,350	7,900	6,900	7,450
	30%	26%	21%	28%	15%	14%

a) The residual values presented correspond to the median of vehicles aged 7 years (and cumulative mileage of 120,000 km), present in our sample. This is just an example. Benefits are lower if the used-car is younger or if the cumulative kilometrage is lower. Conversely, they are higher if the vehicle is older or if the cumulative kilometrage is higher.

b) The term "optimal" price is used in the transplant supplier perspective of revenue maximization and according to the demand curve we estimated for each vehicle type.

Figure 125 (next page) illustrates the impact of transplanted alternatives on the age distribution of traded used-cars and the potential age distribution of transplanted vehicles. We can observe that younger conventional cars have higher probabilities of being chosen in the transplant scenario (vertical black bars in the graph) when compared to the baseline scenario (horizontal black bars). Regarding the age distribution of transplanted cars, mid-aged vehicles are more prone to being transplanted (8.5 years is the overall weighted-average): mid-aged vehicles (6 to 11 years) have the higher probabilities of being transplanted ($P(5 < X \leq 11) = 60\%$), while younger (≤5 years) and older cars (>11 years) have still good chances of being transplanted (20% for both).

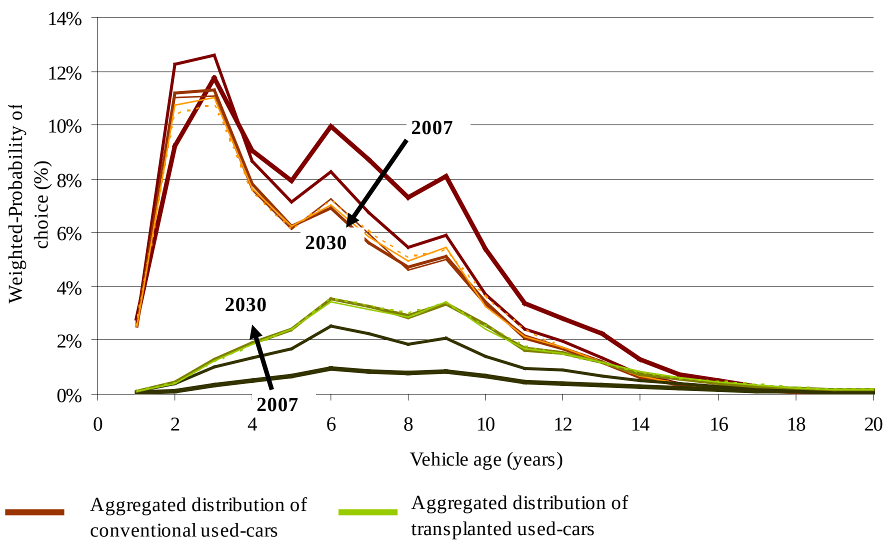
Still, according to our calculations in Chapter 6, the vehicle should be at least 5 years old in order to ensure a positive environmental impact of transplanting operations, if the car is used 6 years after being transplanted (accounting for lifecycle energy consumption and emissions). If a vehicle younger than 5 years is transplanted (less than 10% chances, according to our model), the gains in fuel economy and emissions are not sufficiently high to outweigh the energy consumed and emissions associated with transplanting operations, i.e. materials extraction, manufacturing of the transplanting kits and scrappage of the older powertrain and auxiliary equipments (e.g., exhaust gas after treatment). We note that the probability distribution presented above is based on the utility maximization theory, as mentioned. In other words, our model attempts to capture consumers' behavior through the attributes included in the utility function, assuming that they (consumers) behave rationally. Still, our intuition would advise that it is not fully realistic that car owners would buy transplanted vehicles aged less than 4-5 years, since the energy and emission gains are not significant (as referred above) and we would argue that the consumers are also aware of this. Therefore, our analyses of the results obtained in the forthcoming sections will consider this.



Note: Each series in the graph above correspond to 100% cohort distribution.

Figure 125. Age distribution of conventional and transplanted cars (source: author)

The final probability distribution matrix of remarketed cars (both conventional and transplanted) was estimated for the period of 2007-2030, keeping all attribute-levels constant (2007 values), except for the number of makes and models of transplanted vehicles. The probability distribution was disaggregated according to the vehicle cohorts. The following figure illustrates our estimation of the market shares of conventional and transplanted cars in the Portuguese used-car market.



Note: Curves become lighter as calendar years increase.

Figure 126. Probability-distribution of conventional and transplanted used cars, over time (source: author)

Transplanted vehicles become more competitive in the used-car market, as times goes by, while the percent probability distribution of conventional cars diminishes. As expected, these variations are due to the higher availability of transplant services and, consequently, the higher attractiveness (equivalent to utility) of transplanted cars. The full probability-distribution matrixes are presented in annexes. These include both the baseline and transplant scenario.

Finally, the answer to the question referred in the beginning of this section is that, potentially, transplanted cars can reach 29% of remarketed cars, every year. As mentioned in BCA[78]'s market survey (BCA, 2006), for every new car sold in the EU (every year), there are nearly 3 cars remarketed in EU countries (in average). In Portugal, the ratio of used-to-new car sales is slightly lower ($r_{U:N} \approx 2.5$). Having in mind that, in average, 7% new cars enter the Portuguese stock annually, we conclude that 17.5% (=7% × 2.5) of used-cars are remarketed yearly. Therefore, there is a potential market penetration of 5% (=17.5%×29%) of transplanted vehicles, every year. However, the quantity of transplanted cars in year *t* depends not only on the probability of that alternative being chosen, but also on the availability of that alternative in the market place (refer to Eq.9-7, p.271, for mathematical modeling specifications). The following section presents the expected impact of transplanted technologies on the market shares of the Portuguese car fleet between 2007 and 2030, according to our assumptions.

9.3.2 Estimates of the diffusion of transplant technologies on the baseline car fleet

In section 7.3.3 (p.223), we presented the baseline Portuguese fleet for the time period of 2007 to 2030. In the forthcoming paragraphs, we present the potential impacts of the transplant technologies on the car fleet structure.

The base case we use to estimate the diffusion of transplanted cars in the Portuguese car fleet relies on the following parameters and base data:

- Survival curve: the parameters we used are those calibrated for the year 2005 for the car fleet model, i.e. $\lambda = 13$, $\beta = 35$ and we assumed an extension (w) of the scale parameter (β) equal to 5 (we recall here that the parameter w corresponds to the mathematical formulation of our assumption, i.e. transplanted cars live longer than if they would keep their original powertrain and auxiliary equipment);
- Transplant costs: we use the transplant prices that maximize the revenues for the organ transplant supply chain, presented in Table 46 (p.276), although we recall that these were obtained for monopolistic markets (which we would argue is unlikely to happen unless for models with very small penetration in the Portuguese car market) and, therefore, those prices correspond to maximum possible transplant prices and, correspondingly, minimum possible quantity of organ transplants;

[78] British Car Auctions (BCA) is the largest vehicle remarketing business in Europe.

- Ratio of Used-to-New ($r_{U:N}$) cars: we assumed a constant ratio of 2.5 for future estimates of the used-car market volume (refer to Figure 119, p.268) since the moving-average we calculated stabilizes approximately at this value;
- Diffusion of transplanting kits: as referred previously, we choose the faster diffusion scenario presented in Figure 117 (p.264) and the remaining scenarios are tested in the sensitivity analysis together with other parameters and variables (section 9.5).

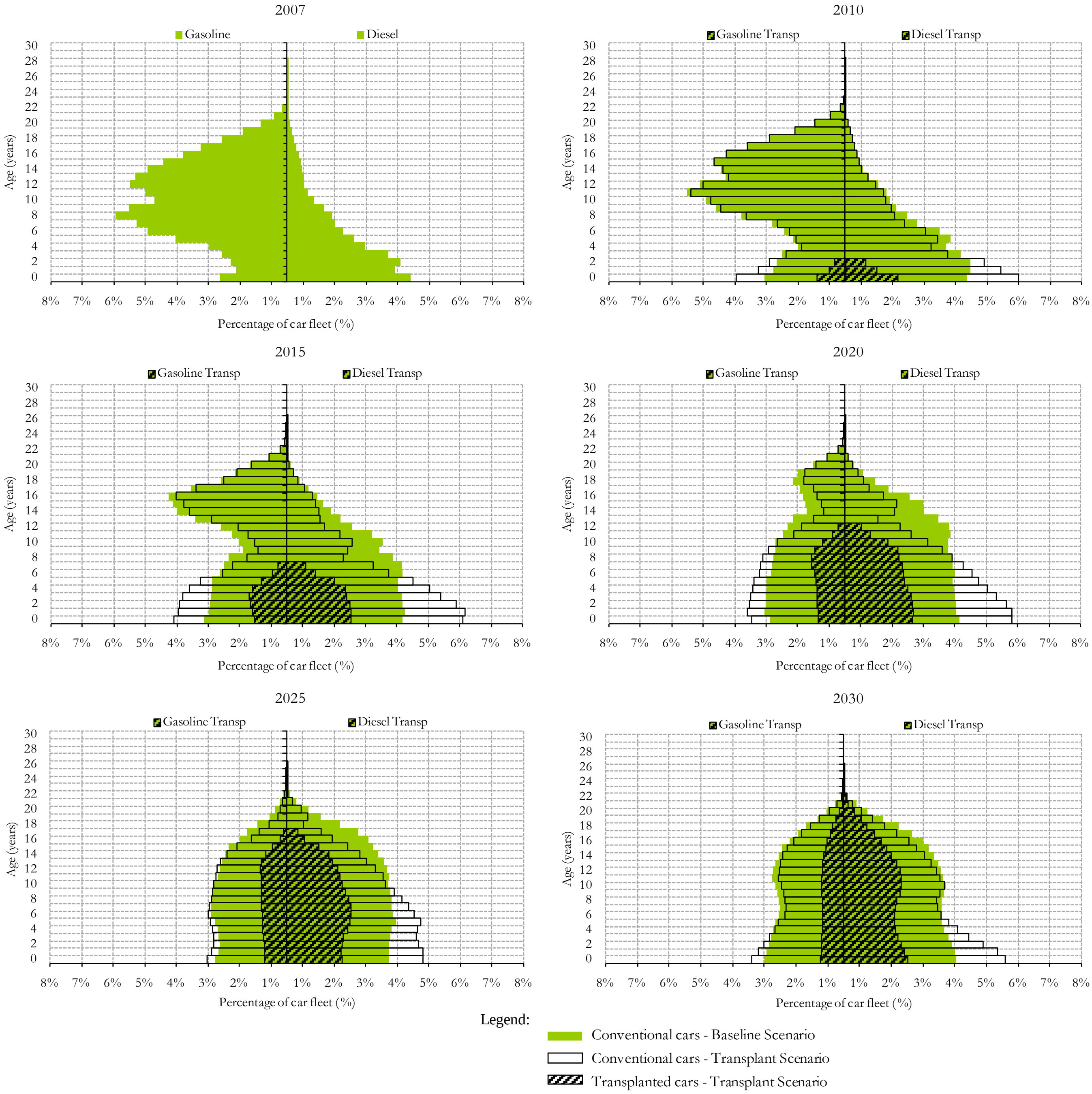


Figure 127. Car fleet age pyramids, from 2007 to 2030 (source: author)

In order to illustrate the general evolution of the Portuguese car fleet (see Figure 127), we used population pyramids (by analogy to demographic studies). The figure presents the evolution of the fleet for both scenarios: green bars correspond to baseline and empty bars to transplant scenario (the dashed bars correspond to the transplanted cars in the transplant scenario). The vertical axis corresponds to the age cohorts we considered (from 0 to 30 years) similarly to those adopted in standard demographic pyramids. The horizontal axis corresponds to the percentage of the total fleet: the left-hand side of the axis reports the gasoline-powered cars, while the right-hand side of the axis reports the diesel-powered cars.

Analyzing firstly the evolution of the baseline scenario (green pyramids), we observe a progressive dieselization of the Portuguese fleet over time and, consequently, the pyramid becomes more symmetrical with respect to the vertical axis. In some ways, this merely reflects the greater competitiveness of diesel-powered vehicles in the car market and, in particular, the attractiveness of less expensive and more efficient small diesel-fuelled cars, which recently entered in the market. Concomitantly, we observe that the pyramid gets more cylindrical as time elapses. This indicates that the fleet is getting older as the shares of newer and older generations become progressively equal and is consistent with the comments presented previously when we referred that the Portuguese fleet is achieving maturity (in terms of car density) and, hence, the respective turnover is lowering.

Now turning to the transplant scenario (empty bars for the conventional and dashed bars for the transplanted cars), we clearly conclude that the trend is to get triangle-shaped pyramids with larger basis and thinner tops than in the baseline scenario. As expected, our simulation indicates that we get a younger fleet after the introduction of transplant technologies with positive consequences in terms of energy and environmental performance. The replacement of older vehicles by vehicles with up-to-date powertrains is also striking: as time evolves, the empty bars are smaller than the green bars for older vehicles (top of the pyramids); conversely, empty bars are bigger for younger cars than green bars (basis of the pyramid). In the previous section, when analyzing the potential market shares of transplanted vehicles, we noted that diesel cars had a higher probability of being chosen over gasoline transplanted cars. In fact, we discern here a bigger shift from the gasoline towards diesel-powered cars, than in the baseline scenario where this shift is already patent.

To examine in more detail the diffusion of transplanted technologies, the previous graphs illustrate the corresponding upsurge of a thinner pyramid (dashed bars). We recall that although transplanted cars have new powertrains (thus, age is 0 years here), the remaining parts and components of the cars remain older. The pyramid is thin and cylindrical not only due to the extent of the diffusion of such cars, but also because these vehicles have shorter lifetimes, i.e., only a very small portion of cars last until 30 years after being transplanted at a very early stage of their life. Here again, we can see that there is a larger share of diesel-transplanted cars. Furthermore, the introduction of transplanted technologies in the market (potentially) induces a shift towards smaller vehicles (not shown in the pyramids): for example, in 2010, the baseline share of small cars is 22% while in the transplant scenario it is 41%. In opposition, the share of big cars is reduced from 41% to 25%. The changes in terms of energy consumption and emissions vary significantly due to such transfers of demand, as we will comment in the next section.

We assume in our model that the introduction of transplanted alternatives would not affect the total demand for private cars. In order to comply with this assumption, demand for new cars decreases with the increase of transplanted cars, since we stipulated that transplanted cars would last longer than their conventional counterpart (refer to section 9.2.2, p.266). As illustrated in the following figure, there are 46,000 fewer new cars sold every year, which corresponds to a cut down of 14% (difference between red curve and red bars in Figure 128), while 155,000 cars are transplanted (pink bars), after 2015. As mentioned previously, this has two opposing consequences: one positive due to the reduction of energy consumption, emissions and solid waste production; one negative due to the cut down of the new cars sales. Part of the latter is compensated with the increase in the sales of car components and parts for transplanting kits in the aftermarket– although not necessarily for the carmakers. Refer to section 3.2.3 (p.69) when we analyze organ transplant in cars in the context of the automotive industry.

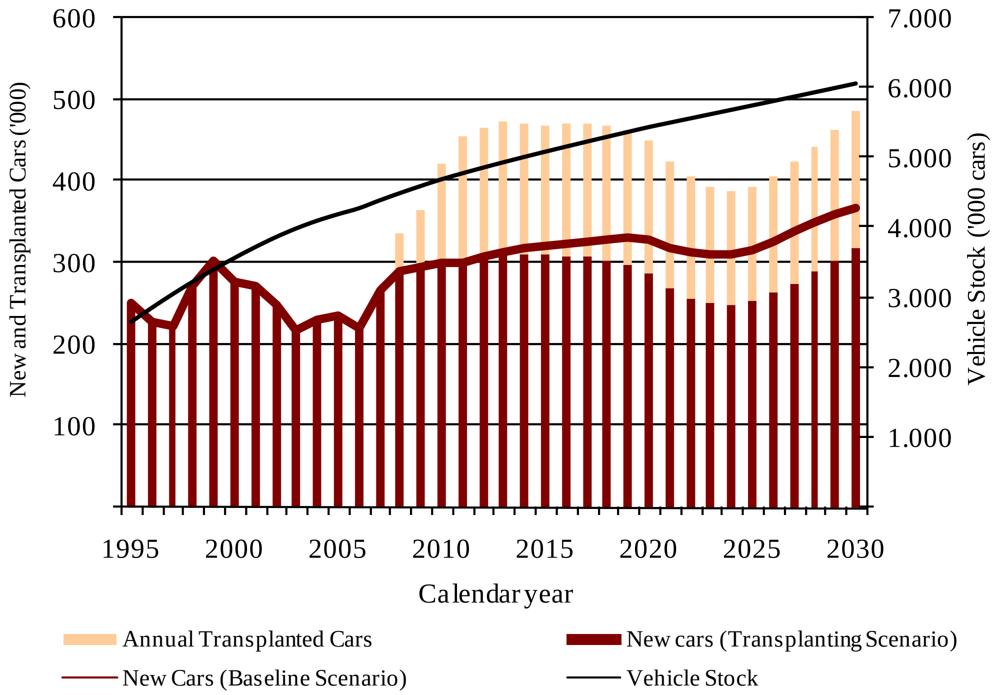


Figure 128. Number of new cars sold and cars transplanted early, from 1995 to 2030 (source: author)

We formerly referred that the annual potential market diffusion rate of transplanted cars was 5% of the fleet. According to the car fleet modeling results, the diffusion of transplanted technologies is lower. The maximum share of transplanted cars in one year is 3.3%, in 2015, ranging from 2.58%, in 2010, to 2.76%, in 2030 (according to the assumptions of our study). Still, this smaller diffusion rate has important impacts on the overall technological composition of the fleet.

The average age of the baseline fleet (8.5 years-old) is expected to decrease 1.5 years with the introduction of transplanted technologies. Apparently, this still is a small impact. However, it becomes more interesting if we analyse which cars are being transplanted with up-to-date and more performing technologies. In this sense, we calculated the 20, 40, 60, 80 and 90 age-percentiles (see Figure 129) before and after the introduction of transplanted alternatives. We conclude that while in the baseline scenario 60% of the fleet was younger than 10 years, in the transplant scenario, 60% of the cars are younger than 8 years. Again, in the baseline scenario, 90% of the vehicles were younger than 16-17 years, while in the transplant scenario, an identical percentage is younger than 14-16 years. Together with the Figure 125 (p.277), the following figure suggests that there are more mid-aged cars are being replaced than older or younger cars. This is due mainly to the higher transplant-probability of such vehicles but also to their higher availability amid remarketed cars.

These impacts get more important, in terms of energy and environmental performance of the fleet, when we know that according to a number of surveys (CARB, 1994, Pokharel *et al.*, 2001, 2002, Bishop *et al.*, 2006)[79], around 70% of the pollution[80] is emitted by the dirtiest 10% of the fleet (although more recent surveys suggest that this proportion could have decreased sharply - Slott, 2007). These are the so-called high-emitters due to ageing or malfunctioning of the vehicles that occur often concomitantly.

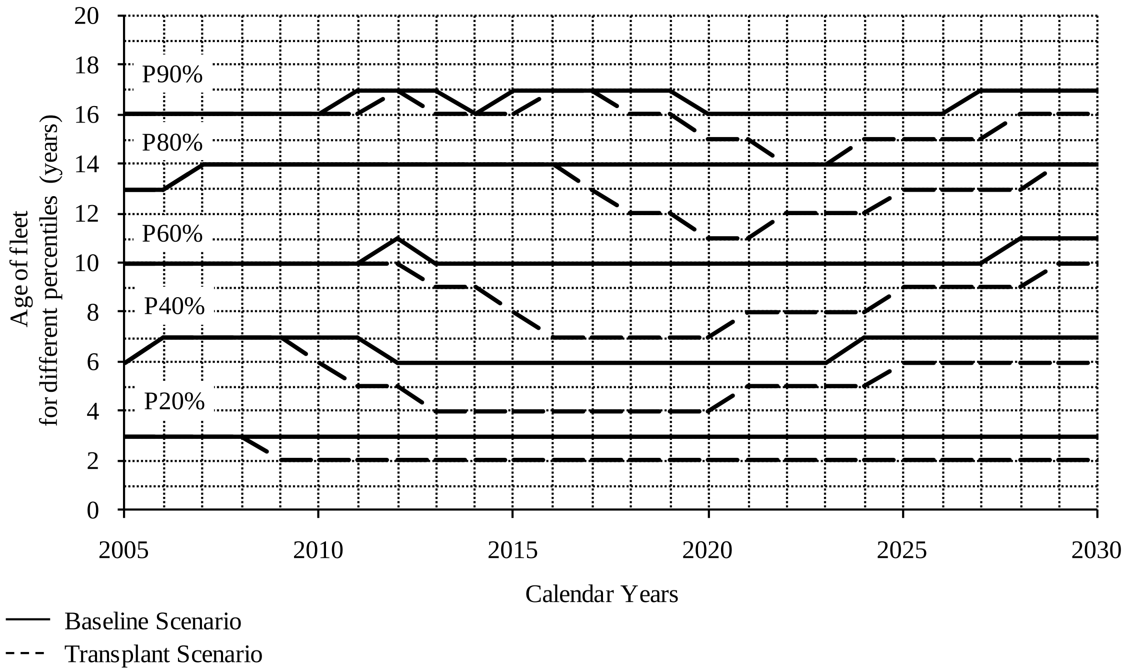


Figure 129. Evolution of the fleet age for percentiles 20, 40, 60, 80 and 90, from 2007 to 2030 (source: author)

Another way of quantifying the impact of transplanted cars is by calculating the fleet's turnover for both scenarios. After 2015 (i.e., after the stabilization of the diffusion of transplanting kits), the turnover is cut down from 17 years to less than 13 years, i.e. a new technology that is introduced in some year takes 4 years less (≈25%) to be fully deployed in the car fleet. As we will see later in this chapter, smaller changes in the diffusion pattern of transplant technologies can cut down the turnover period. For example, a higher ratio of used to new car sales ($r_{U:N}$ = 5 instead of $r_{U:N}$ = 2.5, used in the baseline scenario) would bring the turnover period further down to 10 years.

In addition, it is important to understand how the impacts of transplant technologies translate into the composition of the fleet in terms of the EURO standards, as defined by the EU by which emission limits are determined for the regulated pollutants (i.e., CO, NO_X, NVOC, and

[79] Other surveys have been performed by the same authors for others urban areas, such as Denver, Los Angeles or Chicago, where they obtained similar results regarding the high emitters share of pollution.

[80] The percentage of emissions varies with pollutants.

PM). In section 2.2 (p.21), we presented the limits of each EURO standards and the respective enforcement periods. Figure 130 compares the evolution of the technological composition of the car fleet for the baseline (full-coloured bars) and transplant (dotted bars) scenarios.

If we analyze the year 2020 in more detail, we understand that the diffusion of best available technologies (BAT) is faster when transplant technologies are available than in the baseline scenario. For example, 80% of the cars would comply with EURO 5 and 6 standards, in the transplant scenario, which corresponds to 10% more than in the baseline scenario. As referred before, the mid-aged vehicles (6 to 10 years old) are more prone to being transplanted (p = 60%), although older vehicles also have good chances (p = 20%). On the other hand, we should regard the fact that the time lag between each EURO standards is approximately 4 to 5 years, when analyzing the previous figure. Consequently, any substitution of powertrain and exhaust technologies occurs chiefly between adjacent standards or at the most between every two subsequent standards. This implies that the high-emitters we mentioned earlier are being transplanted with BAT to a lesser extent than younger and less pollutant vehicles. Technological substitution between pre-EURO (those high-emitters) and EURO 5 standards (for example) does occur, but the induced impact is not visible in the previous figure, although it contributes to the reduction of global energy consumption and emissions.

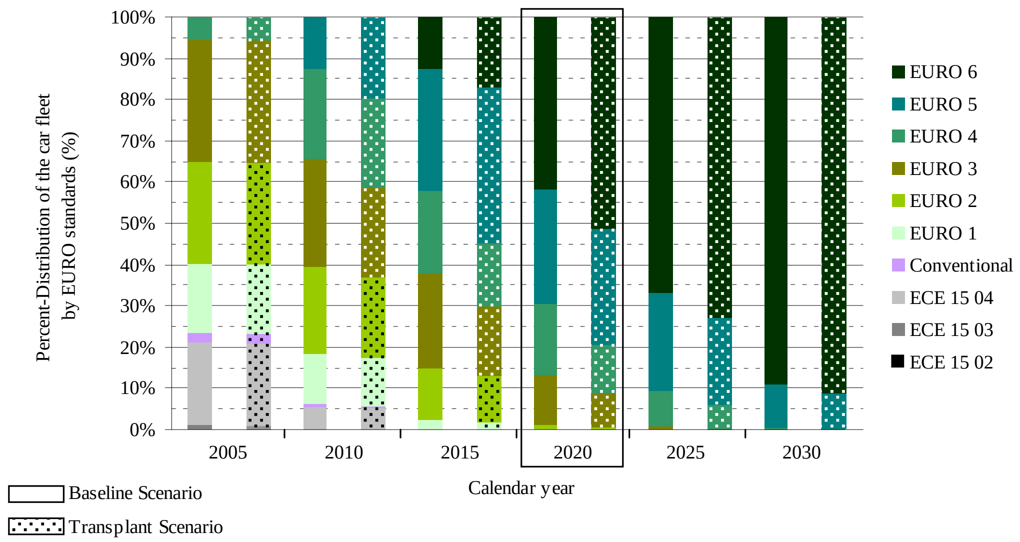


Figure 130. Impact of transplants on the evolution of the technological composition of the car feet, by EURO standards (source: author)

All in all, previous analyses suggest that transplanted technologies are competitive under our transplant scenario and that a substantial share of the used-car fleet could be using them. Having established that transplant technologies are a promising tool (according to our assumptions), the next step is to analyze their lifecycle impacts on the fleet's energy consumption and emissions, not forgetting the consequences in terms of the extraction of raw materials and waste production. This is explored in the following section, which present the results obtained regarding the global energy and environmental impacts from transplant technologies.

9.4. Energy and environmental implications of transplant technologies

We analyze now the energy and environmental implications of the diffusion of transplanted technologies in the Portuguese car fleet. Apart from energy consumption, the present exercise includes the analysis of emissions that include regulated pollutants by the EURO standards – carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), oxides of nitrogen (NO_X), Particulate Matter (PM) – and carbon dioxide (CO_2). Based on the results of the car fleet characterization of the previous section, the calculation of energy consumption and emissions is "fleet-centred" and encompasses all life-cycle stages. The lifecycle model we use here was presented in Chapter 4 (Part B) when we analyzed the energy and environmental burdens associated to car ownership of one person (or household).

9.4.1 Car stock mileage

Until now, we referred to the stock of vehicles, only. However, the calculation of total energy consumption and emissions is based on their activity levels, i.e. annual mileage. In this sense, the average km travelled by car-type and age are required. However, such statistical information is not available, in Portugal[81].

We began our simulations using the EU15-average mileage curves of the TRENDS project (Samaras *et al.*, 2002). However, we had to adjust those curves because the global energy consumption we estimated, from 2000 to 2005, was not consistent with the aggregate energy balances published by the Portuguese energy national authorities – refer to Table 47 (DGGE, 2007). In other words, the consumption of fuels we calculated was higher than the total fuels sales allocated to road transportation, in Portugal[82]. Basically, energy consumption (E, expressed in GJ) is obtained by multiplying the specific fuel consumption of cars (FE, expressed in GJ/vkm) by their annual activity (vkm, expressed in vehicle.kilometers), i.e. $E = FE \times vkm$. If we assume that the fuel economy (FE) we used for each car type is reasonable, we had to adjust the annual kilometres driven by car type. We recall that specific fuel consumption factors were obtained from literature review (refer to chapter 3) and from the latest follow-up reports of the voluntary agreement between the automotive industry and the EU (Brink *et al.*, 2005a, ACEA, 2006).

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[81] One of the goals of the CAReFUL project (Moura et al., 2007) is to address this issue and estimate average annual mileage by car type and vintage.

[82] We assumed that the gasoline sales included in the energy balance for road transportation is allocated to passenger cars only (this is not entirely true since some light duty vehicles are gasoline-fuelled, but to a very small extent). Differently, diesel fuel sales are shared with other road vehicles (for instance, light and heavy duty vehicles used to transport passengers and freight). Hence, we assumed that 40% of the diesel fuel sales are for passenger cars (as estimated in the National Programme for Climate Change - PNAC- by Seixas and Alves, 2006b).

Table 47. Aggregate energy balance (data from DGGE, 2007)

Fuel type	Vehicles	2000	2001	2002	2003	2004	2005
Gasoline	All	90,286	85,046	89,278	86,564	83,146	78,821
Diesel	Passenger cars	64,055	67,759	68,661	69,271	70,239	71,009
	All	160,136	169,398	171,652	173,177	175,597	177,522

Notes: The unit is TJ. In the case of gasoline fuel, we assume that gasoline sales are attributed exclusively to passenger cars and 40% of diesel fuel sales are allocated to passenger cars.

As presented by Samaras et al. (2002) in the TRENDS project and used in the TREMOVE project (Ceuster *et al.*, 2007a), we assumed the same mileage curve for all car types (refer to the next equation) and different first-year mileages (see Table 48).

$$KM_{i,k} = KM_{i,k=0} \times [-0.2056 \times ln(k) + 1.1413] \text{, for } k \in N \text{ and } k>0. \qquad 9\text{-}8$$

, where i refers to the car type and k corresponds to the age cohort.

Figure 131 shows the indexed-mileage curve we used.

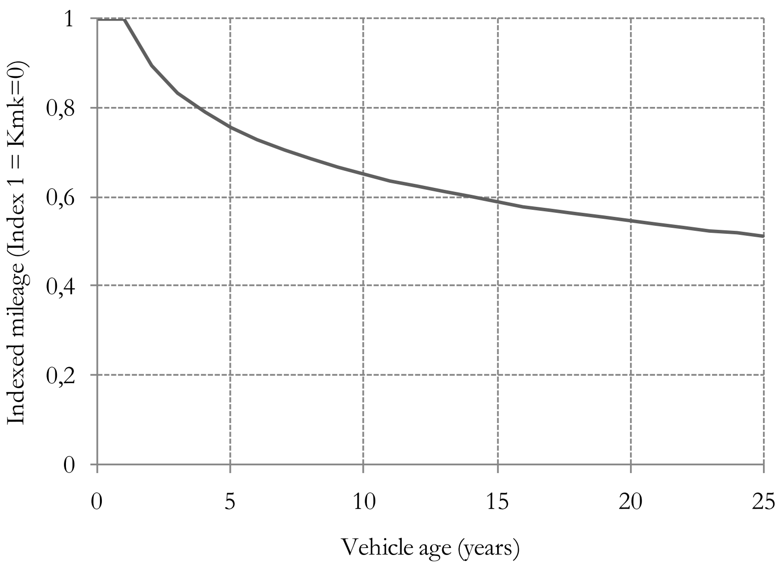


Figure 131. Mileage-reduction curve (Samaras *et al.*, 2002)

The following table shows the 1st year mileage (k=0) before and after our adjustments. With our adjustment, the average-mileage of diesel-powered vehicles increase 30%, while gasoline cars decrease by the same proportion. We note that this is not a calibration procedure, but rather an adjustment to obtain consistent results with the Portuguese reality.

Table 48. First-year mileage by car type

	PCGS	PCGM	PCGB	PCDS	PCDM	PCDB
TRENDS (Samaras *et al.*, 2002)	10,000	13,000	15,000	18,000	18,000	18,000
Adjusted values	8,800	9,200	9,400	22,500	24,000	24,500
% variation	-12%	-29%	-37%	25%	33%	36%

In section 9.2.1 (Figure 115, p.262), we presented a diagram that illustrated the impact of the organ transplant in the car fleet demography. Now we show the same concept but instead of referring to vehicles, we present the shift of kilometers travelled from older to younger cars as a result of car transplants. When transferring an older car to the age cohort of new cars, we assumed that those vehicles will continue to travel the same distance despite having a new powertrain. For example, if we transplant a small gasoline-fuelled cars (PCGS) aged 9 years, we count the same 6,000 km and not 8,800 km, which would be the mileage of a new PCGS. Consequently, the total stock of km-travelled is equal in both scenarios of analysis, for each car type.

However, this does not hold true regarding the overall fleet, since there is a transfer of demand between different car-types. As mentioned in previous sections, diesel and/or smaller cars are more attractive after the introduction of transplant-technologies. Implicitly, there is a shift away from gasoline and/or bigger cars. As we mentioned above, mileages differ widely between diesel and gasoline-powered vehicles, according to our calculations. Likewise, bigger cars travel more than smaller cars. The concomitant shifts from gasoline to diesel and/or from bigger to smaller cars leads to an overall decrease of global activity of the fleet – approximately 4% equivalent to 3×10^9 vkm, by 2030 – although the stock of vehicles remains the same.

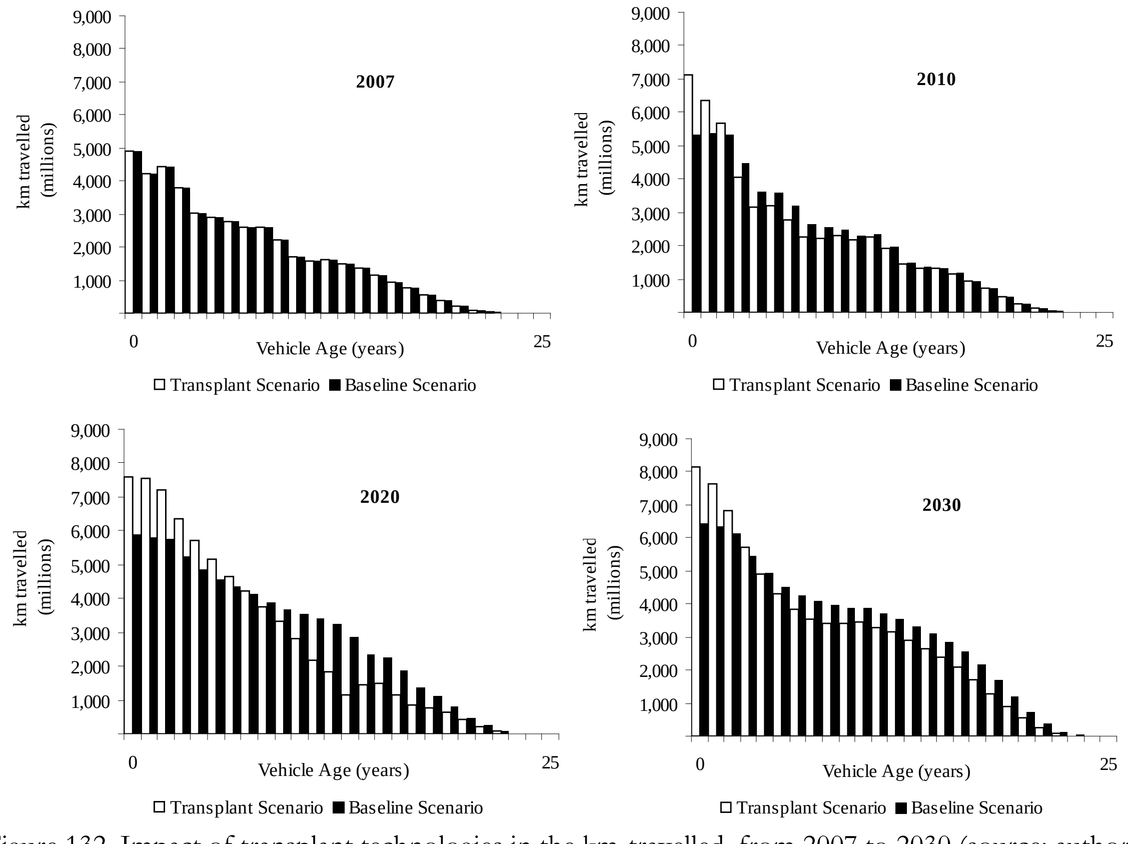


Figure 132. Impact of transplant technologies in the km-travelled, from 2007 to 2030 (source: author)

This result is disputable since higher activity levels from more efficient cars could be expected due to the so-called rebound effect by which the increased efficiency of a vehicle typically leads to an increase of mobility. We referred before that according to Herring (2006), improving energy efficiency lowers the implicit price of energy and hence makes its use more affordable, thus leading to greater use. Although there is intense dispute over its magnitude, the direct rebound effect resulting from increased efficiency is perhaps of the order of 10–20% of km travelled (Greening *et al.*, 2000). This view is supported by reported evidence in the special issue on energy efficiency (June 2000) of the UK journal Energy Policy. In our case, we should analyze to what extent the rebound effect resulting from increased efficiency would offset the gains in fuel use and emissions down the road, perhaps using values of elasticity of travelled mileage with respect to fuel efficiency in the range of 0.1 to 0.2. We will come back to this in the next section where we perform a sensitivity analysis to some critical variables and parameters of our model.

Having discussed the impact of transplanted cars on the global vehicle.km of the fleet and highlighted the consequences of shifting some of the kilometers travelled between car types, we present now the results regarding energy consumption and emissions.

9.4.2 Energy consumption and emissions

Table 49 (next page) presents the global energy consumption and emissions of the Portuguese car fleet, in the baseline and transplant scenarios. Values showed include all lifecycle stages of the new, used or scrapped cars, whether these are conventional or transplanted. It also specifies the energy consumption and emissions resulting from the production of transplanting kits (i.e., raw materials extraction and manufacturing lifecycle stages) and scrappage of substituted powertrains and ancillary equipments. The lower rows of the table present the final balance between both scenarios, and were calculated as follows:

$$\%Savings_{P_t} = \frac{\left(P_{t,VehT} - P_{t,VehB}\right) + P_{t,TranspKitT}}{P_{t,VehB}} \times 100 \qquad 9\text{-}9$$

, where

P_t is the total amount of energy consumption or pollutant emitted in year t,

VehT refers to the vehicles in the Transplant scenario,

VehB refers to the vehicles in the Baseline scenario, and

TranspKitT refers to the Transplanting Kits in the Transplant scenario.

$P_{t,\ TranspKit}$ corresponds to the energy consumption and emissions due to the production of transplanting kits and scrappage of substituted parts and components.

Starting with the baseline scenario, we conclude that the growing trends of LC energy consumption and CO_2 emissions (~20%, until 2030 – see Table 49) are opposing to the decreasing LC emissions of regulated pollutants, as illustrated in the Figure 133. Although energy efficiency of new cars (and, consequently, carbon efficiency) is increasing (Van den Brink and Van Wee, 2001, ACEA, 2006, Zachariadis, 2006), growing activity levels (vkm) largely outweigh the efficiency gains – 175% increase from 2008 to 2030, according to the assumptions used here. Conversely, regulated pollutants experience radical decrease in overall emissions due to the 90% reduction (since EURO 1) of the standard emission limits.

Table 49. Lifecycle energy consumption and emissions, from 2007 to 2030 (Baseline and Transplant scenarios) (source: author)

Scenario	Details	Calendar Year	Energy		CO_2		CO		NMVOC		NOx		PM	
			(TJ)	(%)	(Gg)	(%)	(Gg)	(%)	(Gg)	(%)	(Gg)	(%)	(Gg)	(%)
Baseline	All vehicles	2007	154,823	100	11,543	100	165.689	100	20.082	100	36.040	100	8.761	100
		2010	168,333	109	12,518	108	132.069	80	14.881	74	33.930	94	9.244	106
		2015	180,562	117	13,443	116	95.623	58	10.778	54	30.918	86	8.674	99
		2020	186,228	120	13,911	121	83.615	50	10.195	51	27.167	75	7.913	90
		2025	183,465	118	13,733	119	83.906	51	10.238	51	24.922	69	7.166	82
		2030	184,640	119	13,771	119	89.699	54	10.937	54	23.242	64	7.364	84
Transplant	Conventional and transplanted vehicles	2007	154,823	100	11,543	100	165.689	100	20.082	100	36.040	100	8.761	100
		2010	167,119	108	12,423	108	131.068	79	14.792	74	33.247	92	9.128	104
		2015	175,334	113	13,054	113	93.228	56	10.519	52	28.919	80	8.095	92
		2020	176,275	114	13,205	114	80.151	48	9.603	48	24.034	67	6.825	78
		2025	170,619	110	12,832	111	78.110	47	9.289	46	21.641	60	5.804	66
		2030	173,288	112	12,959	112	84.326	51	10.168	51	21.461	60	6.504	74
Transplant	Transplanting Kits	2007	0	n.a.	0	n.a.	0.000	n.a.	0.000	n.a.	0.000	n.a.	0.000	n.a.
		2010	2,423	100	134	100	1.267	100	0.373	100	0.429	100	0.611	100
		2015	2,863	118	156	117	1.508	119	0.433	116	0.506	118	0.728	119
		2020	2,773	114	152	113	1.514	120	0.412	110	0.492	115	0.718	118
		2025	2,349	97	128	96	1.283	101	0.349	94	0.417	97	0.608	100
		2030	2,733	113	149	111	1.493	118	0.406	109	0.485	113	0.708	116
	Final Balance	2007	0	0.0	0	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
		2010	1,209	0.7	40	0.3	0.266	0.2	0.284	1.9	-0.254	-0.7	0.495	5.4
		2015	-2,366	-1.3	-233	-1.7	-0.886	-0.9	0.174	1.6	-1.492	-4.8	0.150	1.7
		2020	-7,181	-3.9	-555	-4.0	-1.950	-2.3	-0.180	-1.8	-2.641	-9.7	-0.370	-4.7
		2025	-10,497	-5.7	-772	-5.6	-4.513	-5.4	-0.600	-5.9	-2.864	-11.5	-0.753	-10.5
		2030	-8,618	-4.7	-663	-4.8	-3.880	-4.3	-0.362	-3.3	-1.296	-5.6	-0.153	-2.1

Note: Values include all lifecycle stages. The final balance of energy consumption and emissions are estimated by retrieving the outflows resulting from the production of transplanting kits to the difference between the Baseline and the Transplant scenarios. Percentage values in the final balance correspond to the energy and emission savings when relative to the baseline scenario.

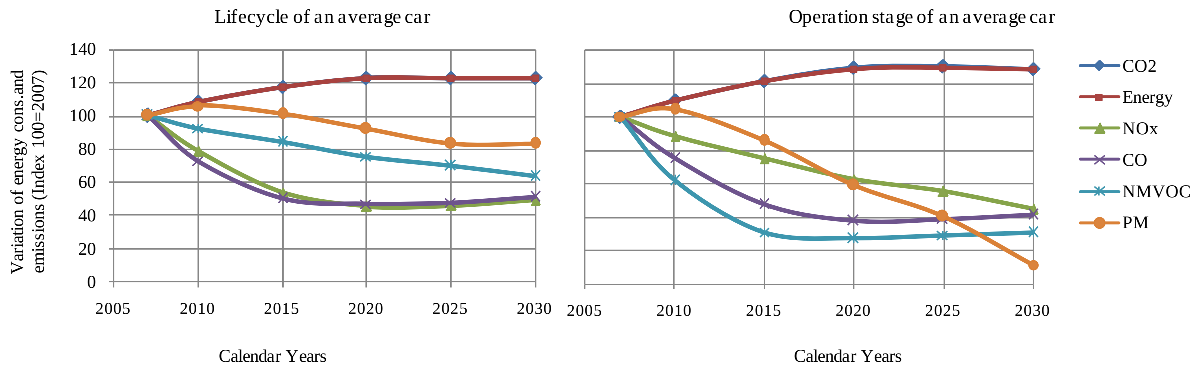


Figure 133. Index variation of energy consumption and emissions, 2007-2030 (Baseline scenario) (source: author)

The growing stringency of the limits since EURO 1 until the (proposed) EURO 6 standards (probably be enforced by 2014 - European Commission, 2006b) have counterbalanced largely the expressive increase in total vkm.

Besides the LC energy consumption and emissions, Figure 133 also presents the operation stage of the Portuguese fleet, by which we highlight its influence in determining the global trend of energy consumption and emissions. As showed in Table 50, 'well-to-wheel' stages (including maintenance and repair) add up to more than 90% of the LC of a car for all items analyzed, except for PM. Importantly, we note that the LC structure of PM emissions is different and the production of car materials accounts for more than 60% of lifecycle emissions followed by the operation stage that shares 47% of total emissions, in the case of gasoline-powered cars, and nearly 50% for diesel cars. Still, the reduction of specific emissions (g of PM/vkm) exceeds the growth of global circulation (vkm) or any increase of emissions in other lifecycle stages.

We recall that we did not consider PM emissions by gasoline-powered vehicles, according to the EMEP/CORINAIR methodology we used (EEA, 2002). In accordance with the EURO 5 standard (probably, by 2009) that imposes PM emission limits to gasoline-powered cars as well, the latest 2006 EEP/CORINAIR Emissions Inventory Guidebook went through a major update with respect to information on emission estimation methodologies for PM (EEA, 2007b). In this revised version PM emissions factors by gasoline-fuelled vehicles are 1 or 2 orders of magnitude lower than diesel-powered cars, for pre-EURO 5 vehicles.

Table 50 also indicates that, in 2008, diesel cars consume in average less energy (during its entire LF) than gasoline-powered cars. Although not shown in the table, we calculated the same indicator for average cars in 2020. We obtained higher LC energy consumption for diesel cars than for gasoline cars, i.e. 560 GJ and 520GJ, respectively. This strives directly from the composition of the fleet that, according to our model, is progressively shifting from gasoline to diesel cars and towards smaller and medium cars. Furthermore, the gasoline-powered stock has a larger share of smaller cars and, on the other hand, cars are generically smaller than diesel-powered vehicles.

Highlighting one additional aspect in the Table 50, we note the difference of one order of magnitude between gasoline and diesel-fuelled cars, in 'tank-to-wheel' CO and NMVOC emissions (although in the second case, to a smaller extent). This strives directly from the emission factor in both cases. However, this difference decreases drastically over time and, in 2030, they are expected to differ by a factor of 3 and 0.5, respectively.

Table 50. Baseline scenario LCA energy consumption and emissions (average cars - 2008) (source: author)

Vehicle type	Lifecycle stage	Energy (GJ)	CO_2 (ton)	CO (kg)	NMVOC (kg)	NOx (kg)	PM (kg)
'Average' Gasoline-fuelled car	Materials production	49 (7)	3 (5)	34 (3)	3 (2)	8 (5)	14 (61)
	Manufacturing	22 (3)	1 (3)	3 (0)	8 (6)	5 (3)	4 (18)
	Well-to-tank	103 (15)	13 (24)	18 (1)	13 (9)	26 (17)	2 (11)
	Tank-to-wheel	524 (74)	37 (68)	1,275 (94)	112 (82)	112 (73)	0 (0)
	Maintenance	11 (2)	1 (1)	27 (2)	2 (1)	2 (1)	2 (8)
	EOL	1.67 (0.24)	0.11 (0.20)	0.53 (0.04)	0.13 (0.10)	0.62 (0.41)	0.18 (0.78)
	Total	711	55	1,358	137	153	23
'Average' Diesel-fuelled car	Materials production	67 (10)	3 (5)	47 (22)	5 (12)	10 (7)	19 (46)
	Manufacturing	30 (5)	1 (3)	4 (2)	11 (28)	6 (4)	6 (14)
	Well-to-tank	74 (11)	8 (17)	12 (6)	5 (14)	15 (10)	1 (3)
	Tank-to-wheel	472 (72)	34 (73)	121 (57)	15 (41)	117 (77)	13 (32)
	Maintenance	12 (2)	1 (1)	29 (14)	2 (4)	2 (1)	2 (5)
	EOL	2.31 (0.35)	0.11 (0.24)	0.73 (0.34)	0.18 (0.49)	0.86 (0.57)	0.25 (0.59)
	Total	657	47	214	37	152	42

Note: Values in parenthesis are the percentage of total. Results refer to one average vehicle, in 2020, and 'well-to-wheel' (incl. maintenance) stages are estimated for a vehicle used during 210,000 km. Our results regarding lifecycle energy use fit within the range (523-1,436 GJ/vehicle) presented in the review by Sullivan and Cobas-Flores (2001) of LCAs of similar cars. The remaining values concerning emissions are consistent with the LC inventory of the generic US family sedan by the USAMP (Sullivan *et al.*, 1998).

Corroborating with what we stated here above, we clearly see in Figure 134 that diesel energy consumption ('All Diesel' in the graph) is in the ascendant trend in opposition to gasoline consumption. Breaking down consumption by car type, Figure 134 also illustrates the striking upsurge of small diesel-powered cars (PCDS) comparatively to the remaining vehicles. PCDS entered the market in the early 00's to reach a share of nearly 20% of the stock, experiencing a growth by a factor of 6.5 between 2005 and 2030 (according to the assumptions of our baseline scenario). Although not so important, diesel fuel consumed by larger vehicles is expected to treble from 2005 (4% of total stock) to 2030 (12% of total stock). These increases are at the expense of lower shares of gasoline-powered cars, cutting down chiefly in medium and big cars.

These trends are generically positive both in terms of fuel consumption and emissions, since diesel-powered cars are more efficient and a generic downsize of the stock is also estimated. Exception is made for PM emissions where diesel-fuelled cars are less performing than its gasoline equivalent, although the automotive industry is in the process of circumventing this disadvantage through after exhaust treatment devices (as referred before).

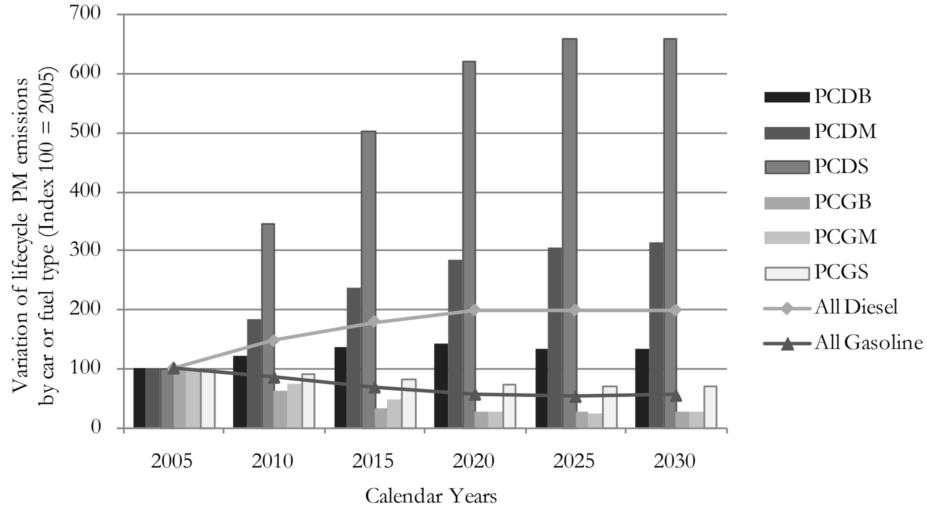
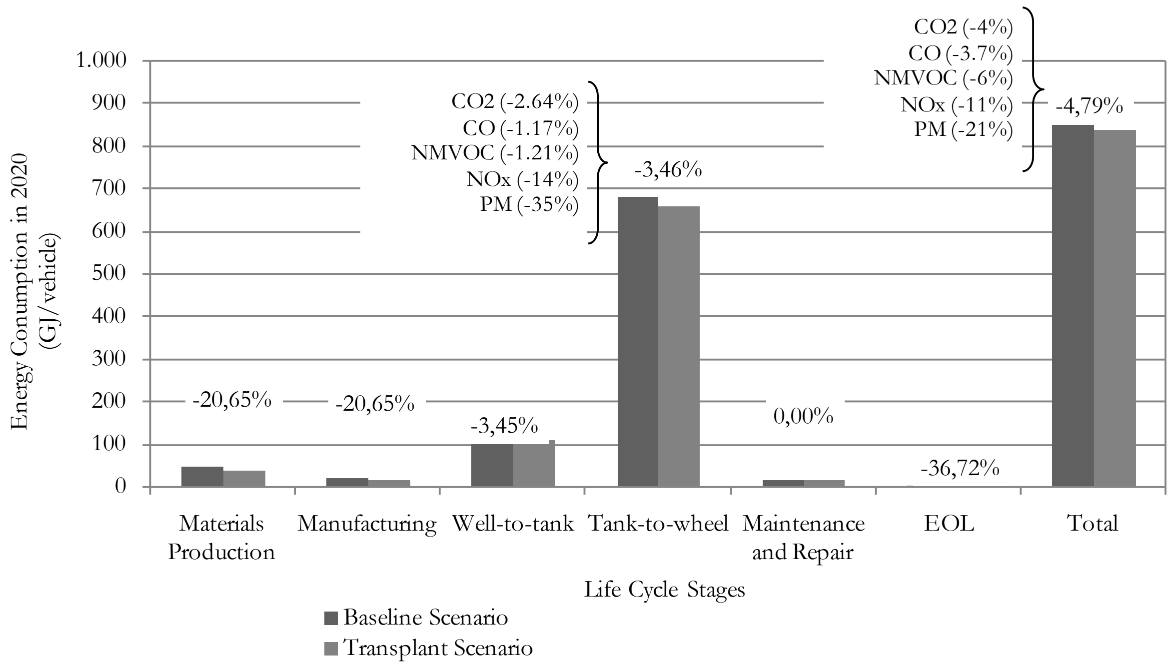


Figure 134. Variation of Baseline LC energy consumption, by car and fuel type (2005-2030) (source: author)

Now that we characterized the baseline energy consumption and emissions and concluded that these vary differently depending on the type of pollutant, we will analyze to what extent transplant technologies can refrain the increase or foster the reduction of those energy consumption and emissions. Figure 135 shows the distribution of LC energy consumption of a Portuguese generic car (i.e., a blend of all size and fuel car types), for both scenarios. Emissions are expressed in GJ/vehicle, where results for 'Well-to-wheel" LC stages (including maintenance and repair) were obtained for 250,000 km lifetime service, after calculating the average fuel economy over all cars of the stock. It also shows the relative saving and increase of fuel consumption (% above bars, in the graph) that occur between the baseline and the transplant scenarios, for each lifecycle stage (when appropriate, percentage in brackets correspond to the relative variation of pollutants). It is worth mentioning that indicators for the lifecycle stages 'Material production' and 'Manufacturing' were calculated by dividing total energy consumption and emissions (resulting from the production of new vehicles and transplanting kits) by the total number of new and transplanted vehicles, in the same year. Similarly, indicators for the 'EOL' stage were estimated by dividing total energy consumption and emissions generated with scrappage of retired vehicles and substituted parts and components, by the total number of scrapped and transplanted vehicles.

According to the assumptions of the base case (refer to the section 9.3.2 for details – p.278), there is an average saving of (-4%) of energy consumption that results from the introduction of transplant-technologies in the Portuguese used-car market, by 2020. Fleet-wide gains are as much outreaching (refer to Table 49), although they are different from unitary savings. For example, total PM emissions are expected to decrease (-10%), in 2020, whereas car-equivalent saving is estimated to be (-21%). Although variations occur in the same direction, there is no linear relationship between both indicators since they are calculated differently: one is car-centred and results are estimated for the vehicle's lifetime service; the other is fleet-centred and calculated for all vehicles in one calendar year.



Note: Percent reductions resulting from the introduction of transplanting technologies are presented above bars. EOL stage of the Transplant Scenario includes the scrappage of substituted powertrains and auxiliary equipment.

Figure 135. Lifecycle energy consumption for the Baseline and Transplant scenarios (2020) (source: author)

Generically, the most significant reductions occur for non-operational LC stages of the car (more than 20%). As referred in chapter 3, these results were calculated based on the curb weight of vehicles (i.e., fuel consumption and emission factors were expressed as MJ/kg of car – or g/kg). If on the one hand, we obtain more "like-new" cars with less materials (since materials used in transplanted vehicles are related to transplanting kits that weigh, in average, 300 kg compared to more than 1,000 kg of a new car), on the other, in the transplant scenario there is a shift to smaller cars and, thus, less materials to be used. The same reasoning applies to the 'manufacturing' and 'EOL' stages, whose energy consumption and emission factors are also based on weight. The noteworthy reduction of EOL emissions (-40%, in 2020) can be misleading since the EOL energy consumption and emissions has a minor importance when compared to the remaining LC stages (<1% of LC).

Although the global percent-variation is apparently low (around 4-5%, depending on the parameter analyzed), it corresponds to expressive reductions in absolute terms. For example, in the case of CO2 emissions, this percentage equals 555 Gg of CO2, in 2020 (or, 780 Gg and 660 Gg, in 2025 and 2030, respectively). As we will discuss in section 9.6, the reduction of emissions is major when compared to the effectiveness of other transport policy instruments included in carbon reduction strategies, for example in the case of the Portuguese National Program for Climate Change (Seixas and Alves, 2006a, http://www.iambiente.pt).

In this case, we must compare 'well-to-wheel' stages only since they did not include the remaining LC emissions of policy measures they analyzed. Likewise energy consumption mentioned earlier, 'well-to-wheel' stages add up to more than 85% of LF emissions. It is here also that gains are more important reaching nearly 3% that corresponds to a reduction of nearly 550 Gg of CO2 emissions per year. Annex A.16 (p.386) presents the measures that are being enforced to reduce the carbon footprint of the transport sector, in Portugal. Comparatively, transplant-technologies would contribute more than any measure of the PNAC (or 25% of total reduction in the transport sector – ~2,150 Gg of CO2), exception made to the introduction of biofuels that is expected to generate a reduction of 1,200 Gg of CO2 emissions. Importantly, the impact of these measures were also analyzed for two of the regulated pollutants (NOx and NMVOC) under the National Emissions Ceiling Program (Instituto do Ambiente, 2004) that aims to comply with the following maximum emissions by 2010: 250 Gg de NOx and 180 Gg of NMVOC (Ministério do AmbienteAPA, 2003). According to our results, the introduction of transplant-technologies would provide a reduction of nearly 1.5 Gg of NOx (~4% of total emissions of passenger cars) and 0.5 Gg of NMVOC (~4% of total emissions of passenger cars), after the stabilization of the diffusion of transplanted cars (i.e., 2015). The measures included in the PTEN (Instituto do Ambiente, 2004) are less outreaching than the results presented here.

Additionally, according to the calculations by Fontaras and Samaras (2007), the average CO_2 emissions from the EU15 fleet emissions was reduced by 5% from 172 g/km to 163 g/km between 1992 and 2003 (11 years, i.e. an average of nearly 1g/km.year), where the 13% reduction was counterbalanced by an 8% increase due to safety, quality and performance aspects (that induced larger, more powerful and heavier vehicles), and also environment issues[83] (see Figure 136). Technological development played a major role in this reduction and, as such, we can say that 4-5% reduction induced by organ transplants could be a major achievement, also.

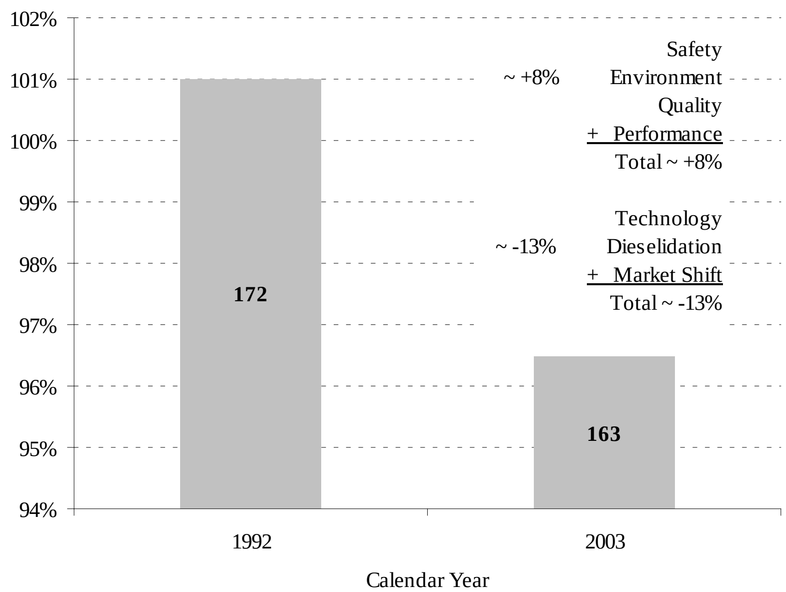


Figure 136. Average CO_2 emissions for 1992 and 2003 (Fontaras and Samaras, 2007)

[83] The latter include in part the exhaust gas after treatment artifacts, such as particulate traps, that contribute to reduce the efficiency of the vehicles due to exhaust gas backpressure (for example, refer to Zelenka et al., 1996).

Analyzing the savings over our period of analysis (2007-2030), we conclude that they are not constant over time. Returning to Table 49, we conclude that, in general terms, the introduction of transplanted alternatives generates a global reduction of energy consumption and emissions after 2015, only (see Figure 137). Before that, the final balance is positive, i.e. there is a 0.3% to 5.4% growth originated by transplanted cars, depending on the parameter under scrutiny.

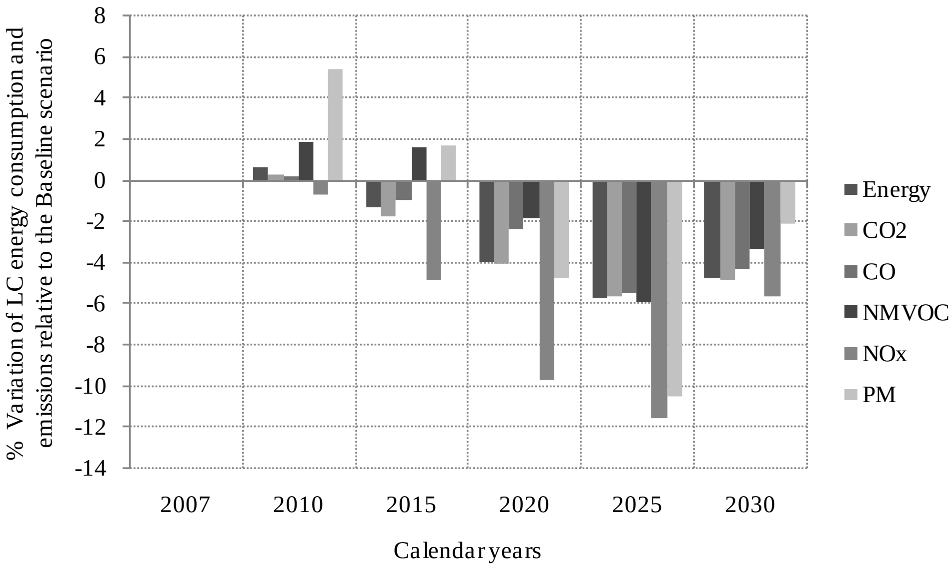


Figure 137. Percent variation of savings after the introduction of organ transplant in cars (source: author)

This initial drawback is due to the diffusion pattern of transplanting kits. On one hand, there is a delay of approximately 3 years to counterbalance the energy consumption and emissions from the production of transplanting kits and scrappage of replaced components (refer to Chapter 6). On the other, in the beginning of organ transplant of cars, the increase in production of transplanting kits is higher (on a mass-basis) than the reduction of new car produced annually. The growth in energy consumption and emissions occurs between the moment when transplanted cars enter the car fleet (2008) and the time (2020) when the avoided quantity of new cars (solid line in Figure 138, next page) surpasses the increase of transplanting kit production (line with triangles). The same logic stands for scrapped cars avoided and substituted parts and components.

As explained before, we assume in our model that the introduction of transplanted alternatives would not affect the total demand for private cars. Therefore, demand for new cars decreases with the increase of transplanted cars (and transplanting kits), since we predetermined that transplanted cars would live longer than if they remained non-transplanted. Consequently, there is a combination of effects between the reduction of materials production and manufacturing of cars (because there are less new cars produced) and the opposing increase of transplanting kits (refer to Figure 138).

On the other hand, if transplanted cars live longer, the overall number of scrapped vehicles (and, consequently, quantity of materials) is expected to reduce with time. However, transplanting kits replace existing powertrains and ancillary equipments that are also scrapped. There is a time lag between 2008 and 2020 during which these opposing forces combine to initially generate more materials production (and, hence, manufacturing of vehicles) and scrappage (dashed area in the graph), and then, ‘down the road’, these converge to an overall reduction (grey area in the graph). This occurs 3 to 5 years after the stabilization of the diffusion process of transplanting kits.

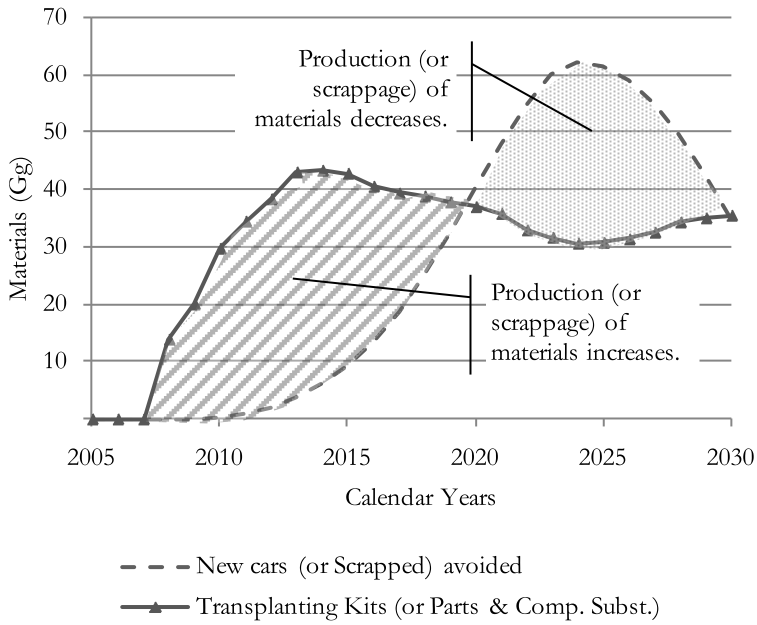


Figure 138. Balance of materials processed between the baseline and transplant scenarios (source: author)

When analyzing the previous figure, the dematerialization trend of car mobility deriving from technological transplant of cars becomes clear (refer to chapter 2 for a discussion on this issue).

Until now, we concluded that there are general gains in fuel consumption and emissions after the introduction of transplant technologies and that these gains vary with the parameter under examination and with time. We observed also that these depend on the diffusion patterns of the transplanting kits due to the energy and environmental consequences of material production and scrappage and manufacturing of vehicles. The initial increase of materials used and scrapped consumes more energy and produces more emissions than those avoided with the increased efficiency of cars during their service period, which, in turn, is induced by the introduction of BAT in the fleet through technological transplantation. Finally, the global balance depends also on the transformation of the composition of the fleet. According to our discrete-choice model, consumers prefer smaller diesel-powered cars to the remaining alternatives. Except for PM emissions, these are likely to be more efficient than larger gasoline-fuelled vehicles.

To conclude our analysis of results, we calculated global unit efficiency indicators. These were obtained by dividing LC energy consumption and emissions by the total vkm travelled by the Portuguese stock, for both scenarios. Results are necessarily different since we concluded that, after the introduction of transplanted alternatives, transfers between car types in the stock induced downward changes in the total vkm travelled. However, we do not know if the reduction of emissions is induced by an increase in the LC efficiency of cars or is due to the overall reduction of vkm travelled. After calculating those indicators, we estimated the percent-variation between scenarios over time (see Eq.9-10) to test if transplant-technologies increase unitary efficiency of cars.

$$\Delta P_t = \left(\frac{P_{t,TranspScen} \big/ vkm_{t,TranspScen}}{P_{t,BaselineScen} \big/ vkm_{t,BaselineScen}} - 1 \right) \times 100 \qquad 9\text{-}10$$

where

⊿Pt is the percent variation of unit efficiency between scenarios, in year *t*,

Pt is the total amount of energy consumption or pollutant emitted in year *t*,

TranspScen refers to the Transplant scenario, and

BaselineScen refers to the Baseline scenario.

TranspKitT refers to the transplanting kits in the Transplant scenario.

As illustrated in Figure 139, we conclude that, in terms of unitary efficiency, transplanted technologies are expected to bring benefits to the system. According to our calculations, a decline of efficiency would occur during the transition period after the introduction of transplanting kits in the aftermarket. This period would last longer for PM and NMVOC emissions. After this period (i.e., around 2012), LC efficiency of vehicles is expected to increase for all parameters analyzed (later in the case of PM and NMVOC emissions).

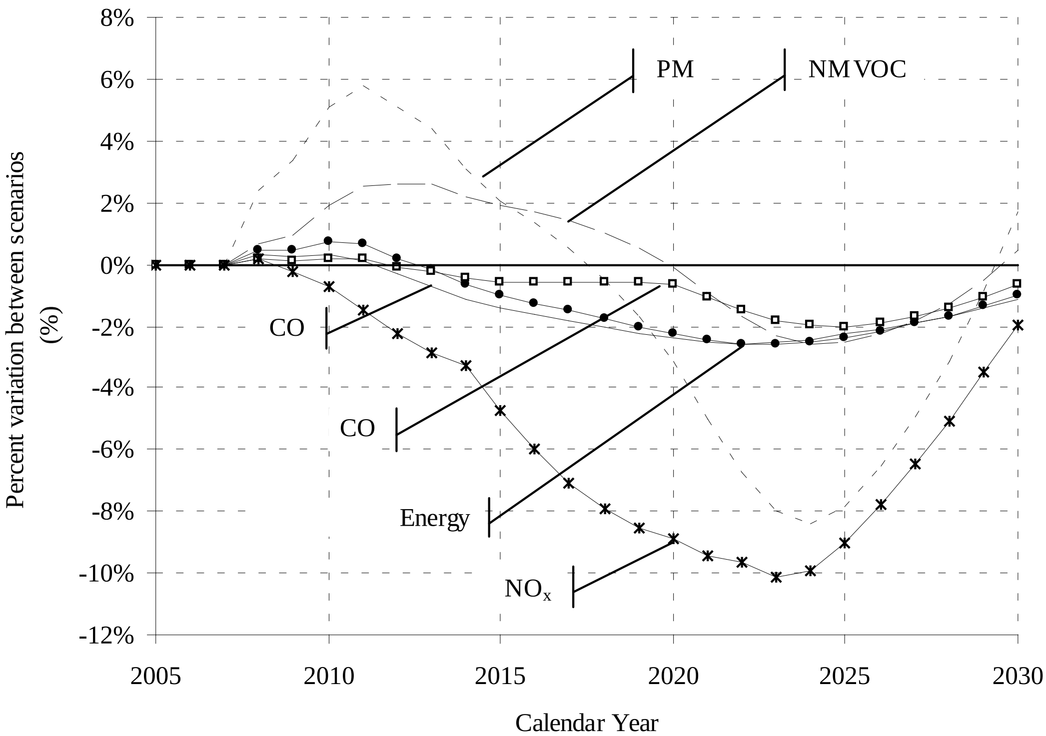


Figure 139. Percent-variation of Energy consumption, CO_2 and regulated pollutants after the introduction of transplant technologies, from 2005 to 2030 (on the basis of per vkm unit) (source: author)

Clearly, the decrease of efficiency by the end of our period of analysis is due to the deceleration of the fleet's turnover and the reduction in the number of transplanted vehicles. The decline of transplantable used-cars in the Portuguese fleet occurs from 2017 onwards, since a larger share of used-cars (more than 30%) was already transplanted. We recall our assumption that a car would be transplanted no more than once during its lifetime. Moreover, we assumed in our methodology that EURO standards would decrease until 2014 with the enforcement of the EURO 6 limits. Thereafter, emissions stabilized. Therefore, differences between car vintages will progressively slow down as well. This also explains the attenuation of the efficiency gains patent in the previous figure, by the end of 2020's.

We simulated the evolution of the car fleet over a longer time period (until 2050) and concluded that after 2030 the car density is expected to stabilize and the population of license holders in Portugal might decrease due to the overall demographic downturn. Therefore, the overall demand for new cars will decrease considerably in the Baseline scenario, according to our simulation and assumptions. In the Transplant scenario, the number of transplanted vehicles also diminishes and the impacts on the purchase of new cars are intensified. With a reduced technological turnover, LC efficiency decreases and, under the framework and assumptions we adopted in our study, the impact of transplanted technologies will probably become minor. However, we mentioned before that disruptive automotive technologies might also be transplanted into conventional vehicles. We mentioned before that, for instance, hybrid powertrains or fuel-cells could possibly be fitted into conventional cars. In this case, the LC efficiency of cars could perhaps increase and the product-life extension philosophy through organ transplant in cars could be useful for the automotive industry in the longer run.

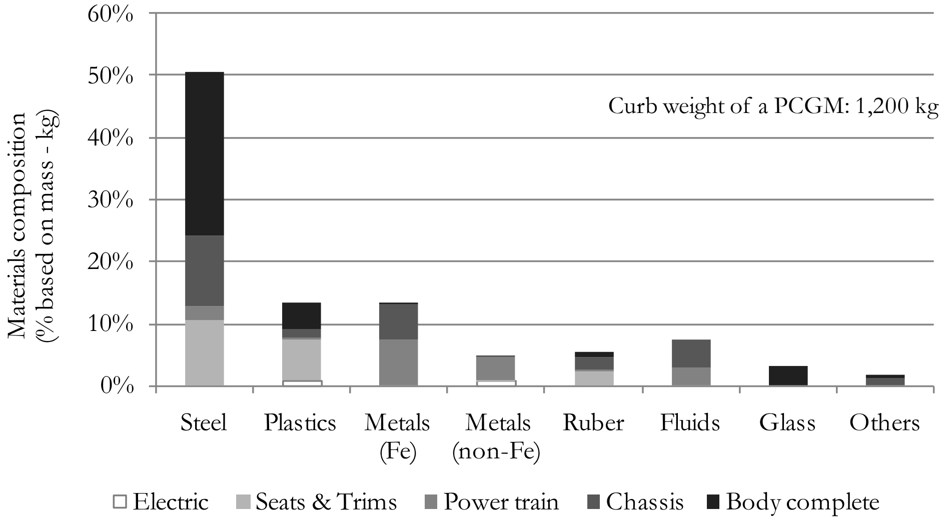
All things considered, the comparison of the lifecycle inventory between the car fleet with and without transplanted technologies shows that transplanting vehicles in Portugal can provide significant reductions in energy consumption and emissions. We are now going to analyze what are the expectable consequences on raw materials consumption and waste generation.

9.4.3 Materials consumption and waste generation

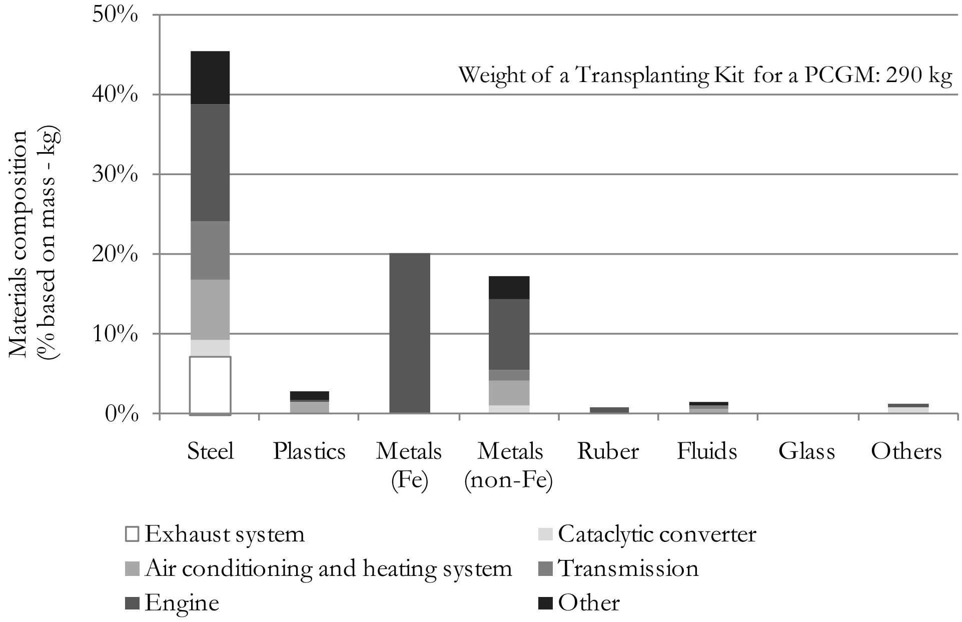
In Part B of this dissertation, we concluded that transplanting a single vehicle compared to producing a new vehicle provided significant reductions in material consumption and waste generation. We will now analyze the impact of a fleet-wide application of car organ transplant on these parameters. We used the components and material compositions described in Chapter 4, both for a vehicle and transplanting kit (which we illustrate in Figure 140, next page).

Figure 138 (p.295) showed the balance of materials use after the introduction of transplant technologies. It clearly indicates that, until 2020, there is an increase of materials use due to the higher growth of transplanted vehicles (and thus production of transplanting kits) than the reduction of demand for new cars (and thus the equivalent production of vehicles). Nonetheless, the quantity of materials used differs depending on the type of material we analyze. For example, a transplanting kit was estimated not to have glass in its composition. Therefore, there is a net reduction of glass use for every new car that is not produced. On the contrary, for every car transplanted, there is an increase of 70 kg of iron. Allegedly, if this transplanted car substitutes a new car that weighs approximately 160 kg of iron, the net reduction would be 90 kg of iron (=160-70), i.e. 44% net reduction. If the increase of transplanted cars is greater than the decrease of new cars produced, then the final balance can easily be positive, i.e. transplant-technologies can induce an increase of consumption of some materials, as we will discuss hereafter.

In Chapter 4, we explained that the estimation the raw materials' consumption was based on the typical material flows characterized by Ginley for the US automotive industry (Ginley, 1994, cited by Graedel and Allenby, 1997). Likewise, the calculation of material losses, reuse or final disposal was based on the same flow characterization. We remind that these are figures presented for the USA context and therefore EU values might present some differences, although to a small extent. The following table recalls the load factors of each material. They are indexed to the total weight of materials used when the car is ready for service (i.e., operation LC stage).



a)



b)

Figure 140. Components and material composition a vehicle (a) and transplanting kit (b) (source: author)

Table 51. Load factors of raw material consumption and waste disposal (source: author)

Materials	Upstream to vehicle use: Raw material consumption	Upstream to vehicle use: Losses	Downstream to vehicle use: Reuse	Waste disposal: Recycle	Waste disposal: Waste	Waste disposal: Landfill
Steel	115	20	10	81	5	4
Aluminum	90	24	67	26	6	1
Copper	90	24	52	43	5	0
Lead and Zinc	70	10	40	50	5	5
Plastics	106	8	4	0	5	91
Miscellaneous	101	19	22	0	5	73

Note: Index 100 = Weight of material in the 'ready-to-use' vehicle.

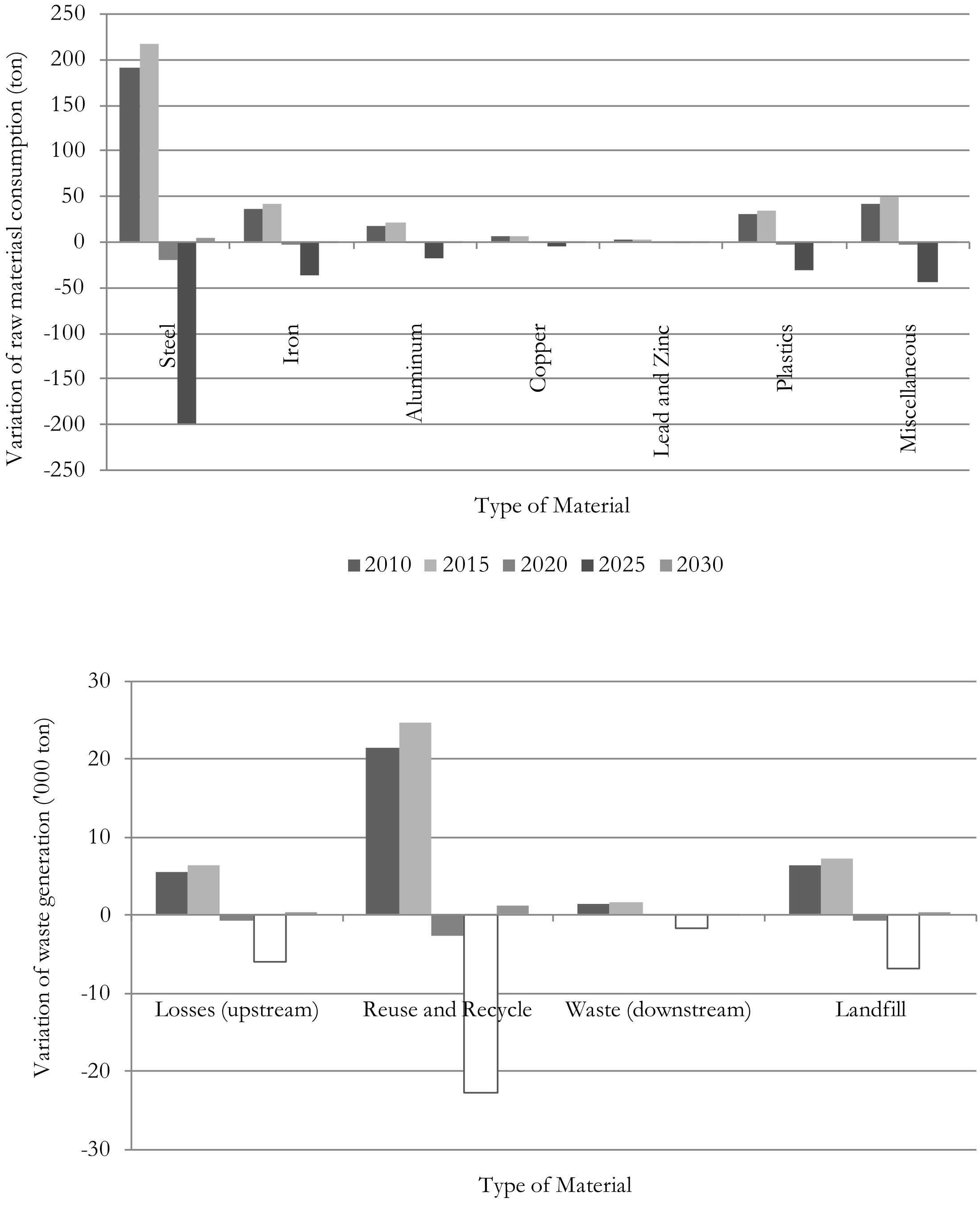
Our exercise is not to quantify thoroughly raw material consumption and solid waste generation and disposal, in Portugal, but instead to have a perception of the impact one can expect from the introduction of transplant technologies. Assuming the rates presented by Ginley for all car types, we estimated raw material consumption and waste generation (and disposal) for the entire fleet over our time horizon, for both scenarios of analysis.

Figure 141 shows the variation between the Baseline and Transplant scenarios, expressed in tones of materials. After the introduction of transplanted alternatives, we can look ahead to a decrease of materials' consumption (-10% by 2020) and waste generation (-14% by 2020), after 2015. The majority of waste (nearly 80%) is reused or recycled (as expectable, attending to the load factors presented before).

9.5. Sensitivity analysis to selected model parameters

The present sensitivity analysis is motivated by some of the limitations of the analysis presented in the previous sections. These include, for example, the fact that some important input variables and parameters of our model were determined based on other studies. For instance, scrappage and mileage curves could not be calibrated since no data was available for the Portuguese fleet, and we used data from the TRENDS project (Samaras *et al.*, 2002). In addition, the utility function influences chiefly the diffusion rate and patterns of transplanted vehicles over the fleet. In this sense, we tested the sensitivity of transplant price and circulation taxes that are two important attributes of the utility perceived by car consumers. Finally, we address the possible rebound effect resulting from an increase in energy efficiency of the transplanted cars by testing the extended used of 10% and 20% of those vehicles, in a mileage basis. Importantly, these analyses can provide important insights for the discussion of policy implications regarding technological transplants.

The next table presents the LC energy and emissions savings obtained (potentially and according to the assumptions of our base case), after introducing transplanted alternatives to remarketed cars, until 2020. The gains are expressed in TJ and tones, whether they refer to energy or pollutants, respectively. We also present those gains as a percentage relative to the baseline emissions (in brackets). As referred previously, the reductions differ among the parameters analyzed. The larger savings are for PM (-44%) and NO_x (-30%) emissions, followed by energy consumption and CO_2 emissions (-23%) and finally CO and NMVOC with smaller gains (-2%).



b)

Figure 141. Changes in (a) materials consumption and (b) waste generation (and disposal) after the introduction of transplant technologies, from 2010 to 2030 (source: author)

Table 52. LC variation in energy consumption and emissions in the Baseline and Transplant scenarios between 2007 and 2020 (Base Case) (source: author)

Scenario	Energy (TJ)	CO_2 (kton)	CO (ton)	NMVOC (ton)	NO_x (ton)	PM (ton)
Baseline	31,405	2,369	-82,074	-9,887	-8,872	-848
Transplant	24,224 (-23%)	1,814 (-23%)	-84,024 (-2%)	-10,067 (-2%)	-11,513 (-30%)	-1,218 (-44%)

Table 53 (next page) presents the results we obtained from the sensitivity analysis to the parameters and variables referred in the opening paragraphs of the present section. Comments are made separately for each analysis in the forthcoming sections.

Table 53. Results of sensitivity analysis (source: author)

Parameters and variables	Variation between 2007 and 2020 (In brackets, find the % variation relative to the baseline scenario presented in Table 52)					
	Energy (TJ)	CO_2 ('000 ton)	CO (ton)	NMVOC (ton)	NO_x (ton)	PM (ton)
Lower Transplant price (-50%)	21,867 (-9.7%)	1,638 (-9.7%)	-84,986 (1.1%)	-10,184 (1.2%)	-12,097 (5.1%)	-1,359 (11.6%)
Higher Transplant price (+50%)	26,456 (9.2%)	1,989 (9.6%)	-83,435 (-0.7%)	-10,027 (-0.4%)	-10,658 (-7.4%)	-1,138 (-6.6%)
Taxes are equal for all MY	24,225 (0.0%)	1,814 (0.0%)	-84,025 (0.0%)	-10,067 (0.0%)	-11,513 (0.0%)	-1,218 (0.0%)
Less efficient cars pay higher taxes	24,531 (1.3%)	1,839 (1.4%)	-84,030 (0.0%)	-10,077 (0.1%)	-11,265 (-2.2%)	-1,199 (-1.6%)
Lower remarketed-car universe ($r_{U:N}$ = 1)	27,670 (14.2%)	2,081 (14.7%)	-83,071 (-1.1%)	-9,987 (-0.8%)	-10,221 (-11.2%)	-1,061 (-12.9%)
Higher remarketed-car universe ($r_{U:N}$ = 5)	20,565 (-15.1%)	1,543 (-14.9%)	-85,498 (1.8%)	-10,252 (1.8%)	-12,417 (7.9%)	-1,460 (19.9%)
Slower diffusion of transplanting kits	25,898 (6.9%)	1,928 (6.3%)	-83,286 (-0.9%)	-9,936 (-1.3%)	-10,972 (-4.7%)	-975 (-20.0%)
Radical diffusion of transplanting kits	23,613 (-2.5%)	1,778 (-2.0%)	-84,734 (0.8%)	-10,181 (1.1%)	-11,423 (-0.8%)	-1,284 (5.4%)
Shorter lifetime of transplanted cars (w = 0)	27,471 (13.4%)	2,013 (11.0%)	-82,162 (-2.2%)	-9,667 (-4.0%)	-11,100 (-3.6%)	-636 (-47.8%)
Longer lifetime of transplanted cars (w = 10)	23,534 (-2.8%)	1,772 (-2.3%)	-84,421 (0.5%)	-10,155 (0.9%)	-11,607 (0.8%)	-1,348 (10.7%)
Rebound effect of 10% increase of vkm	28,904 (19.3%)	2,176 (20.0%)	-82,047 (-2.4%)	-9,864 (-2.0%)	-10,901 (-5.3%)	-1,176 (-3.4%)
Rebound effect of 15% increase of vkm	31,244 (29.0%)	2,357 (29.9%)	-81,059 (-3.5%)	-9,763 (-3.0%)	-10,595 (-8.0%)	-1,155 (-5.2%)
Rebound effect of 20% increase of vkm	33,583 (38.6%)	2,538 (39.9%)	-80,070 (-4.7%)	-9,661 (-4.0%)	-10,289 (-10.6%)	-1,134 (-6.9%)

9.5.1 Transplant price

As explained before, we estimated the transplant prices that would maximize the revenues as performing car organ transplant without charging the value added would result in no benefits for the transplant supply chain. In this sense, we estimated the total-profit curves for every car type analyzed here. However, these should be regarded carefully since they were estimated under monopolistic market conditions, which are unlikely to occur (except for some car types that show small market diffusion). As such, transplant costs directly influence the price of transplanted cars by summing to the residual price of the remarketed car. Variations in transplant costs have consequences on the diffusion of transplant technologies, over time. Therefore, we tested the impact of a reduction (and an increase) of 50% on the transplant price we obtained before.

As presented in Table 53, the impact of 50% variation of transplant prices in the LC energy or CO_2 savings is approximately ±10% (and lower for the remaining pollutants), which we consider to be sufficiently high to fine tune our estimates of transplant costs, in future research.

9.5.2 Circulation taxes

As referred previously, calculations of the circulation taxes were based on the Portuguese law – Lei n.º 22-A/2007 de 29/06 - Série I nº 124 – refer to annex A.12 (p.382). As mentioned in the annex, this law underwent a fundamental modification, in 2007. The former version of this regulation was dependent on the engine size and model year of the vehicle. The new version relies on the engine size and CO_2 emissions (as indicated by the automaker). From the beginning of 2008 onwards, circulation taxes are applied as follows:

- Cars registered prior to 1981 are freed of any taxes,
- Cars registered after 2007 (inclusive) are subject to the new tax formula, and
- Taxes for the remaining cars are calculated according to the former regulation.

We compared it with the older version of the regulation. The following figure illustrates the circulation taxes according to the old (solid lines) and new (dashed lines) versions of the law for gasoline-fuelled cars.

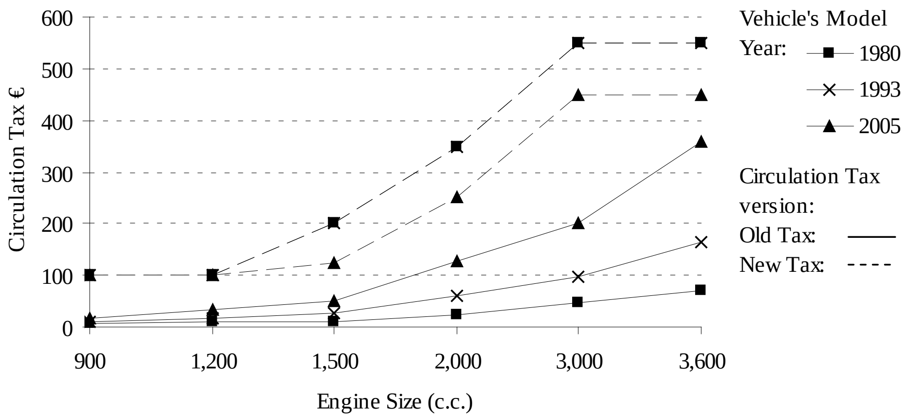


Figure 142. Portuguese Circulation Taxes: Comparison between old and new regulation (source: author)

As illustrated in the figure above, there are noticeable differences between the new and older regulations. We calculated both taxes for a 2005 large gasoline-fuelled car (3,000c.c.) and the new tax formula would result in 250€/year higher than the former one. In the case of a 1980 large gasoline-fuelled car, this difference would amount to 500€/year. We can see clearly that the differences increase with the vehicle's age. In fact, in the older version of the law, taxes decreased with the vehicle's age, whereas today taxes increase as carbon efficiency of the vehicles decreases (i.e., as model years get older).

To analyze the sensitivity of this variable in the overall results of our simulation, we compared a scenario where the regulation is applied as indicated above (for different model years) and another scenario by which the new regulation is applied to all model years, i.e. independently of the registration date. Results presented in Table 53 clearly suggest that there are no differences between savings in both scenarios we analyzed. We conclude that overall results do not vary much when we change the circulation taxes. This is probably related to the fact that circulation taxes are not important when compared to other ownership costs. A new big gasoline-powered car (3,000 c.c.), emitting 200gCO_2/km, would paid 450€, in 2008. This corresponds to approximately 5 to 6 60-liter tanks (considering 1.4€/liter$_{gasoline}$) or running approximately 3,500 km (for a fuel consumption of 9 liters/100km), i.e. less than 20% of one year typical mileage of this car type. In addition, the elasticity of used-car demand with respect to circulation taxes is (-0.23) by which we can see that it is quite inelasticity (as we analyzed in section 8.3.4). With other words, the Portuguese used-car purchaser is quite indifferent to the circulation taxes he/she will have to pay when deciding upon which car they are going to buy.

We note that the present analysis does not include the influence one would expect on the level of activity of cars, i.e. variation of circulation taxes does not induce changes in vkm travelled by cars. We consider that it is not a drawback of our analysis given that the present law (whether it is the older or newer version) does not depend on the annual distance travelled. According to Goodwin et al (2004), the elasticity of fuel consumption with respect to price is in the order of (-0.3). Therefore, we would expect that a 10%-increase of the circulation taxes (provided that the tax varies with the km travelled) would induce a decrease of (-3%) of km travelled (and, therefore, fuel consumption). The present regulation does not influence the activity levels of cars, which we consider a flaw. The impact of circulation taxes would probably become more expressive in that case. This is an interesting point for further research.

Nonetheless, we tested a different variation of the circulation taxes by which less efficient vehicles would pay more taxes than according to the present regulation. Figure 143 illustrates the changes proposed here.

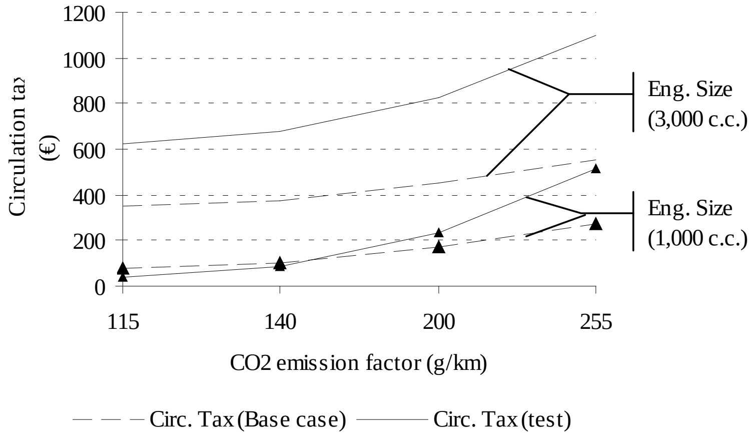


Figure 143. Illustration of our sensitivity analysis to circulation taxes (source: author)

Surprisingly, by imposing heavier taxes on less efficient vehicles, the final balance is that there would be a decrease in overall emission savings. The number of transplanted cars would be slightly lower, the number of new cars would decrease and the amount of scrapped vehicles would increase somewhat. All things considered, the technological turnover of the fleet would decrease, held back by taxes that privilege older vehicles under the former regulation (as illustrated in Figure 142). To better understand this result, it should be reminded that cars registered before 2007 do not suffer any tax changes since they are subject to the older tax formula (which does not include CO_2 emissions). What the model results reflect is that using newer cars becomes more expensive than using older cars. According to our model, consumer preferences go for the latter (not forgetting that these results are bound to the utility function attributes we could model and the rational behavior in consumption underlying this kind of models). Still, energy and emissions savings are very similar to those in the baseline scenario. We conclude that circulation taxes is not a sensitive variable of our model.

9.5.3 Ratio of used-to-new cars

One important aspect in our modeling approach is the quantity of cars that are remarketed every year. Accordingly, the annual number and type of transplanted cars is equal to the annual stock of remarketed cars multiplied by the transplant-technology matrix (which, in turn, is determined by our discrete-choice model). We recall that the stock of remarketed cars is estimated on the basis of the used-to-new cars ratio ($r_{U:N}$) that is calculated with the moving-average of the previous 5 years.

Apparently, there is a complimentary trend between new and used car sales. According to the BCA market study (BCA, 2006), while new car sales are in the upper trend, remarketed cars tend to lower. Conversely, if new car sales decrease, used-car sales increase. In turn, variations in the new car market are due mainly to the economic environment and the consumer debt. If the former softens and/or the latter rises, new car sales decrease. However, the ratio $r_{U:N}$ varies within a narrow band. For example, in the UK, it varied between 2.5 and 3.0, since 2001. As mentioned before, the Portuguese $r_{U:N}$ oscillated between 1.9 and 2.6 since 1996. Our base case was calculated based on a $r_{U:N}$=2.5. We tested the variation of the values of $r_{U:N}$ =1 and $r_{U:N}$ = 5 and analyzed the respective impacts on the overall LC energy and emission savings.

As presented in Table 53, variation of energy consumption and emissions savings vary (+15%) for $r_{U:N}$ =1 and (-15%) for $r_{U:N}$ =5. Differently, the impact of this parameter on regulated pollutants is lower (around ±1% for CO and NMVOC, ±4% for NO_X and ±17% fo PM) and with opposite signs, i.e. LC emissions increase if the used-to-new cars ratio decreases. This is because increase of emissions in the up and downstream LC stages to car use are higher than the reduction of exhaust emissions. We recall that according to our modeling approach, emission factors stops decreasing after 21013 when the EURO 6 standards entries into force. Although the production of new cars diminishes if $r_{U:N}$ increases, the number of transplanting kits produced increases accordingly. The overall balance is not favorable for regulated pollutants in opposition to energy consumption and emissions when such variation occurs.

We conclude that depending on the parameter the universe of remarketed cars influences somewhat our final results although we tested very strong variation of the base case parameters.

If we can find a $r_{U:N} = 1$ in Spain, there is no EU country where we could find $r_{U:N} = 5$. Importantly, the introduction of transplanted cars in the used-car market would generate energy and emission savings, in the worst case scenario ($r_{U:N} = 1$).

9.5.4 Diffusion of transplanting kits

As referred previously, we analyzed three scenarios of diffusion of transplanting kits:

- a scenario of slow diffusion of transplant kits, by which these would be available for 100% of makes and models by 2025 (Figure 117a, p.264);
- a scenario of faster diffusion of transplant kits, by which these would be available for 100% of makes and models by 2015 (Figure 117b); and
- a scenario of radical diffusion of transplant kits, by which these would be available for 100% of makes and models in 2009 (Figure 117c).

Our base case was calculated on the basis of the faster diffusion of transplanting kits. According to the results presented in Table 53, there is an average deviation of 2% with regards to the base case savings (higher for PM emissions and lower for other pollutants, likewise previous analyses). In short, the diffusion pattern has little influence on the overall system's performance, in the longer run.

9.5.5 Survival curves of transplanted cars

We begin by briefly bringing to memory the procedure we used to calculate the survival rates for transplanted cars. For simulation purposes, we considered that the maximum lifetime of a conventional car is 30 years. In the case of transplanted cars, we extended this maximum to 35 years. For example, if the used-car is transplanted after 10 years, we consider that its maximum surviving age is 25 years, after transplant. Or, if it is transplanted at the age of 16, it will last 19 years from then on (at the most). As lifetime extension is determined arbitrarily, we will test the impact of different values. Eq. 9-5 (section 9.2.2, p.269) presents the formula we used to calculate the survival pdf of transplanted where we extended the scale parameter β with the parameter *w*, in order to properly incorporate the assumption presented above: $\beta t_{i,k_t} = \beta_i - k_t + w$, where k_t is the age of the vehicle when it is transplanted. We assumed for the calculations of our base case, that $w = 5$. For the present sensitivity analysis, we tested firstly a shorter survival period for transplanted vehicles, by which $w = 0$, i.e. the survival probability of a transplanted car is equal to that of a conventional car. Secondly, we analyzed the situation where a car lives longer and $w = 10$. Interestingly, the results obtained in terms of LC energy and emission savings are not much different than those achieved when testing for the different diffusion patterns of transplanting kits.

Without coincidence, the effects of the two analyses are similar since they both influence the turnover rate of the fleet. If cars live longer, we would expect that the turnover decreases. Conversely, if transplanted cars experience shorter lives, the turnover should increase. Respectively, the LC energy savings where (-13%) and (-25%), compared to (-23%) of our base case. Again, these impacts are more sensitive in the case of PM emissions and less important in the case of the remaining pollutants. We conclude that survival rates have a minor influence (around 2%) on the overall results of our analysis. A policy implication striving from this analysis is that, accelerated vehicle retirement programs, combined with organ transplant of older cars, can induce overall savings, although the degree of success varies with the pollutant under analysis. Our results and interpretations are consistent with the findings by other authors (van Wee *et al.*, 2000, Dill, 2004, Kim *et al.*, 2004) concerning EOL vehicles' scrappage policies.

9.5.6 More efficient cars drive more ('rebound effect')

We assumed in our methodological approach that when a car is transplanted at age k_t, it keeps its annual mileage as if it remained non-transplanted. According to the one of the fundamental assumptions of our thesis, by which a transplanted car is efficient like a new car, the transplant car we referred above would drive the same annual kilometers although it is more efficient.

As mentioned before, this is disputable. According to the *rebound effect* principle, higher activity levels from more efficient cars could be expected, improving energy efficiency lowers the implicit price of energy and hence makes its use more affordable, thus leading to greater use. We found in the literature that the direct rebound effect resulting from increased efficiency is perhaps of the order of 10–20% of km travelled (Goodwin, 1992, Greening *et al.*, 2000, Binswanger, 2001, Goodwin *et al.*, 2004). In our case, we analyze to what extent the rebound effect resulting from increased efficiency would offset the gains in fuel use and emissions down the road. In this sense, we analyzed the values of elasticity of mileage with respect to fuel efficiency in the range of 0.1 to 0.2. The following figure illustrates our methodological approach to evaluate this rebound effect on the total mileage by the Portuguese fleet, after the introduction of transplanted alternatives.

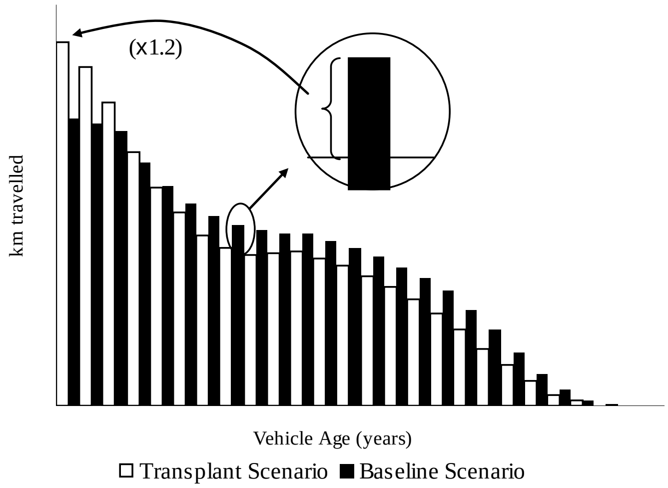


Figure 144. Illustration of the 'rebound effect' on the kilometers travelled by used cars after being transplanted (source: author)

Table 53 shows that our base case results would be offset if the rebound effect induced by the increased efficiency of transplanted cars is higher than 15%, which stays within the interval of typical rebound effect values, according to the literature we reviewed. Alcott's (2005) concluded from his discussion on the Jevons Paradox that "since greater efficiency, *ceteris paribus* and given latent demand, must raise, not lower, environmental impact, efficiency policies are wrong". Considering his arguments and according to our comparative statics on the possible 'rebound effect', we would argue that car organ transplant being an efficiency policy, it is potentially wrong from the energy and carbon emissions viewpoint. Nonetheless, the previous analyses hold true if the mileage curve (which determines the decrease in annual km travelled as the car ages) we used is well adapted to the Portuguese car use. The following section analyses this situation. In any case, car organ transplant is always interesting from the air quality point of view, independently of the extent of 'rebound effect' we tested.

9.5.7 What about the mileage curve?

We present hereafter the impacts of assuming different mileage curves, by which the annual km travelled by a car decrease linearly as from the 3rd year. We tested two cases that differ in the gradient of the linear decrease: linear decrease I with a lower gradient and linear decrease II with a higher gradient.

However, by changing the mileage curve (as showed in the following figure), we are also changing our baseline scenario. Therefore, Table 54 presents the new results obtained for the baseline scenario. It also details the results for the base case transplant scenario and, finally, the sensitivity analyses for the two different gradients of linear decrease we tested. The sensitivity analysis includes also a rebound effect of 20% increase in km travelled.

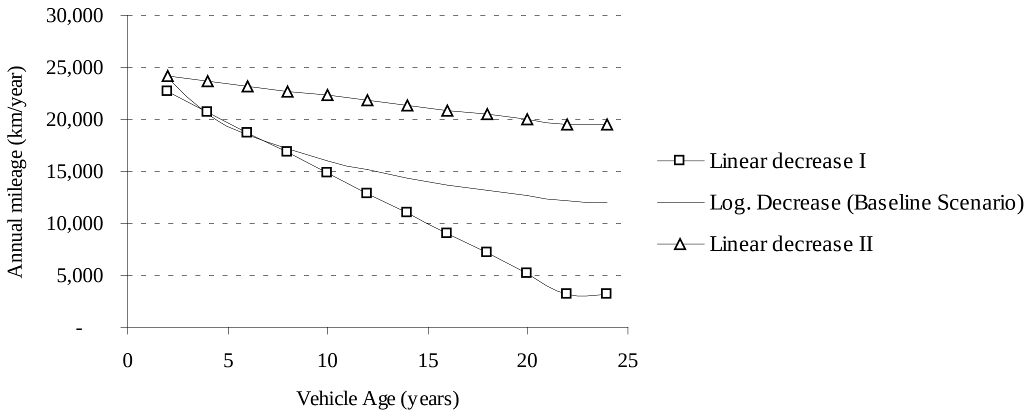


Figure 145. Comparison of mileage curves of the baseline scenario and of sensitivity analysis for a medium-sized diesel-powered car (source: author)

We conclude that the mileage curve has a strong impact on the overall results obtained. For example, while emissions of CO_2 increase 31.5 Mton in our initial baseline scenario, the equivalent increase when assuming a mileage curve with smaller decreasing gradient is 43Mton (+40%). On the contrary, when assuming a mileage curve with higher decreasing gradient, emissions of CO_2 increase 27 Mton (-16%). Patterns of variation are similar in the case of energy consumption and the remaining pollutants, exception made for NO_x and PM emissions that showed inverted variation.

Table 54. Results of sensitivity analysis to mileage curves (source: author)

	Energy (TJ)	CO_2 (kton)	CO (ton)	NMVOC (ton)	NOx (ton)	PM (ton)
Initial Baseline Scenario	31,405	2,369	-82,074	-9,887	-8,872	-848
Initial Transplant Scenario	24,224	1,814	-84,024	-10,067	-11,513	-1,218
	(-23%)	(-23%)	(-2%)	(-2%)	(-30%)	(-44%)
Linear Decrease I - Baseline scenario	42,954	3,233	-122,078	-13,461	-11,138	-751
- Transplant scenario	35,283	2,641	-123,855	-13,622	-14,608	-1,282
	(-18%)	(-18%)	(-1%)	(-1%)	(-31%	(-71%)
Linear Decrease I & Rebound effect of 20% increase of vkm	48,256	3,645	-118,412	-13,064	-12,901	-1,166
	(12%)	(13%)	(3%)	(3%)	(-16%)	(-55%)
Linear Decrease II - Baseline scenario	27,094	2,046	-60,847	-7,580	-7,312	-966
- Transplant scenario	18,908	1,415	-63,160	-7,812	-9,791	-1,300
	(-30%)	(-31%)	(-4%)	(-3%)	(-34%)	(-35%)
Linear Decrease II & Rebound effect of 20% increase of vkm	26,888	2,032	-59,757	-7,459	-8,759	-1,229
	(-1%)	(-1%)	(2%)	(2%)	(-20%)	(-27%)

Regarding the transplant scenario in both situations, we conclude that in all cases, transplanted alternatives bring LC savings in energy consumption and emissions. Naturally, when using the mileage curve with smaller decreasing gradient, gains are smaller than with the mileage curve with higher decreasing gradient. Finally, if we now analyze the impact of the rebound effect of 20% increase in annual km travelled on these linear curves, we conclude that transplanted alternatives induce LC savings in the 2nd case, i.e. when the mileage decreases faster with the vehicle's age.

All things considered, we conclude that the analysis of the rebound effect on the overall results should be made together with a more rigorous definition of our mileage curves. Otherwise, we could underestimate the potential impact of car organ transplant on the performance of the Portuguese fleet. On the other hand, this analysis reinforces the need to calibrate those curves, for the different car types considered. We recall that this task is included in the CAReFUL project that is undergoing (Moura *et al.*, 2007).

9.6. Summary and conclusions

As referred in the introduction of this dissertation, the present chapter is mostly analytical by which we try to explore to what extent transplant technologies are expected to diffuse in car fleets and, consequently, how is 'organ transplant' in cars expected to foster the technological turnover of fleets? After developing the required modeling tools in chapters 7 and 8 in order to simulate how the car stock evolves and how remarketed cars are selected from choice sets (respectively), the present chapter presents our results and conclusions regarding that research question by applying those models to the Portuguese car stock.

To evaluate the possible entrance of transplanted technologies in the car stock, we used the discrete choice model estimated for remarketed cars in chapter 8. In this sense, the present chapter begins with the presentation of the necessary modeling specifications to include the new transplanted entrants in the choice set of remarketed cars. One first important assumption was made with respect to using our remarketed car discrete choice model. While we analyze the market share of transplanted cars using a discrete choice model based on revealed preferences (RP), theory indicates that such analyses should be based on stated preferences (SP) in that new entrants correspond to new alternatives in the choice set that may induce possible impacts on the choice behavior of customer due to competition between products (that did not exist when collecting RP data). Avoiding such potential biases would involve further data to be collected so as to produce new models. As we explained before, we could not do so due to budget and time constraints. However, we also pointed out that organ transplant in cars is not a completely new alternative in that it does not alter the look of cars and does not implicate changes in the owner's behavior regarding car driving and servicing. As such, we interpret our results with this limitation in mind.

Three additional assumptions were made to enable the simulation of the diffusion of transplanted technologies:

1. Transplanted vehicles compete with remarketed cars and choices are essentially influenced by the characteristics of cars, for instance, type of vehicle (e.g., fuel type and vehicle size), investment cost (used-car price and/or organ transplant cost), age, operation costs, taxes, and the number of makes and models with transplanting kits available in the market.

2. If a vehicle is transplanted with a newer propulsion system, its performance in terms of energy consumption and emissions is that of a new system.

3. A used-car is transplantable once during its lifetime.

Implicitly, we assume that new cars are not included in the choice set and as such they are not included in the universe of transplantable cars (which to our understanding is fairly acceptable in that new cars are not prone to being transplanted as we concluded in Chapter 5). In this sense, the universe of transplantable cars was estimated by adopting a simple approximation of reality and using the moving-average of the ratio of used-to-new cars ($r_{U:N}$), with a time window of the previous 5 years. By doing so, we make sure that transplanted vehicles do not compete directly within the new car market (i.e., one of our assumptions).

To estimate the potential market share of transplanted technologies annually we added a transplanted alternative to each of the prior car types considered. Consequently, the choice set includes now twelve alternatives (when it included six alternatives in the original choice set). The tree structure of the nested logit remains the same and includes two fuel nests where each alternative disputes directly its share with the remaining alternatives of the same fuel nest, but any variation in one alternative's attributes of one nest implies an equal variation in all the alternatives of the other nest. Regarding the attributes of the new entrants, the only differences from their conventional counterparts were fuel costs (as transplanted alternatives are expected to more efficient – Assumption 2 of the model) and car prices, that include the transplant costs for each car type (approximately 4,500€).

In order to capture possible resistance to the performing organ transplant in the early stages of diffusion, we included the number of models for which there are transplanting kits available in the aftermarket. The logic behind this attribute is that the more there are models with available transplanted kits in the aftermarket, the more consumers will get acquainted with this technological alternative and consumers will lower their *a priori* resistance. To model the variation of this attribute we used Rogers (2003) generalization of technological diffusion and tested three different scenarios: slow, fast and radical diffusion of transplanted kits where full displacement periods varied accordingly.

The discrete choice model provided us the annual technological distribution and number of cars that are transplanted. Complementarily, we added some specifications to the car fleet evolution model to simulate the diffusion the transplanted alternatives. For instance, we considered that it is expectable that the lifetime of a car is extended a few years after being transplanted, although it wouldn't be reasonable to consider that its age would be reset as it was new (i.e., age = 0 years). This is why we define a new survival curve for the transplanted-cars which is a conditional probability of survival after being transplanted, knowing that it already survived until X years. For simulation purposes, we considered that the maximum lifetime of a transplanted car 35 years (while the maximum for conventional cars was 30 years). Since transplanted cars last longer than conventional cars and assuming that the total stock of cars remains equal on both Baseline and Transplant scenarios, we expect a reduction of new cars sold after the diffusion of transplanted alternatives. On one hand, this has a positive environmental impact since there is a reduction of raw material consumption (by reducing the production of new cars), besides the reduction of energy consumption and emissions during the operation phase since transplanted cars are expected to be more efficient than their conventional counterpart. On the other hand, this might have a negative economic impact on the automotive industry since the demand for new cars decreases, although there would be an increase of the production of car parts and components (for transplanting purposes).

According to our assumptions and considering transplant prices (for the final consumer) equal to transplant costs, the potential market share of the transplanted technologies would be nearly half of the consumers of remarketed cars. Accordingly, there would be a shift from gasoline to diesel-powered vehicles, in general terms, as the majority of transplanted cars are diesel-fuelled. In addition, we estimated the optimal price that would maximize revenues for the transplant supply chain and concluded that prices would be higher than transplant costs by a factor of 2.5, approximately. Consequently, demand would lower and the potential market share of transplanted cars would become nearly 30%. At the end, we concluded that, for example, a car owner who buys a 7-years old, midsize gasoline-powered car after being transplanted would pay around 21,400€ that account for: the vehicle's residual value 11,500€; 4,400€ of transplant costs; and 5,500€ of value added and other costs (e.g., taxes). These are good grounds for the transplant business since the potential gross benefit (26%=5,500/21,500×100) would allow several stakeholders to participate in the value chain of transplanting services although we note that this profit margins are over-estimated.

In reality, transplant prices are overly priced and this is related to the approach we used in that it did not include potential competitors, no economies of scale (due to lower material costs), and no benefits of a learning curve (due to gaining expertise in manufacturing and operating). The shifts of market shares were estimated as if there was only one transplanter for each car type and therefore they would behave monopolistically in their specific market. As such, the optimal price obtained here is higher than the one that would be practiced under perfect competition conditions. Accordingly, the transplanter would have to increase the quantity of organ transplants for profit-maximization. We conclude that the share of transplanted vehicles would lie somewhere between 30% and 50% of remarketed cars. In Chapter 6, we concluded that the payback period for a car transplanted at the age of 6 years, would correspond to 7 years, if transplant prices were 50% of base costs, i.e. roughly 7,000€. In this case, the overall market share for transplanted vehicles we round to 40% of remarketed cars.

Our results suggest also that the cars that are more attractive for organ transplant are aged between 6 and 11 years old. This is consistent with the results we obtained in Chapter 6 when we concluded that the vehicle should be at least 5 years old in order to ensure a positive environmental impact of transplanting operations, if the car is used 6 years after being transplanted (accounting for lifecycle energy consumption and emissions). In reality, if a vehicle younger than 5 years is transplanted (which according to our model has less than 10% chances of taking place), the gains in fuel economy and emissions are not sufficiently high to outweigh the energy consumed and emissions associated with transplanting operations (manufacturing and scrappage lifecycle stages of transplanting kits and replaced equipments).

Transplanted cars are expected to diffuse at an annual rate of 3% of the total stock. Considering that new technologies were conventionally diffused through the entrance of new cars in the stock, organ transplant in cars increases the technological turnover from 7% to 10%, i.e. the full deployment of a new technology is potential cut down by 4 years. The main impacts related to the introduction of transplanted cars in the used-car market are:

- The average age of the baseline fleet is expected to decrease 1.5 years (from 8.5 to 7 years) where the percentile 60% decreases from 8 to 6 years of age and percentile 90% decreases from 16 to 14.
- The introduction of transplanted technologies in the market induces a shift towards smaller and diesel powered vehicles, i.e. potential downsizing of the car stock.
- After 2015, we estimate the production of new cars is cut down by 50 thousand new cars (i.e., a difference of (-14%) compared to the baseline scenario), while 155 thousand cars are transplanted (we recall that approximately 350 thousand cars are sold annually).
- In the longer run (i.e., after 2020), more than 30% of the fleet would have been transplanted with new and more efficient modules and systems, according to our assumptions.

These impacts are potentially more expressive, considering that there are significant differences in fuel consumption and emissions between smaller and larger vehicles and that older vehicles are normally higher emitters (although they have lower annual mileages). The stock dieselization has both an upside and a downside impact: whereas diesel cars consume less than equivalent gasoline cars (and, for itself, it emits less carbon dioxide), they generate more particulates and NO_X (although these can be solved through after exhaust treatment equipment). The car stock technological transformation is also reflected in its distribution in terms of the EURO standards. Assuming that transplanted cars behave and are classified like new cars, organ transplant in car could increase the number of EURO 5 and 6 vehicles by 20% until 2020, compared with the baseline scenario.

Generically, lifecycle energy consumption and emissions are reduced after organ transplant in cars is introduced as an alternative to conventional car ownership and servicing. According to our assumptions, there is an overall saving of (-4%) of energy consumption, by 2020. Higher reductions are expected during the material production and car manufacturing lifecycle stages (in the order of -20% reductions) mainly due to the fact that transplanted cars last longer and, consequently, we expect a decrease in the production of new cars required to match annual stock demand. For the same reason, less cars are expected to be scrapped annually, and although there is an increase of energy consumption from the scrappage of replaced equipment, the final balance is that EOL energy consumption is reduced by (-40%), in 2020. Still, EOL energy consumption and emissions correspond to less than 1% of total LC. Similar results were obtained for the remaining parameters that we analyzed, i.e., emissions of CO_2, CO, NMVOC, NOx and PM. Accordingly, after the introduction of transplanted alternatives, we can look ahead to a decrease of raw material consumption (-10% by 2020) and waste generation (-14% by 2020). The majority of waste (nearly 80%) is reused or recycled (as expectable, attending to the load factors we used).

Although the global percent-variation is apparently low (around 4-5%, depending on the parameter analyzed), it corresponds to expressive reductions in absolute terms. For example, in the case of CO_2 emissions, this percentage equals 555Gg, 780Gg and 660Gg, in 2020, 2025 and 2030, respectively. This potential for emissions reduction is major when compared to the effectiveness of other transport policy instruments included in carbon reduction strategies. For example, transplant technologies would contribute more than any measure of the Portuguese National Program for Climate Change (PNAC), except for the introduction of biofuels that is expected to generate a reduction of 1,200 Gg of CO_2 emissions. Complementarily, the introduction of transplant-technologies would also provide an annual reduction of nearly 1.5 Gg of NOx (~4% of total emissions of passenger cars) and 0.5 Gg of NMVOC (~4% of total emissions of passenger cars), after 2015. The measures included in the Portuguese National Emissions Ceiling Program (PTEN) are less outreaching than the results presented here.

Importantly, the reduction of LC energy consumption and emissions is not constant over time, as transplant technologies diffuse progressively. On one hand, there is a delay of approximately 3 years to counterbalance the energy consumption and emissions from the production of transplanting kits and scrappage of replaced components (refer to Chapter 6). On the other, in the beginning of organ transplant of cars, the increase in production of transplanting kits is higher (on a mass-basis) than the reduction of new car produce annually. Clearly, we concluded also that reductions are expected to decrease by the end of our period of analysis (i.e., 2030) mostly due to the deceleration of the fleet's turnover and the reduction in the number of transplanted vehicles. The decline of transplantable remarketed cars in the Portuguese fleet occurs from 2017 onwards, since a larger share of used cars (nearly, 30%) was already transplanted (and we recall that a car can be transplanted only once during its service time – according to our assumptions).

Finally, we performed a sensitivity analysis to criteria parameters of the model. We resume the main conclusions hereafter:

- Transplant prices slightly influence the final results of our model (±10% for a variation of 50%of prices).
- With respect to circulation taxes, we concluded that the outputs of our model are not sensitive, which is consistent with our discussion in Chapter 8 where we analyzed the parameters of the discrete choice model.
- Savings in LC energy consumption and CO_2 emissions are sensitive (±15%) to changes in the ratio of used-to-new ($r_{U:N}$) cars we used to estimate the annual population of transplantable vehicles.
- Diffusion of transplant technologies was analyzed for two complementary scenarios: slow and radical diffusion. We conclude that sensitivity of LC energy consumption and emission savings is low (±5%).
- We analyzed the survival curves of transplanted cars and concluded that final savings are more sensitive in the case of energy consumption, CO_2 and PM emissions (around ±7% for a variation of ± 5 years to the maximum service time of cars). For the remaining parameters, variations are lower.
- We tested the rebound effect by which cars would drive more as a result of to increased fuel efficiency. We tested 3 scenarios: 10%, 15% and 20% increases in annual kilometers driven for all car types. Importantly, we conclude that if there is a rebound effect of more than 15%, the gains in fuel efficiency are outweigh by the increase in the use of cars. This is an important conclusion since it delimits the range of effectiveness of the concept we explore here, i.e., organ transplant in cars contributes positively to energy and environmental efficiency if it is implemented with complementary measures to restrain the increase in mobility.
- Finally, after analyzing the impact of different mileage curves (slower and higher mileage decrease with age), we conclude that overall LC energy consumption and emissions are sensitive to mileage of cars. We concluded also that the analysis of the rebound effect on the overall results should be made together with a more rigorous definition of our mileage curves. Otherwise, we could underestimate the potential impact of organ transplant on the performance of the Portuguese fleet. On the other hand, this analysis reinforces the need to calibrate those curves, for the different car types considered.

Part C is now concluded and we present in the next chapter a summary of the main conclusions from the present research. We discuss some important policy implications related to the results we obtained when exploring the concept of organ transplant in cars. Finally, we review the limitations of our methodological approach and present the outlook for further research developments outcoming from the present dissertation.

Chapter 10. Summary, conclusions, research restrictions and future work

This dissertation has attempted to explore the concept of organ transplant in cars by addressing two main objectives and related themes through: on one hand, the lifecycle impacts of organ transplant for different car ownership scenarios and, on the other, the systemic impacts of the car organ transplant in a car fleet, over time. This was motivated by the fact that realizing the goals of sustainable mobility represents a significant and complex challenge for which the current set of solutions has not given a satisfactory response, both on the management of travel demand and on the diffusion of new and more efficient technologies. The elements of sustainable development that this dissertation has focused on are those most relevant to the automotive system, particularly in terms of the impacts of current patterns of car ownership on energy demand, climate change, and local and regional air pollution. Other aspects of environmental sustainability are also addressed and relate to material use and waste generation throughout a car's lifecycle.

The first objective was to develop a comprehensive set of scenarios and tools to analyze the potential attractiveness of such concept from the car owner's perspective. We used lifecycle analysis to evaluate the possible energy and environmental impacts of organ transplant in cars over a period of 20 years. Our analysis would have been incomplete if we had discarded the economic analysis of car ownership and had not analyzed the comparative attractiveness of transplanting cars instead of keeping the car as it is or acquiring a remarketed car. In these contexts, we tried to bring answers (mostly, in part B of the dissertation) to our first research question, i.e., does car organ transplant reduce lifecycle energy and environmental impacts when compared to conventional car ownership approaches, and is it attractive for car owners when comparing its total ownership costs to those of conventional approaches? Here, the methodological approach was to compare different scenarios of ownership of a midsize gasoline car by separately analyzing the competitiveness of the specific lifecycle profiles. However, we did not analyze how transplanted vehicles would systemically accommodate in a car fleet, over time, and how these would generally affect the fleet's performance.

Accordingly, the second main objective of this dissertation was to study the potential impact of organ transplant in cars on an entire fleet and discern possible systemic effects. In this sense, we developed a second set of tools that warranted a more detailed analysis of potential market share transfers reflecting trade-offs between competing alternatives of car ownership – specifically, choosing among different car types (six combinations of fuel and engine size) with different vintages. The systemic analysis followed a lifecycle approach of car use and conclusions include not only energy and environmental performance but also material consumption and waste generation. We presented the corresponding research developments and conclusions in Part A of the present dissertation that bring the answers to our second research question, i.e., to what extent are transplant technologies expected to diffuse in car fleets and, consequently, how is 'organ transplant' in cars expected to foster the technological turnover of fleets? For that reason, what are the corresponding energy and environmental impacts considering whole fleets?

Throughout our research, we calculate energy and material consumption or emissions and waste generation by multiplying the number of each car type with the respective energy/environmental coefficients (and mileage curves, when appropriate). Whereas emissions from car use are based on the EMEP/CORINAIR guidelines from the European Environmental Agency (EEA, 2007b), the remaining coefficients were collected from the scientific literature and from industry reports.

The remainder of this chapter presents a summary and the main conclusions of the two main parts dealt with in this dissertation. We finish by presenting the main research restrictions we faced and present potential improvements to our analytical framework and future research developments.

10.1. Research scope and key findings

Despite the diffusion of more efficient new vehicles, the concentration of air pollutants in many urban areas often exceeds air quality standards and there is strong evidence that climate change is being increasingly induced by anthropogenic emissions of greenhouse gases. In reality, higher efficiency of cars is being off-set by increased motorization and mobility and by diverting the technological improvement gains into non-fuel saving vehicle features. As such, the transition to a more sustainable transportation system requires a fleet conversion policy that efficiently absorbs new, clean technologies and retires old, high-polluting technologies.

However, the technological turnover of fleets has been largely determined by the pace of retirement of older vehicles and replacement by new models and the total displacement of older technologies can last more than 40 years. One environmental implication of slower diffusion rates is technological obsolescence of the running stock. Furthermore, we observed (from literature review) that accelerating the turnover of fleets for faster diffusion of technologies can potentially increase environmental lifecycle impacts associated to more intensive construction and scrapping of vehicles. As such, organ transplant in cars arises as one additional solution as part of an energy consumption and environmental impact reduction strategy for automobility by which the service time of vehicles would be extended while keeping them technologically up-to-date. The objective is to replace any component of the powertrain and energy intensive parts of the car that are technologically outdated, downgraded or malfunctioning while keeping the remaining state-of-the-art and fully operative components and parts, in order to improve its energy and environmental performances and possibly reach 'like new' standards.

The next section resumes the main conclusions of part B of the dissertation where we explored this concept form the car owner's perspective.

10.1.1 Car organ transplant, car ownership and lifecycle burdens

We used lifecycle analysis to evaluate the possible energy and environmental impacts of organ transplant in cars over a 20-year ownership of midsize gasoline-powered car (Chapter 1). We quantified lifecycle emissions of greenhouse gases and regulated pollutants. Whereas greenhouse gases have global effects (particularly through global warming and consequently climate change), regulated pollutants have local effect on air quality (and importantly on public health). Although regulated pollution has local impacts (and therefore each lifecycle stage has a consequence in a different location), our approach links those lifecycle emissions of the car to the final user, i.e. the car owner.

Our analysis comprised the following lifecycle stages in a LCI (lifecycle inventory) model: material production; vehicle manufacturing; car use; maintenance and repair; end-of-life disposal. Whereas this lifecycle characterization refers mainly to the car *per se*, and is usually referred to 'cradle-to-grave', we included also the lifecycle burdens related to the fuel used to operate cars, which is usually referred to 'well-to-tank' and that include fuel refining, transportation and delivery. In the case of transplanting kits, we considered three lifecycle stages: material production, components manufacturing and parts assembly, and EOL processing of replaced components. As referred in section 3.2.2 (p.66), the selection of the transplanting kit parts and components was based on the influence these might have on the energy and environmental efficiency of the car and, in short, they include the components of the powertrain, electronic command and control, climate control and exhaust systems. Importantly, the energy and environmental intensity of each lifecycle stage reduces over time as technological development generally makes processes more efficient, whether these relate to car production, use or scrappage. As such, the LCI model we developed is dynamic, in the sense that coefficients decrease over time.

Generally, the operation stage of the cars lifecycle is responsible for more than 90% of energy consumption or emissions, while the production stages are more intensive regarding material consumption and EOL disposal is more important with respect to waste generation. EOL stage is not significant (<1%) in terms of energy consumption or emissions in the context of the vehicle's lifecycle. Importantly, burdens are more important (factor of 3) during the first year as fixed burdens are allocated to that year and relate to material and car productions. The second year is the less intensive in all respects and, thereafter, efficiency decreases smoothly as the car ages. In this case, marginal burdens increase as technology loses efficiency, i.e., to a large extent, energy consumption and emissions factors increase as the car accumulates kilometers.

The trade-off between fixed and marginal burdens plays an important role. Organ transplant in cars is to be successful only when the reduction of marginal burdens during the operation stage offsets the initial fixed burdens. As a matter of fact, the energy and environmental burdens associated to the production of transplanting kits correspond roughly to 20% of the vehicle's lifecycle burdens. We concluded that organ transplant in cars can generate energy and environmental benefits, depending on the age of transplant and the period the vehicle is used thereafter. According to our assumptions, the payback period of technological transplant (i.e., the time period necessary for the cumulative marginal reductions in efficiency to offset the initial fixed burden) can range from 2 to 19 years, if the car is transplanted at the age of 5. The range of payback periods is related to the expected technological development that is different among energy and environmental burdens. If emissions are expected to decrease significantly (e.g., NMVOC) then marginal gains are higher and, as such, the payback period is shorter. Conversely, if technology development is not expected to delivery much (e.g., NO_X), than payback periods are longer. Importantly, the estimated weighted payback period was 6 years, for the same transplant age (the weighted payback period was obtained by converting energy and environmental burdens into monetary units). Furthermore, producing a transplanting kit requires less 1,200 kg of raw materials and less 100 GJ than a conventional midsize car. Likewise, the production of a car generates 670 kg of solid waste, almost 7 times more by mass than is generated during transplanting kits production (i.e., 100 kg of solid waste per kit).

Consequently, we conclude also that car transplant (alone) reduces material flows when compared to a conventional car.

The previous analysis was extended to the total car ownership cost – TOC (Chapter 5). These costs included depreciation, financing, fees and taxes, insurance, fuel, scheduled maintenance and unscheduled repairs. We concluded that the highest costs of car ownership are related to the depreciation of the car over its service time. Conversely to energy and environmental burdens, per km unit cost of car ownership (all costs considered) decreases significantly as the car ages (up to 55% for a 20-years service time). Importantly, the fixed costs of car ownership (which include financing, depreciation, insurance and taxes) are always dominant during the vehicle's service time. During the first 5 years, these correspond to more than 80% of total costs and 50% of total costs over the entire service time. These analyses suggest that, from the economic perspective, extending the service time of the car is a rational and more profitable option.

We estimated that transplant costs of a midsize gasoline-car are approximately 4,400€ (i.e., 25% of remarketed car whose residual value is nearly 18,000€ or 15% of a new car costing 30,000€). We conclude from our analyses that organ transplant in cars might be an interesting option for some car owners, since they can recover their investment after a reasonable period of time (i.e., approximately 5-7 years depending on the age of transplant, although this depends strongly on the transplant price to be adopted by transplanters). In addition, there are environmental gains from transplant operations by which increased emissions are recovered after shorter periods of time (i.e., 4-5 years), as well due to the production of transplanting kits and scrappage of replaced components. We recall that we do not include in this environmental damage accounts, the avoidance of raw materials consumption and waste production. Therefore, the payback periods should be even lower. Furthermore, if the transplanting kit includes remanufactured parts and/or components, the overall energy, environmental and economic burdens can be potentially lower.

Besides the analysis of the vehicle profile in economic and environmental terms, we compared several ownership alternatives (Chapter 6), i.e., we evaluated the potential environmental and economic benefits of organ transplant in used-cars when compared to conventional cars, new or used. We compared the LCI and TOC of five scenarios for 20-years car ownership. As such, we analyzed the lifecycle for five different car ownership alternatives: keep car over 20 year; buy new car periodically, over the same time period; buy remarketed cars; buy remarketed cars that were transplanted; or keep car while transplanting new and cleaner technologies periodically.

We assumed a base case where cars are replaced or transplanted every 7 years and remarketed cars are bought with 6 years of age (when applicable). Our analyses show that organ transplant in cars provides significant reductions in overall energy consumption, i.e. 3% less than keeping the car over 20 years. Likewise, air emissions (-6.2% for CO, -25% for NMVOC and -4% for CO_2) and solid waste production (-20%) are reduced. Technological transplant is (logically) more material-intensive (more 40%) than keeping a car over 20 years. Still, transplanting cars consumes half of the raw material used if cars are replaced by new cars periodically (e.g., every 7 years). Importantly, additional environmental burdens from technological transplant are recovered over a reasonable number of years, given the gains of efficiency achieved – we obtained 6 years for a car transplanted at the age of 5, based on a multi-objective function by which environmental burdens are converted into monetary terms (except for material consumption and waste). On one hand, energy consumption and emissions are cut down as a result of the installation of cleaner technologies that increase the efficiency of the vehicle. On the other, car demand is restrained due the extension of cars' service time after transplant. Consequently, car production and scrappage is avoided and material use and waste generation are reduced.

Exceptions are made for PM and NO_X emissions. In the first case, PM emissions produced by gasoline-fuelled cars are not significant and, therefore, reductions from technological upgrades are null. And, NO_x emissions factors are not reducing as strongly, over the last years, contrarily to the other pollutants. As such, marginal gains do not offset fixed burdens related to the production of transplanting kits.

Finally, we conclude also that technological transplant contributes positively to the reduction of TOC and transplanting the car twice over 20 years reduces overall costs by 4% when compared to keeping the car over the same period of time. The extent of the LC gains (whether environmental or economic) varies with the age of the transplanted car. All costs and pollutants considered, maximum benefits are reached at the age of 9 (and 5) for environmental damage (or economic costs). However, reasonable payback periods (less than 7 years) are obtained if cars are transplanted after the age of 5. After that payback periods decrease (almost linearly) as the transplanting age increases. Technological transplant is potentially attractive for car owners, considering that the break-even of the initial investment is reached over a reasonable time horizon, while contributing to reducing LC environmental impacts.

When comparing all scenarios of ownership, we conclude that transplanting the car twice over 20 years results in the smallest economic ownership costs. Conversely, buying three new cars in 20 years is the least attractive economic option, according to the assumptions used here. Likewise, the best alternative is to transplant cars or buy transplanted cars, whereas the worst alternative is to buy a new car every 7 years (although the total environmental costs differ little between scenarios). Furthermore, transplanted cars are more efficient than conventional used or remarketed while transplant operations consume fewer materials than producing new cars. Our analysis suggests that consumers could be guided to consider organ transplant when deciding to swap their car and that the automotive industry can envisage a new approach to car ownership by providing new car servicing approaches and commercial links with their customers. For instance, they could include in the programmed servicing the possibility of organ transplant throughout the vehicle's service time. We will return to this point later.

10.1.2 Car fleet, technological turnover, energy and environmental benefits

In Part C of the dissertation, we extend our assessment of car organ transplant to the entire fleet. It is important to bear in mind that there are three main differences to Part B:

- Firstly, the analysis is centered on the overall fleet and not on the ownership of car over 20 years (as in part B) and, as such, the life expectancy of cars is determined probabilistically (with survival curves) and the ownership of cars is important to the extent that we need to estimate the number of cars that are prone to being transplanted (the choice of ownership alternative is determined probabilistically through a nested logit);

- Secondly, we consider six car types (combination of two fuel types with three engine sizes) and all vintages (from 0 to 25 years), contrarily to part B where we considered a midsize gasoline-fuelled car; and,
- Thirdly, the analysis is systemic in the sense that all car types compete under equal circumstances for their market share.

In this sense, we developed a combined model of 'aggregate time series' (Chapter 7) to estimate the car demand (the running stock) over time (1995-2007) with a 'static disaggregate car-type discrete choice model' to build a reasonable approximation of the Portuguese car fleet, where policy sensitive variables are included to explore different policy scenario analyses. We used this model to evaluate the possible future diffusion of transplanted cars over time. The overall technological composition of the fleet over time is obtained by estimating which car types are retired and sold yearly. Finally, to estimate the diffusion capacity of transplanted technologies, which depends on the consumer's preferences and behavior regarding this kind of technology, we develop a discrete choice model to simulate the options of consumers when facing a finite set of remarketed-car alternatives, including transplanted cars (Chapter 8).

The first step was to estimate the evolution of total car density of the Portuguese using a logistic curve (Chapter 7). The car density was based on the population of license holders and we obtained the following parameters: K=900; a=-0.189; b=378 (R^2=0.99). Our results indicate that car density can reach 890 cars/1,000 license holders (which is equivalent to 600 cars/1,000 inhabitants) by 2030 and that it should stabilize thereafter. After estimating the annual global stock of cars and knowing how many vehicles are scrapped yearly, we calculate the number of new vehicles entering the car stock each consecutive year. With respect to the scrappage of cars, we used a probabilistic approach using a Weibull s-shaped curve and calibrated the corresponding parameters (shape and scale) on a 5-year basis to approximate our fleet technological composition and volume to the figures presented by ACAP (ACAP/AUTO INFORMA, 2007). As such, the parameters vary but, generally, we estimate that 20% of cars would be retired after they are approximately 15 years old (results should be viewed taking into account that they result from modeling calibration as there are no thorough statistics for scrappage in Portugal). This is equivalent to 150,000 scrapped cars yearly. According to our assumptions and calculations, long-term annual sales should stabilize at approximately 350 thousand passenger cars a year (although fluctuations can occur due to economic and market circumstances that our aggregate modeling approach does not capture). The technological structure of new cars sold yearly (i.e., combination of fuel type and engine size of each car) was determined exogenously by adopting the estimates from TREMOVE (Ceuster *et al.*, 2007b).

Furthermore, we conclude that as the car fleet reaches maturity (i.e., car density stabilizing at 900 cars/1,000 license holders), the technological structure also stabilizes, according to our assumptions and modeling results. These indicate that the gasoline stock is 6 years old, in 1995. By 2010, it should get older (11 years) and stabilize at 9 years of age, thereafter. Differently, the diesel stock gets younger from 6 to 5 years, from 1995 to 2010 (probably due to the dieselization of the Portuguese car stock), and then it stabilizes at 9 years of age (although later than the gasoline stock). Accordingly, we conclude that in 2005 nearly 25% of the stock is equipped with technologies complying with pre-EURO standards (model years before 1991). Likewise, our estimates indicate that these vehicles correspond to 5% of the stock, by 2010, while 60% should comply with post-EURO 2 standards. Furthermore, 70% of cars should be fitted with post EURO 4 technologies, by 2020. Importantly, significant reductions in emission factors (more than 80%) occur after the introduction of EURO 1 technologies. As such, much reduction can be achieved through a faster technological turnover of the fleet.

Differently to the technological structure of new car sales that was taken from Ceuster *et al.* (2007b), we developed a discrete choice model to simulate the options of consumers when facing a finite set of remarketed car alternatives in order to include the option of transplanted cars and analyze the potential diffusion of such technologies in the future (Chapter 8). Three important assumptions were made to enable the simulation of the diffusion of transplanted technologies:

1. Transplanted vehicles compete with remarketed cars and choices are essentially influenced by the characteristics of cars: type of vehicle (e.g., fuel type and vehicle size), investment cost (used-car price and/or organ transplant cost), age, operation costs, taxes, and the number of makes and models with transplanting kits available in the market (these were the attributes included in the utility function of the nested logit we estimated).

2. If a vehicle is transplanted with a newer propulsion system, its performance in terms of energy consumption and emissions is that of a new system.

3. A used-car is transplantable once during its lifetime.

Implicitly, we assume that new cars are not included in the choice set and as such they are not included in the universe of transplantable cars (which to our understanding is fairly acceptable in that new cars are not prone to being transplanted as we concluded in Chapter 5). In this sense, the universe of transplantable cars was estimated by adopting a simple approximation of reality and using the moving-average of the ratio of used-to-new cars ($r_{U:N}$), with a time window of the previous 5 years. The discrete choice model provided us the annual technological distribution and number of cars that, according to our assumptions, can potentially be transplanted among this universe. In this sense, we added a transplanted alternative to each of the prior car types considered. Consequently, the choice set included twelve car alternatives (when it included six alternatives in the original choice set). In addition, we divided the transplanted alternatives into four different vintage ranges, i.e., one alternative with the same age as its conventional counterpart, and three additional alternatives from the following ranges: 1 to 4, 5 to 8, and more than 9 years. All in all, we had 30 different car alternatives: 6 conventional car types + 6 transplanted car types × 4 vintage ranges.

Complementarily, we added some specifications to the car fleet evolution model to simulate the diffusion the transplanted alternatives. For instance, we considered that it is expectable that the lifetime of a car is extended a few years after being transplanted, although it wouldn't be reasonable to consider that its age would be reset as it was new (i.e., age = 0 years). Since transplanted cars last longer than conventional cars and considering that the aggregate demand of cars (the running stock) remains equal whether there are transplanted alternatives or not, we expect a reduction of new cars sold after the diffusion of transplanted alternatives. On one hand, this has a positive environmental impact since there is a reduction of raw material consumption (by reducing the production of new cars), besides the reduction of energy consumption and emissions during the operation phase since transplanted cars are expected to be more efficient than their conventional counterpart. On the other hand, this might have a negative economic impact on the automotive industry since the demand for new cars decreases, although there would be an increase of the production of car parts and components (for transplanting purposes).

According to our assumptions and considering transplant prices (for the final consumer) equal to transplant costs, the potential market share of the transplanted technologies would be nearly half of the consumers of remarketed cars. Accordingly, there would be a shift from gasoline to diesel-powered vehicles, in general terms, as the majority of transplanted cars are diesel-fuelled. In order to include some profit margins for the transplant supply chain, we estimated the optimal price that would maximize their revenues and concluded that prices would be higher than transplant costs by a factor of 2.5, approximately. We recall that our approach for determining the optimal price is indicative since we did not include potential competitors, no economies of scale (due to lower material costs), and no benefits of a learning curve (due to gaining expertise in manufacturing and operating). The shifts of market shares were estimated according to the demand curve we obtained and as if there was only one transplanter for each car type that would hence behave monopolistically in his own market. Under such circumstances, the optimal price we obtained is higher than the one that would be feasible under realistic competition conditions.

Assuming the prices we obtained, demand would lower and the potential market share of transplanted cars would become less than 30%. At the end, we concluded that, for example, a car owner who buys a 7-year old, midsize gasoline-powered car after being transplanted would pay around 21,400€ that account for: the vehicle's residual value 11,500€; 4,400€ of transplant costs; and 5,500€ of value added and other costs (e.g., taxes). These are good grounds for the transplant business since the potential gross benefit (26%=5,500/21,500×100) would allow several stakeholders to participate in the value chain of transplanting services although we note that the profit margins are over-estimated.

Under perfect competition conditions, the transplanter would have to increase the quantity of organ transplants for profit-maximization, in face of a price reduction. We conclude that the share of transplanted vehicles would lie somewhere between 30% and 50% of remarketed cars. In Chapter 6, we concluded that the payback period for a car transplanted at the age of 6 years, would correspond to 7 years, if transplant prices were 50% above base costs, i.e. roughly 7,000€. In this case, the overall market share for transplanted vehicles we round to 40% of remarketed cars.

Our results suggest also that the cars that are more attractive for organ transplant are aged between 6 and 11 years old. This is consistent with the results we obtained in Chapter 6 when we concluded that the vehicle should be at least 5 years old in order to ensure a positive environmental impact of transplanting operations, if the car is used 6 years after being transplanted (accounting for lifecycle energy consumption and emissions). In reality, if a vehicle younger than 5 years is transplanted (which according to our model has less than 10% chances of taking place), the gains in fuel economy and emissions are not sufficiently high to outweigh the energy consumed and emissions associated with transplanting operations (manufacturing and scrappage lifecycle stages of transplanting kits and replaced equipments).

Furthermore, our results indicate that transplanted cars are expected to diffuse at an annual rate of 3% of the total stock. Considering that new technologies were conventionally diffused through the entrance of new cars in the stock, organ transplant in cars increases the technological turnover from 7% to 10%, i.e. the full deployment of a new technology is potentially cut down by four years. The main impacts related to the introduction of transplanted cars in the used-car market are:

- The average age of the baseline fleet is expected to decrease 1.5 years (from 8.5 to 7 years) where the percentile 60% decreases from 8 to 6 years of age and percentile 90% decreases from 16 to 14.
- The introduction of transplanted technologies in the market induces a shift towards smaller and diesel powered vehicles, i.e. potential downsizing of the car stock.
- After 2015, we estimate the production of new cars is cut down by 50 thousand new cars (i.e., a difference of (-14%) compared to the baseline scenario), while 155 thousand cars are transplanted (we recall that approximately 350 thousand cars are sold annually).
- In the longer run (i.e., after 2020), more than 30% of the fleet would have been transplanted with new and more efficient modules and systems, according to our assumptions.

These impacts are potentially more expressive, considering that there are significant differences in fuel consumption and emissions between smaller and larger vehicles and that older vehicles are normally higher emitters (although they have lower annual mileages). The stock dieselization has both an upside and a downside impact: since diesel cars consume less than equivalent gasoline cars (and, consequently, it emits less carbon dioxide), but they generate more particulates and NO_X (although these can be solved through after exhaust treatment equipment). The car stock technological transformation is also reflected in its distribution in terms of the EURO standards. Assuming that transplanted cars behave and are classified like new cars, organ transplant in car could increase the number of EURO 5 and 6 vehicles by 20% until 2020, compared with the baseline scenario.

Generically, lifecycle energy consumption and emissions are reduced after organ transplant in cars is introduced as an alternative to conventional car ownership and servicing:

- There is an overall saving of (-4%) of energy consumption, by 2020. Higher reductions are expected during the material production and car manufacturing lifecycle stages (in the order of 20% reductions) mainly due to the fact that transplanted cars last longer and, consequently, we expect a decrease in the production of new cars required to match annual stock demand.

- For the same reason, less cars are expected to be scrapped annually, and although there is an increase of energy consumption from the scrappage of replaced equipment, the final balance is that EOL energy consumption is reduced by (-40%), in 2020.
- Similar results were obtained for the remaining parameters that we analyzed, i.e., emissions of CO_2, CO, NMVOC, NOx and PM.
- Finally, we can look ahead to a decrease of raw material consumption (-10% by 2020) and waste generation (-14% by 2020). The majority of waste (nearly 80%) is reused or recycled (as expectable, attending to the load factors we used).

Although the global percent-variation is apparently low (around 4-5%, depending on the burden under analysis), it corresponds to expressive reductions in absolute terms. For instance, carbon reductions (555Gg, 780Gg and 660Gg, in 2020, 2025 and 2030, respectively) are important when compared to the effectiveness of the transport policy instruments included the Portuguese National Program for Climate Change (PNAC), where for example, the introduction of biofuels is expected to generate a reduction of 1,200 Gg of CO_2 emissions. Complementarily, the introduction of transplant-technologies would also provide an annual reduction of nearly 1.5 Gg of NOx (~4% of total emissions of passenger cars) and 0.5 Gg of NMVOC (~4% of total emissions of passenger cars), after 2015. The measures included in the Portuguese National Emissions Ceiling Program (PTEN) are less outreaching than the results presented here.

Importantly, we concluded also that reductions are expected to decrease by the end of our period of analysis (i.e., 2030) mostly due to the deceleration of the fleet's turnover and, consequently, the reduction in the number of transplantable vehicles. The decline of transplantable remarketed cars in the Portuguese fleet occurs from 2017 onwards, since a larger share of used cars (nearly, 30%) was already transplanted (and we recall our assumption that a car can be transplanted only once during its service time).

10.1.3 Further implications of organ transplant in cars

We concluded in Chapter 2 that there are transport environmental problems that can possibly be fixed through technology (mostly those related to regulated pollutants) while major challenges remain unsolved in the longer term, particularly those related to energy supply and greenhouse gas emissions. While there are many ways to decoupling mobility growth from economic development and therefore manage transport demand, technology is a fundamental element to leave the current unsustainable mobility path. Many technological developments are likely to emerge in the automotive industry – both incremental and radical – that may help to solve or minimize those energy and environmental challenges. However, the transport system has a big inertia and it is resistant to the fast diffusion of new technologies. This downside of the transport system is currently hindering the full-potential of best available technologies to reduce the system's consumption of energy and materials and minimize the generation of emissions and waste.

Ultimately, the main issue is how to accelerate the pace of technology diffusion. In the previous sections of the conclusions, we presented mainly our modeling results that, in a general sense, indicate that organ transplant in cars can bring energy and environmental benefits both in individual and systemic terms, for the car owner and society, respectively. Although we performed an economic analysis for the car owner only, we would expect positive spillovers for the economy since an additional business stream for the automotive aftermarket would arise. As we mentioned earlier, the downside for the car makers would be that the number of car sales (in a whole) would eventually decrease. However, as we reviewed in Chapter 3, there is a strong cross-subsidization from the aftermarket sales (parts and components) to the manufacturing stages (refer to Figure 31, p.71). Accordingly, it is expectable that OEMs would benefit from the new business stream as they (still) are the producers of the main powertrain sub-system.

We mentioned also that reaching a sustainable transport system with a low impact on the global climate, which ensures other long term development goals (including economic development), requires deep and broad changes in the current socioeconomic standpoint. The transformation of the intricate structure of technological artifacts, infrastructures and institutions – which characterizes the automobile technosystems, including fuels – from their current position to one that is compatible with the strategic goals of a sustainable mobility is a long term process. Roadmapping is potentially a far-reaching tool to understand and influence how this process might unfold.

In this sense, organ transplant in cars could be envisaged as an important tool to foster the pace of technological development and deployment and, potentially, curtail the transition period to more efficient and cleaner technologies. On the other hand, it could be criticized by the fact that it somehow contributes to extend the current automotive technological 'lock-in' by protracting the higher competitiveness of the cars in the current mobility system. Still, we argue that the analytical approach we used to explore organ transplant in ICE vehicles should deliver higher reduction in energy and environmental burdens within a new drive-by-wire paradigm where efficiency is expected to become much higher and the mechanical restrictions are displaced by electric and electronic systems. In future work, we could include such technologies although adaptation costs are harder to estimate and, as such, future estimates are more prone to bias, besides the uncertainty related to those new technologies as they still lack of market penetration (and cost reduction expectable from learning processes and economies of scale).

With respect to the mechanical restrictions of current transplant operations, one fundamental and unavoidable feature of the organs to be transplanted is the intergenerational interchangeability between models (and desirably between brands) that is not automatically ensured by car makers today, while (intra-) generational compatibility is naturally required and planned when designing cars for the sake of spares parts interchangeability. Furthermore, car organ transplant would involve new conceptions of car serviceability in that the aftermarket should be prepared to ensure easy, fast and cheap organ transplants. As such, new approaches to car design should include such features, i.e. increased modularity and serviceability in design.

One prominent aspect of today's extremely competitive automotive industry is the pressure for cutting down costs and diversification of supply by widening the range of variants to satisfy an increasingly eclectic demand. In this sense, some industry experts foresee radical changes in the manufacturing system and industry structure by which increased customization in supply is required with further leaning production while guarantying mass production to benefit from economies of scale. Standardization and modularization (in design and in production) are regarded as promising approaches to enable such changes together with the increased outsourcing of larger and more complex pre-assembled modules. These changes are expected to have profound consequences in the value chain of the automotive industry in that suppliers should continue to gain increasing shares in the original value added of the final vehicle together with importance in the technological development of the modules they supply, turning OEMs into assemblers rather than full chain manufacturers (as they originally were). The concept of organ transplant in cars would benefit and contribute also to the wider and faster diffusion of such practices and changes in the automotive industry.

One possible outcome for car makers would be to designing cars that would be transplantable after the car leaves the assembly line, provided that intergenerational compatibility is ensured. In a new paradigm where car makers would shift from car providers to car mobility service providers, designing parts and components for intergenerational compatibility, and planning/designing cars accordingly, could bring lifecycle benefits for car makers as mentioned previously (refer to section 3.1 where we debate the car organ transplant and industrial ecology principles). In the new paradigm, OEMs would hold car property from 'cradle-to-grave' (as such, following the 'Extended Producer Responsibility' principle of industrial ecology) while selling automobility services to their customers. This is similar to car renting solutions provided today by finance companies (mostly). However, the difference is that after the contract comes to an end, the finance company gets rid of the vehicle (usually, reselling the car in the second hand market) whereas the automobility provider would transplant the car (if necessary) and use it for new contracts, possibly aiming to different market segments than customers looking for new cars.

Another possibility would be to change the current contractual relationship between car makers and car customers by which the former lose control over their clients after the car leaves the retail store because they compete in the aftermarket for servicing and repairs (particularly in the US and since the EU block exemption has been relieved). A new contractual relationship between car makers and car customers could be inspired by the 'evolutionary military acquisition system' that is standard practice in the US Department of Defense (2003). The analogy in the automotive industry would be a new 'evolutionary car selling system' by which OEMs would provide their customers the possibility of programmed organ transplant over an extendable service time bundled to the car they sell or alternatively the mobility service associated to the vehicle they 'rent' or 'lease'. As such, car makers would enhance customer loyalty by changing the current contractual relationship by postponing the investment in a new car over longer periods while the car maker would guarantee a periodic system refitting through the transplant of new organs. This is consistent with the notion that product loyalty is more likely to be bought while service loyalty is more likely to be earned (which currently happens in the aftermarket where competition is fierce) (Edvardsson et al., 2000). In addition, as customers remain satisfied and loyal, opportunities arise to generate increased revenues. This revenue growth comes from two general sources: the cross-selling of additional products or services and an increase in purchase volume or account penetration. Importantly, the corresponding business model suggested here would be encouraged if (and when) car owners would have to pay for their carbon and pollutant emissions, in the sense that they would be running in fine tuned cars equipped with cleaner technologies.

All in all, organ transplant in cars would bring the automotive industry closer to the principles of industrial ecology in that it may potentially hold back the voracious automotive industrial metabolism. As a matter of fact, the service time of cars would potentially be extended (unless abrupt interruption occurs – e.g., car crash), while keeping the car technologically updated and more performing. Consequently, virgin materials would potentially be saved (or at the least, their extraction is delayed) and waste materials minimized (including dissipative pollution).

We present in the next section the main restrictions of our research. Thereafter, we anticipate potential improvements and future work striving from our research conclusions.

10.2. Research restrictions, potential improvements and future work

The analysis in this dissertation has explored in detail the concept of organ transplant in cars. This was sustained by the development of a comprehensive and integrated set of modeling tools that were applied to the case of the Portuguese car stock. However, despite the extensive methodological and analytical work presented herein, our research had some restrictions and has only touched upon some more technical aspects that include those related to the mechanics of cars. We describe the principal restrictions in the nest section and some of the additional improvements and applications are outlined in section 10.2.2.

10.2.1 Research restrictions

- We did not use energy and emission factors for the Portuguese context regarding upstream and EOL treatment lifecycle stages to the use of car. Instead, we used factors from EU research reports (for instance from Edwards *et al.*, 2006), from automotive industry reports (Toyota Europe, 2001, among others) and from US research reports (for example, Sullivan *et al.*, 1998).
- Scrappage and cumulative mileage functions of cars in Portugal are yet to be modeled accurately.
- We did not include the possibility of new car buyers to opt for transplanted alternatives. This restriction was imposed by the author since we could not estimate a combined model that would consider such possibility, mainly due to lack of base data. Such a model would require stated preferences data to be collected through surveys. As we will refer in the next paragraphs, we could not do so due to time and budget constraints.
- The lack of data to estimate our discrete remarketed-car choice model was probably our biggest restriction. To overcome this difficulty we based the model estimation on emulated data of revealed preferences from a data set of remarketed cars, provided by Abmotors – a consultant of the car market in Portugal.
- Furthermore, we analyze the market share of new entrants using a discrete choice model based on revealed preferences while the most adequate methodological approach indicates that such analyses should be based on stated preferences. As we referred previously, new entrants in the market are new alternatives in the choice set with possible impacts on choice behavior through competition. In theory, modeling new market entrants would require

further data to be collected so as to produce new models, namely stated preferences from new surveys. However, we could not do that due to budget and time constraints. Given that there are similar approaches to organ transplant in cars currently available in the market (for example, retrofitting and car tuning) and that the objective of our research regarding discrete choice modeling was to have an understating of the pervasiveness of transplanted alternatives in future car stocks, we consider that the present exercise is of sufficient strength in support of the conclusions we obtained.

- We assumed at an early stage of this dissertation that we wouldn't explore the mechanics of organ transplant in cars. Instead, we would assume a fixed configuration of transplanting kits and accept that it would be feasible, for our exploratory endeavor.
- Although our cost modeling of the transplant operation was thoroughly based on the breakdown cost model by Delucchi *et al.* (Delucchi *et al.*, 2000), we recognized that it is specific to the models they analyzed, i.e. Ford Escort and Ford Taurus, and for the US automotive industry. As such, the specific weight-based unit cost might bias our calculations.
- We did not include the possibility of transplanting more radical technologies in the future, such as EDV whether these are full-electric, hybrid of fuel cell.

10.2.2 Potential improvements and future work

The obvious improvements to the current analytical framework would be to relieve the restrictions we outlined above. Regarding the Portuguese-specific coefficients for the stages of material and car production, we could calculate the weighted energy consumption and emission factors based on the sales distribution and using home-country industrial performance coefficients. Furthermore, we could calculate the energy consumption coefficients of EOL disposal based on data from VALORCAR. With respect to scrappage and cumulative mileage curves for the Portuguese car stock, the CAReFUL project is currently pursuing this endeavor (Moura *et al.*, 2007). Regarding the estimation of the discrete remarketed-car choice model, further research includes the possibility of performing stated preferences surveys of two populations: conventional car buyers and car tuners. A comparison of both results would possibly provide us with an understanding of the realistic or optimistic behavior, respectively.

Furthermore, our results provide grounds to leave numerical research and begin hands-on experimental research by transplanting new organs into older model years (including different vintages – for example, 5, 10 and 15-year gaps). The research would include thorough lifecycle quantification of:

- Transplanting operation costs, including the components and parts of the transplanting kit, adaption costs (if any), duration of transplant, specialized labor of mechanics and overheads (both economic and environmental – for example, emissions from electricity production).
- After transplantation, an experimental phase would follow during which transplanted cars would operate under normal driving conditions in order to test the effective on-road gains (in terms of fuel consumption and emissions) striving from newer and cleaner technologies. These would be performed with on-board fuel consumption and emissions monitoring

equipments. With this respect, refer to experimental research developments by Gonçalves and Farias (2005). Moreover, possible failures due to intergenerational incompatibility could also be tested.

Our analysis could possibly be improved on the mechanics side of organ transplant in cars. A more comprehensive survey should be performed to delimit the physical restrictions to such practice and, possibly, define more accurately which are the optimal transplanting kit configurations for different time gaps between model years.

In addition, our modeling framework is also suitable for exploring the role of additional and more speculative technologies. Throughout this dissertation more radical technology breakthroughs were not considered due to their very high uncertainty. However, breakthroughs may substantially alter the picture presented here, and a natural next step may be to examine the potential impact of some more radical technology options and analyze the feasibility of including them in the set of transplanting kits. One such option mentioned in chapter 3 is electric-drive powertrains in all configurations.

Although uncertainty related to costs of such technologies is high, there are prospects of radical changes to our understanding of what a car is and does today. For instance, with vehicle-to-grid (V2G) systems, in which parked vehicles are used to provide electricity to the grid, cars would become supplemental and decentralized energy micro-generators instead of energy consumers. V2G systems may play an important role in accelerating the shift to more sustainable transport technology options and reducing emissions from the stationary sector. The potential of these technologies is investigated further in Moura (2006) and Turton and Moura (2008).

Finally, in the introduction of this dissertation we referred that an important contribution would be to give insights to a possible business model configuration. Analyzing the business model of the concept is useful to suggesting complementary solutions of car design for automakers, of complementary alternatives for downstream car sales, and complementary car servicing in the aftermarket. In theory, business models include the value propositions offered to the market, identification of possible target customers, description of the type of firms and network of partners potentially involved, and description of the revenue model, the cost structure and the business model's sustainability.

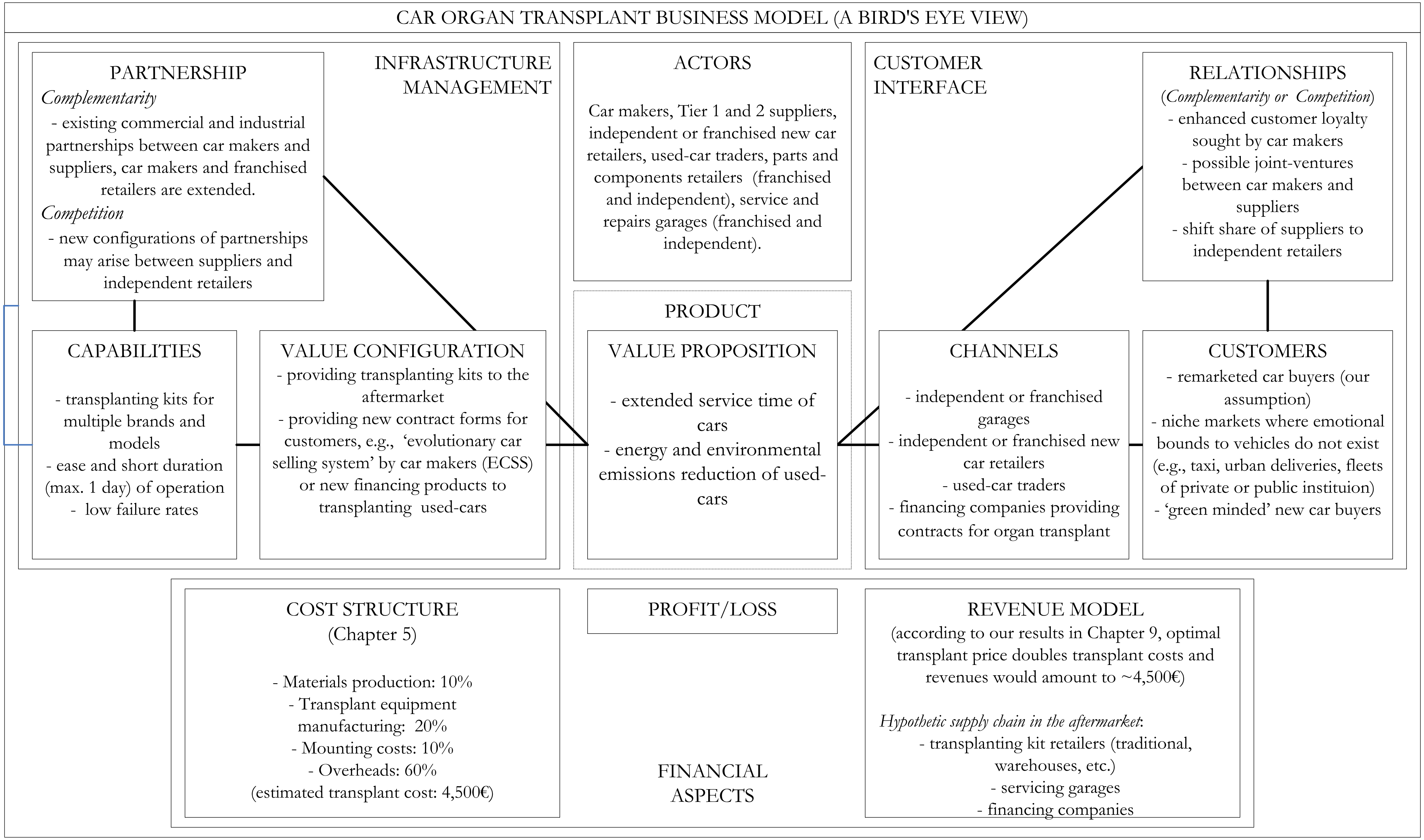


Figure 146. Basis for the definition of a business model of organ transplant in cars (Source: author based on Ostenwalder, 2004)

Based on the guidelines by Ostenwalder (2004), we propose in the previous diagram a possible configuration of business model that will, hopefully, pave the way for more thorough future developments (refer to the bird's eye view of the model in Figure 146, above). Most of the information and background required for the completion of the following diagram was provided along the present dissertation, mainly in Chapters 3, 5 and 9.

This section has provided a snapshot of the potential applications and improvements to the analytical framework developed as part of achieving the objectives of this dissertation. In addition, we have identified possible future work that would provide insights beyond those presented in this dissertation, particularly leaving the numerical modeling to more experimental research and address some of the inherent uncertainties associated to hands-on organ transplant in cars. Furthermore, we concluded with an illustration of the configuration of the business model sustaining the concept and how further research can start from our conceptual proposal, particularly regarding the arrangement of the supply chain and how actors of the aftermarket can interact and share revenues.

REFERENCES

1. ACAP/AUTO INFORMA (2007) Commercial surveys and statistics on the Portuguese automobile sector. Lisbon, Portugal, http://www.autoinforma.pt/.

2. ACEA (2003) Monitoring of ACEA's Commitment on CO2 Emission Reductions from Passenger Cars (2002), Brussels, European Commission.

3. ACEA (2006) Monitoring of ACEA's Commitment on CO2 Emission Reductions from Passenger Cars (2004), Brussels, European Commission, COM(2006) 463 final.

4. AHMAN, M. (2003) Assessing the future competitiveness of alternative powertrains. Int. J. of Vehicle Design, 33, 309-329.

5. ALCOTT, B. (2005) Jevons' paradox. Ecological Economics, 54, 9-21.

6. AMATAYAKUL, W. & RAMNAS, O. (2001) Life cycle assessment of a catalytic converter for passenger cars. Journal of Cleaner Production, 9, 395-403.

7. ANDERSEN, B. (1999) The hunt for S-shaped growth paths in technological innovation; a patent study. Evolutionary Economics, 9, 487-526.

8. ANDRE, J.-M., HAMMARSTRÖM, U. & REYNAUD, I. (1999) Driving statistics for the assessment of pollutant emissions from road transport - Meet deliverable 15, INRETS, LTE 9906.

9. ANDRE, M., JOUMARD, R., VIDON, R., TASSEL, P. & PERRET, P. (2006) Real-world European driving cycles, for measuring pollutant emissions from high- and low-powered cars. Atmospheric Environment, 40, 5944-5953.

10. ANG, B. W., FWA, T. F. & POH, C. K. (1991) A statistical study on automobile fuel consumption. Energy, 16, 1067-1077.

11. APA (2003) Tectos de Emissão Nacionais, Agência Portuguesa do Ambiente, D.L. 193/2003, (http://www.apambiente.pt/politicasambiente/Ar/EmissoesAtmosfericas/PTEN/Paginas/default.aspx access in April 20th, 2006).

12. APA (2007) Portuguese National Inventory Report on Greenhouse Gases (1990-2005) Lisbon, Agência Portuguesa do Ambiente (Portuguese Environmental Agency).

13. ARANTES, A. (2005) A importância da logística na indústria de fornecedores Portugueses do sector automóvel.PhD from the Department of Civil Engineering and Architecture. Lisbon, Instituto Superior Técnico / Universidade Técnica de Lisboa.

14. ARTHUR D. LITTLE (2002) Guidance for transportation technologies: fuel choice for fuel cell vehicles (Phase II Final Deliverable to DOE), Cambridge, Massachussets, Arthur D. Little, Inc., 35340-00.

15. ASPO (2004) Oil and gas liquids 2004 Scenario. USA, Association for the Study of Peak Oil, http://www.peakoil.net/uhdsg/Default.htm.

16. AUSTIN, S. & ROSS, M. (2001) History of emissions reductions: normal emitters in FTP-type driving, Society of Automotive Engineers 2001 Detroit Congress, Detroit, Michigan, SAE.

17. AUSUBEL, H., MARCHETTI, C. & MEYER, P. S. (1998) Toward green-mobility: The Evolution of Transport. European Review, 6, 137-156.

18. AUTO BASIC MOTOR S.A (2007) ABmotors - New and used cars for sale. ABmotors http://www.abmotor.pt.

19. AUTOMOBILE CLUB (2005) Budget de l'automobiliste - 2005, Paris, Fédération Française des Automobiles-Clubs et Usagers de la Route.

20. AUTOMOTIVE ALUMINUM (2007) Aluminum Content for Light Non-Commercial Vehicles Assembled in North America, Japan and the European Union in 2006. Ducker Worldwide, http://www.autoaluminum.org/downloads/duckerppt.pdf.

21. AUTOMOTIVE NEWS (2007) A look into our crystal ball. Automotive News, 82, 33-33.

22. AYRES, R. (1994) Industrial metabolism: Theory and policy. IN AYRES, R. U. & SIMONIS, U. E. (Eds.) Industrial Metabolism: Restructuring for Sustainable Development Tokyo, United Nations University Press.

23. AYRES, R. U. & AYRES, L. (Eds.) (2002) A handbook of industrial ecology, UK, Edward Elgar Publishing.

24. AYRES, R. U. & SIMONIS, U. E. (Eds.) (1994) Industrial Metabolism: Restructuring for Sustainable Development, Tokyo, The United Nations University.

25. BALDWIN, C., CLARK, K., RESEARCH, D. O. & SCHOOL, H. B. (2006) Modularity in the Design of Complex Engineering Systems. IN BRAHA, D., MINAI, A. A. & BAR-YAM, Y. (Eds.) Complex Engineered Systems. Cambridge, Massachusetts, Springer.

26. BALDWIN, C., YOUNG, C. & CLARK, K. (2000) Design rules: The power of modularity, Cambridge, Massachussetts, MIT Press.

27. BALDWIN, C. Y. & CLARK, K. B. (2002) The Option Value of Modularity in Design. Harvard Business School, http://www.people.hbs.edu/cbaldwin/DR2/DR1Option.pdf, (09/09/2008).

28. BANISTER, D. (2008) The sustainable mobility paradigm. Transport Policy, 15, 73-80.

29. BANISTER, D. & BUTTON, K. J. (1993) Transport, the environment and sustainable development, London, UK, Taylor & Francis.

30. BCA (2006) BCA Used Car Market Report - 2006 London, Sewells - Information & Research.

31. BÉDARD, M., GUYATT, G. H., STONES, M. J. & HIRDES, J. P. (2002) The independent contribution of driver, crash, and vehicle characteristics to driver fatalities. Accident Analysis & Prevention, 34, 717-727.

32. BEN-AKIVA, M. (1973) Structure of Passenger Travel Demand Models.PhD from the Dept. of Civil and Environmental Engineering. Boston, Massachusetts Institute of Technology.

33. BEN-AKIVA, M. (2007) Logit Mixture Models and Simulation-Based Estimation. TransportNET's 3rd Training Course on Transport Modeling and Forecasting. Chios, Greece.

34. BEN-AKIVA, M. & LERMAN, S. R. (1985) Discrete Choice Analysis: Theory and Application to Travel Demand, Cambridge, Massachussets/London, England, MIT Press.

35. BEN-AKIVA, M., MCFADDEN, D., ABE, M., BÖCKENHOLT, U., BOLDUC, D., GOPINATH, D. A., MORIKAWA, T., RAMASWAMY, V., RAO, V., REVELT, D. & STEINBERG, D. (1997) Modeling Methods for Discrete Choice Analysis. Marketing Letters, 8, 273–286.

36. BEN-AKIVA, M., WALKER, J., BERNARDINO, A. T., GOPINATH, D. A., MORIKAWA, T. & POLYDOROPOULOU, A. (1999) Integration of Choice and Latent Variable Models. Massachusetts Institute of Technology. Cambridge, USA.

37. BICKEL, P. & SCHMID, S. (1999) Externalities of Energy-Part II: External costs of transports. Stuttgart, Germany, Institute of Energy Economics and Rationale Use of Energy, http://www.externe.info/oldvolumes/vol9e.pdf, (06/05/2008).

38. BICKEL, P., SCHMID, S., KREWITT, W. & FRIEDRICH, R. (1997) External costs of Transport in ExternE, Seville, Funded by the European Commission, JOS3-CT95-0004.

39. BINSWANGER, M. (2001) Technological progress and sustainable development: what about the rebound effect? Ecological Economics, 36, 119-132.

40. BISHOP, G. A., BURGARD, D. A. & STEDMAN, D. H. (2006) On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 5, Denver,, Department of Chemistry and Biochemistry, University of Denver.

41. BMW GROUP (2008) Sustainable Value Report - Indicators for Sustainability. Munich, Germany, BMW, http://www.bmwgroup.com, (22/04/2008).

42. BOSCH (2004) BOSCH Automotive Handbook, Gemany, John Wiley and Sons.

43. BRINK, P. T., SKINNER, I., FERGUSSON, M., HAINES, D., SMOKERS, R., BURGWAL, E. V. D., GENSE, R., WELLS, P. & NIEUWENHUIS, P. (2005a) Service contract to carry out economic analysis and business impact assessment of CO2 emissions reduction measures in the automotive sector, Brussels, IEEP - Institute for European Environmental Policy / TNO / CAIR - Centre for Automotive Industry Research, B4-3040/2003/366487/MAR/C2.

44. BRINK, P. T., SKINNER, I., FERGUSSON, M., HAINES, D., SMOKERS, R., BURGWAL, E. V. D., GENSE, R., WELLS, P. & NIEUWENHUIS, P. (2005b) Service contract to carry out economic analysis and business impact assessment of CO2 emissions reduction measures in the automotive sector, Brussels, IEEP - Institute for European Environmental Policy; TNO; CAIR - Centre for Automotive Industry Research, B4-3040/2003/366487/MAR/C2.

45. BRITANNICA ONLINE ENCYCLOPEDIA (2008). Britannica Encyclopedia, http://www.britannica.com, (13.10.2008).

46. BROWNE, M., ALLEN, J. & ANDERSON, S. (2005) Low emission zones: the likely effects on the freight transport sector. International Journal of Logistics, 8, 269-281.

47. BRUNTLAND, G. (Ed.) (1987) Our common future: The World Commission on Environment and Development, Oxford, Oxford University Press.

48. CAMPBELL, C. J. & LAHERRERE, J. H. (1998) The end of cheap oil. Scientific American, 278, 60-5.

49. CAMUFFO, A. (2000) Rolling out a "World Car": globalization, outsourcing and modularity in the auto industry. Department of Business Economics and Management / Ca' Foscari University of Venice, http://imvp.mit.edu/papers/0001/camuffo1.pdf, (04'03'2008).

50. CARB (1994) On-Road Remote Sensing of CO and HC emissions in California, Sacramento, California, California Air Resources Board Contract No. A032-093.

51. CARB (2004) The Carl Moyer Clean Engine Incentive Program. Sacramento, California, California Air Resources Board.

52. CARB (2006) The Carl Moyer Program Guidelines - Proposed 2006 Revision to Project Criteria for Light-Duty Vehicles. Sacramento, California, California Air Resources Board - Mobile Source Control Division.

53. CARRASCO, J. A. & ORTÚZAR, J. D. D. (2002) Review and assessment of the nested logit model. Transport Reviews, 22, 197 - 218.

54. CASTELLS, M. (1998) Information Technology, Globalization and Social Development, UNRISD Conference on Information Technologies and Social Development,, Palais des Nations, Geneva.

55. CEC (1992) "Sustainable Mobility" - Green Paper on the Impact of Transport on the Environment, Commission of the European Communities, COM(92) 46 final.

56. CEUSTER, G. D., HERBRUGGEN, B. V. & LOGGHE, S. (2006a) TREMOVE - Description of model and baseline version 2.41, Brussels, Belgium, TRANSPORT & MOBILITY LEUVEN for European Commission, B4-3040/2002/342069/MAR/C.1.

57. CEUSTER, G. D., HERBRUGGEN, B. V. & LOGGHE, S. (2006b) TREMOVE BASELINE DATA version 2.40. Leuven, http://www.tremove.org/download/index.htm.

58. CEUSTER, G. D., HERBRUGGEN, B. V. & LOGGHE, S. (2007a) TREMOVE - Description of model and baseline version 2.52, Brussels, Belgium, TRANSPORT & MOBILITY LEUVEN for European Commission, B4-3040/2002/342069/MAR/C.1.

59. CEUSTER, G. D., HERBRUGGEN, B. V. & LOGGHE, S. (2007b) TREMOVE BASELINE DATA version 2.52. Leuven, http://www.tremove.org/download/index.htm.

60. CHALK, S. G. & MILLER, J. F. (2006) Key challenges and recent progress in batteries, fuel cells, and hydrogen storage for clean energy systems. Journal of Power Sources, 159, 73-80.

61. CHEAH, L., EVANS, C., BANDIVADEKAR, A. & HEYWOOD, J. (2007) Factor of Two: Halving the Fuel Consumption of New US Automobiles by 2035. Laboratory for Energy and the Environment, Massachusetts Institute of Technology, Cambridge, Mass.

62. CHESTER, M. & HORVATH, A. (2007) Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas, and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air, Berkeley, California, UC Berkeley for Future Urban Transport UCB-ITS-VWP-2007-7, (http://www.its.berkeley.edu/publications/UCB/2007/VWP/UCB-ITS-VWP-2007-7.pdf access in 22/04/2008).

63. CHOATE, W. T. & GREEN, J. A. S. (2003) U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits and New Opportunities, California, USA, BCS, Incorporated for the U.S. Department of Energy Energy Efficiency and Renewable Energy

64. CLARKE, R. M. (1990) Engine Swapping Tips and Techniques, USA, Brooklands Books.

65. COLE, D. E. & LONDAL, G. F. (2000) DELPHI X: forecast and analysis of the North American automotive industry. Volume 1: technology, Ann Arbor, Transportation Research Institute (UMTRI), UMTRI-2000-3-1.

66. COM(2005)261 FINAL (2005) Proposal of a Council Directive on passenger car related taxes. COM(2005)261 final.

67. CONSOLI, F., ALLEN, D., BOUSTEAD, I., FAVA, J., FRANKLIN, W., JENSEN, A., OUDE, N. D., PERRIMAN, R. P. R., POSTLETHEWAITE, D., QUAY, B., SÉGUIN, J. & VIGON, B. (1993) Guidelines for Life-Cycle Assessment: A Code of Practice, Brussels, Belgium, SETAC, 90-5607-003-7.

68. DALY, H. (1991) Steady-state economics. IN CAHN, M. A. & O'BRIEN, R. (Eds.) Thinking about the Environment: Readings on Politics, Property, and the Physical World. London, England, M.E. Sharpe.

69. DAVIS, S. C. & DIEGEL, S. W. (2006) Transportation Energy Data Book: Edition 25, Washington, D.C., Oak Ridge National Laboratory for the U.S. Department of Energy.

70. DEAKIN, E. (2001) Sustainable Development and Sustainable Transportation: strategies for economic prosperity, environmental quality and equity. California Futures Network. Berkeley.

71. DECICCO, J., AN, F. & ROSS, M. (2001) Technical Options for Improving the Fuel Economy of U.S. Cars and Light Trucks by 2010–2015, Washington, DC, American Council for an Energy Efficient Economy,.

72. DELUCCHI, M. (1997) The annualized social cost of motor-vehicle use in the U.S., 1990-1991: summary of theory, data, methods and results, Davis, California, Institute of Transportation Studies, UCD-ITS-RR-96-3 (1).

73. DELUCCHI, M. (2003) A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials, Davis, California, Institute of Transportation Studies - University of California, UCD-ITS-RR-03-17.

74. DELUCCHI, M. (2004) Summary of the nonmonetary externalities of motor-vehicle use, Davis, California, Institute of Transportation Studies - University of California, UCD-ITS-RR-96-3 (9) rev. 1.

75. DELUCCHI, M., BURKE, A., LIPMAN, T. & MILLER, M. (2000) Electric and Gasoline Vehicle Lifecycle Cost and Energy-Use Model, Davis, California, Institute of Transportation Studies - University of California, UCD-ITS-RR-99-4.

76. DELUCCHI, M. & LIPMAN, T. (2001) An analysis of the retail and lifecycle cost of battery-powered electric vehicles. Transportation research Part D, 6, 371-404.

77. DGEMP (2005) Consommations de carburants des voitures particulières en France (1988-2004). Paris, Direction Générale de l'Énergie et des Matières Premières, Observatoire de l'Énergie, http://www.industrie.gouv.fr/energie/statisti/pdf/consom_carbu_04.pdf.

78. DGGE (2007) Balanços Energéticos 1990-2005 (Aggregate energy balances). Direcção-Geral de Energia e Geologia / Ministério da Economia, http://www.dgge.pt/.

79. DILL, J. (2004) Estimating emissions reductions from accelerated vehicle retirement programs. Transportation Research Part D: Transport and Environment, 9, 87-106.

80. DOMENCICH, T. A. & MCFADDEN, D. (1975) Urban Travel Demand: A Behavioural Analysis, Amsterdam North Holland.

81. DUNCAN, R. C. (2001) World Energy Production, Population Growth, and the Road to the Olduvai Gorge. Population & Environment, 22, 503-522.

82. DUNCAN, R. C. & YOUNGQUIST, W. (1999) Encircling the Peak of World Oil Production. Natural Resources Research, 8, 219-232.

83. EARPA (2004) FURORE-Future road vehicle research, a roadmap for the future, Graz, Austria, European Automotive Research Partners Association, (http://www.furore-network.com access in 16/10/2008).

84. ECMT (1999) Cleaner cars : fleet renewal and scrappage schemes, Paris, European Conference of Ministers of Transport ; OECD Publications Service.

85. ECMT (2005) Making cars more efficient-Technology for real improvements on the road, Paris, European Conference of Ministers of Transport ; OECD Publications Service.

86. EDMUNDS.COM (2008) True costs to own. http://www.edmunds.com/apps/cto/about.jsp.

87. EDVARDSSON, B., JOHNSON, M., GUSTAFSSON, A. & STRANDVIK, T. (2000) The effects of satisfaction and loyalty on profits and growth: products versus services. Total Quality Management & Business Excellence, 11, 917-927.

88. EDWARDS, R., LARIVÉ, J.-F., MAHIEU, V. & ROUVEIROLLES, P. (2006) Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, Brussels, EUCAR/CONCAWE/JRC, EUR 22342 EN, (http://ies.jrc.cec.eu.int/fileadmin/Documentation/Reports/Emissions_and_Health/EUR_2006-2007/EUR_22342_EN.pdf access in 16/03/2008).

89. EEA (2002) EMEP/CORINAIR Emission Inventory Guidebook - Road Transport Methodology Chapter, Copenhagen, European Environment Agency, (http://reports.eea.eu.int/EMEPCORINAIR3/en/page002.html).

90. EEA (2003) Transport emissions of air pollutants (CO, NH3, NOx, NMVOC, PM10, SOx) by mode, Copenhagen, Denmark, European Environmental Agency, TERM 2003 03 EEA-31.

91. EEA (2006) Transport and environment: facing a dilemma. TERM 2005: indicators tracking transport and environment in the European Union, Copenhagen, European Environment Agency.

92. EEA (2007a) EMEP/CORINAIR Emission Inventory Guidebook - Road Transport Methodology Chapter, Copenhagen, European Environment Agency, (http://reports.eea.eu.int/EMEPCORINAIR3/en/page002.html).

93. EEA (2007b) EMEP/CORINAIR Emission Inventory Guidebook - Road Transport Methodology Chapter (5th version), Copenhagen, European Environment Agency, (http://reports.eea.europa.eu/EMEPCORINAIR5/en/page002.html access in 6 Jan 2008).

94. EEA (2007c) Europe's environment - The fourth assessment, Copenhagen, Denmark, European Environment Agency - Office for Official Publications of the European Communities.

95. EHRLICH, P. R. & HOLDREN, J. P. (1971) Impact of Population Growth. Science, 171, 1212-17.

96. ELLRAM, L. M. & SIFERD, S. P. (1998) Total cost of ownership: a key concept in strategic cost management decisions Journal of Business Logistics, 19, 75-84.

97. EMBARQ (2007) Diesel Retrofit Pilot Project in Mexico City - Saving lives with cleaner transportation, Mexico, World Resources Institute and the Centro de Transporte Sustentable.

98. ENERGY FOUNDATION (2002) Bellagio Memorandum on Motor Vehicle Policy - Consensus Document Bellagio, Italy, (http://www.ef.org/bellagio access in 21/10/2008).

99. ENGINE REPOWER COUNCIL (2006) Benefits of a Remanufactured/Rebuilt Engine - Cost comparisons. Engine Repower Council, http://www.carcare.org/Repower/index.html.

100. EPA (2008) History of the Clean Air Act. IN ENVIRONMENTAL PROTECTION AGENCY, U. (Ed.). USA, http://www.epa.gov/air/caa/caa_history.html.

101. ERKMAN, S. (1997) Industrial ecology: An historical view. Journal of Cleaner Production, 5, 1-10.

102. ETO (2008) European Tuning Organization. Europe, Specialty Equipment Market Association, http://www.e-t-o.org.

103. EUROPEAN COMMISSION (2001) European Transport Policy for 2010: Time to Decide. White Paper, Brussels, Directorate General for Transport and Energy, COM(2001)370 final.

104. EUROPEAN COMMISSION (2006a) Introduction to Life Cycle Assessment. European Commission - DG Joint Research Centre, http://lca.jrc.ec.europa.eu/lcainfohub/introduction.vm.

105. EUROPEAN COMMISSION (2006b) Proposal for a regulation (COM(2005)0683 – C6-0007/2004 – 2005/0282(COD)), Brussels, Committee on the Environment, Public Health and Food Safety, PE 376.385v01-00.

106. EUROSTAT (2003a) Panorama of transport: Statistical overview of transport in the European Union - Data 1970-2001 (Part 1), Luxembourg, Office for Official Publications of the European Communities, KS-DA-04-001-EN-N.

107. EUROSTAT (2003b) Panorama of transport: Statistical overview of transport in the European Union - Data 1970-2001 (Part 2), Luxembourg, Office for Official Publications of the European Communities, KS-DA-04-001-EN-N.

108. EUROSTAT (2008) Environmental data. European Commission, http://epp.eurostat.ec.europa.eu/.

109. FERRÃO, P. & AMARAL, J. (2006) Assessing the economics of auto recycling activities in relation to European Union Directive on end of life vehicles. Technological Forecasting and Social Change, 73, 277-289.

110. FERREIRA, J., MARTINS, H., MIRANDA, A. I. & BORREGO, C. (2005) Population exposure to atmospheric pollutants: the influence of urban structure. IN ARAL, M. M. (Ed.) Environmental Exposure and Health. UK, Wessex Institute of Technology.

111. FEYCHTING, A., JACOBSSON, M., NILSSON, A. & RYAN, D. (2002) Environmental Zones in Europe - Trendsetter, Stockholm, Stockholm Real Estate and Traffic Administration, 2002:1.

112. FINKBEINER, M., HOFFMANN, R., RUHLAND, K., LIEBHART, D. & STARK, B. (2006) Application of Life Cycle Assessment for the Environmental Certificate of the Mercedes-Benz S-Class. International Journal of Life Cycle Assessment, 11, 240-246.

113. FONTARAS, G. & SAMARAS, Z. (2007) A quantitative analysis of the European Automakers' voluntary commitment to reduce CO2 emissions from new passenger cars based on independent experimental data. Energy Policy, 35, 2239-2248.

114. FRB (2008) Leasing is different from buying. Here's how . . . Washington, USA, Federal Reserve Board, http://www.federalreserve.gov/pubs/leasing/.

115. FREDRIKSSON, P. & GADDE, L.-E. (2005) Flexibility and rigidity in customization and build-to-order production. Industrial Marketing Management, 34, 695-705.

116. FREEMAN, C. & LOUÇÃ, F. (2002) As Time Goes by: From the Industrial Revolutions to the Information Revolution, Oxford University Press.

117. FREIRE DE SOUSA, J. & GUIMARAES, R. C. (1997) Setting the length of the planning horizon in the vehicle replacement problem. European Journal of Operational Research, 101, 550-559.

118. FREIRE DE SOUSA, J. & GUIMARÃES, R. C. (1997) Setting the length of the planning horizon in the vehicle replacement problem. European Journal of Operational Research, 101, 550-559.

119. FROSCH, R. A. & GALLOPOULOS, N. E. (1989) Strategies for Manufacturing. Scientific American, 261, 144-152.

120. FUKASAKU, Y. (1995) Energy and environment policy integration: The case of energy conservation policies and technologies in Japan. Energy Policy, 23, 1063-1076.

121. GARCIA, M., BRAY, O., ENERGY, D. O., LABORATORIES, S. N. & STATES, U. (1997) Fundamentals of Technology Roadmapping, Sandia National Laboratories.

122. GEERLINGS, H. & RIENSTRA, S. (2003) Exploring 'weak signals" as potential challenges in transport: an inventory of potential future technology developments. Transportation Planning and Technology, 26, 469 - 489.

123. GERSHENSON, J. & ISHII, K. (1993) Life-cycle serviceability design. IN KUSIAK, A. (Ed.) Concurrent Engineering: Automation, Tools, and Techniques. Wiley-Interscience.

124. GINLEY, D. M. (1994) Material flows in the transport industry : An example of industrial metabolism. Resources Policy, 20, 169-181.

125. GOEDKOOP, M. & SPRIENSMA, R. (2001) The Eco-Indicator 99 - A damage oriented method for life cycle impact assessment, PRé Consultants B. V.

126. GOLDBERG, P. K. & VERBOVEN, F. (2001) The Evolution of Price Dispersion in the European Car Market. Review of Economic Studies, 68, 811-848.

127. GOMPERTZ, B. (1825) On the Nature of the Function Expressive of the Law of Human Mortality, and on a New Mode of Determining the Value of Life Contingencies. Philosophical Transactions of the Royal Society of London, 115, 513-585.

128. GONÇALVES, G. & FARIAS, T. (2005) On-Road Measurements of Emissions and Fuel Consumption of Gasoline Fuelled Light Duty Vehicles, Clean Air 2005 - Eight International Conference on Technologies and Combustion for a Clean Environment, Lisbon.

129. GOODWIN, P., DARGAY, J. & HANLY, M. (2004) Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review. Transport Reviews, 24, 275-292.

130. GOODWIN, P. B. (1992) A Review of Demand Elasticities with Special Reference to Short and Long Run Effects of Price Changes. Journal of Transport Economics and Policy, 26, 155-169.

131. GRAEDEL, T. E. (1998) Streamlined life-cycle assessment New Jersey, Upper Saddle River: Prentice Hall.

132. GRAEDEL, T. E. & ALLENBY, B. R. (1997) Industrial Ecology and the Automobile Prentice Hall.

133. GREENE, D. L. & DULEEP, K. G. (1992) Costs and benefits analysis of automotive fule economy improvement: a partial analysis, Oak Ridge, Tenessee, Center for Transportation Analysis of the Oak Ridge National Laboratory, ORNL--6704.

134. GREENE, D. L. & WEGENER, M. (1997) Sustainable Transport. Journal of Transport Geography, 5, 177-190.

135. GREENING, L. A., GREENE, D. L. & DIFIGLIO, C. (2000) Energy efficiency and consumption -- the rebound effect -- a survey. Energy Policy, 28, 389-401.

136. GRÜBLER, A. (1990) The rise and fall of infrastructures - Dynamics of evolution and technological change in transport, Laxenburg, Austria, Physica-Verlal Heidelberg.

137. GRÜBLER, A. (1998) Technology and global change, Cambridge, UK, Cambridge University Press.

138. GRÜBLER, A. & CUTLER, J. C. (2004) Transitions in Energy Use. Encyclopedia of Energy. New York, Elsevier.

139. GRÜBLER, A. & GRITSEVSKYI, A. (2002) A model of endogeneous technological change through uncertain returns on innovation. IN GRÜBLER, A., NAKICENOVIC, N. & NORHAUS, W. D. (Eds.) Technological change and the environment. Washington, D.C., Resources of the Future.

140. GRÜBLER, A. & NAKICENOVIC, N. (1991) Evolution of transport systems: past and future, Laxenburg, International Institute of Applied Systems Analysis, RR-91-8.

141. GRÜBLER, A., NAKICENOVIC, N. & VICTOR, D. G. (1999) Dynamics of energy technologies and global change. Energy Policy, 27, 247-280.

142. HACKNEY, J. & DE NEUFVILLE, R. (2001) Life cycle model of alternative fuel vehicles: emissions, energy, and cost trade-offs. Transportation Research Part A: Policy and Practice, 35, 243-266.

143. HAJ-SALEM, H. & PAPAGEORGIOU, M. (1995) Ramp metering impact on urban corridor traffic: Field results. Transportation Research Part A: Policy and Practice 29, 303-319.

144. HANLY, M. & DARGAY, J. M. (2000) Car Ownership in Great Britain—A Panel Data Analysis, London, ESRC, Transport Studies Unit, University College London.

145. HARRINGTON, W. (1997) Fuel Economy and Motor Vehicle Emissions. Journal of Environmental Economics and Management, 33, 240-252.

146. HAUSMAN, J. & MCFADDEN, D. (1984) Specification Tests for the Multinomial Logit Model. Econometrica, 52, 1219-40.

147. HEATHER AND LAVE, M. & LESTER, B. (1998) A life cycle model of an automobile. SAE Technical Paper Series, 982200.

148. HELPER, S. & MACDUFFIE, J. (2000) E-volving the Auto Industry: E-Commerce Effects on Consumer and Supplier Relationships. E-Business and the Changing Terms of Competition: A View From Within the Sectors. Berkeley, California, http://e-conomy.berkeley.edu/conferences/9-2000/EC-conference2000_papers/MacDuffieHelper.pdf, (November 10th, 2008).

149. HELPER, S., MACDUFFIE, J. P., PIL, F., SAKO, M., TAKEISHI, A. & WARBURTON, M. (1999) Modularization and Outsourcing: Implications for the Future of Automotive Assembly. Cambridge, USA, IMVP.

150. HENSHER, D. & BUTTON, K. (Eds.) (2003) Handbook of Transport and the Environment, Elsevier Science.

151. HENSHER, D. & BUTTON, K. J. (2000) Handbook of Transport Modelling, Oxford, Uk, Pergamon.

152. HENSHER, D. A., ROSE, J. M. & GREENE, W. H. (2005) Applied Choice Analysis - A Primer, Cambridge, UK, Cambridge University Press.

153. HERRIGES, J. A. & KLING, C. L. (1996) Testing the consistency of nested logit models with utility maximization. Economics Letters, 50, 33-39.

154. HERRING, H. (2006) Energy efficiency - a critical view. Energy, 31, 10-20.

155. HILLS, P. J. (1996) What is induced traffic? Transportation, 23, 5-16.

156. HUNKELER, D. & REBITZER, G. (2005) The Future of Life Cycle Assessment. International Journal of Life Cycle Assessment, 10, 305-308.

157. HUNT, R. G., SELLERS, J. D. & FRANKLIN, W. E. (1992) Resource and environmental profile analysis: A life cycle environmental assessment for products and procedures. Environmental Impact Assessment Review, 12, 245-269.

158. IEC 60300-3-3 (2004) Dependability management - Part 3: Application guide –Section 3: Life cycle costing. IEC 60300-3-3.

159. INE (2004) Projecções de População Residente - 2000-2050, Lisbon, Instituto National de Estatística, ISSN: 1645-7633.

160. INE (2007) Estudos Demográficos. Revista dos Estudos Demográficos, 41, 79.

161. INSTITUTO DO AMBIENTE (2004) PTEN - Programa Nacional para os Tectos Nacionais de Emissão, Lisbon, DCEA/FCT and CEEETA for the Instituto do Ambiente.

162. INTERLABORATORY WORKING GROUP (1997) Scenarios of Carbon Reductions: Potential Impacts of Energy technologies by 2010 and Beyond, Washington, Office of Energy Efficiency and Renewable Technologies, U.S. Department of Energy.

163. INTERNATIONAL ENERGY AGENCY (2008) Key World Energy Statistics - 2008, Paris, International Energy Agency publications.

164. IPCC (2000) Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge, Intergovernmental Panel on Climate Change, Cambridge University Press.

165. IPCC (Ed.) (2001) Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of theIntegovernmental Panel on Climate Change, Cambridge,United Kingdom, and New York, NY, USA,, Cambridge University Press.

166. IPCC (Ed.) (2007) Climate Change 2007: Synthesis Report. A Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Integovernmental Panel on Climate Change, Cambridge,United Kingdom, and New York, NY, USA,, Cambridge University Press.

167. IPPC (2001a) Best Available Techniques Reference Document on the Production of Iron and Steel. Seville, Spain, Integrated Pollution Prevention and Control (IPPC), http://eippcb.jrc.es/pages/FActivities.htm, (01/04/2008).

168. IPPC (2001b) Reference Document on Best Available Techniques in the Non-Ferrous Metals Industries. Seville, Spain, Integrated Pollution Prevention and Control (IPPC), http://eippcb.jrc.es/pages/FActivities.htm, (01/04/2008).

169. ISO 14040 (Ed.) (1997) Environmental Management - Life Cycle Assessment - Principles and Framework (revised in 2006).

170. ISO 14040 (Ed.) (2006) Environmental Management - Life Cycle Assessment - Principles and Framework.

171. JAFFE, A. B., NEWELL, R. G. & STAVINS, R. N. (2001) Technological Change and the Environment. Resources for the Future. Washington, D.C.

172. JENSEN, A. A., HOFFMAN, L., MØLLER, B. T., SCHMIDT, A., CHRISTIANSEN, K., BERENDSEN, S., ELKINGTON, J. & DIJK, F. V. (1997) Life cycle assessment: a guide to approaches, experiences and information sources, Copenhagen, European Environment Agency, 6.

173. JONG, G. D., FOX, J., DALY, A., PIETERS, M. & SMIT, R. (2004) Comparison of car ownership models. Transport Reviews, 24, 379-408.

174. JONG, G. D., FOX, J., PIETERS, M., VONK, L. & DALY, A. (2002) Audit of Car Ownership Models Leiden, RAND Europe, 01192.

175. JORGENSEN, F. & WENTZEL-LARSON, T. (1990) Forecasting Car Holding, Scrappage and New Car Purchase in Norway. Journal of Transport Economics and Policy, 24, 139-156.

176. KANIUT, C., CETINER, H. & JENS, F. (1997) Life cycle assessment of a complete car - The Mercedes-Benz approach. SAE Technical Paper Series, nº 971166, 8.

177. KAPLAN, R. S. & COOPER, R. (1998) Cost & Effect: Using Integrated Cost Systems to Drive Profitability and Performance, Boston, Massachussetts, Harvard Business School Press.

178. KAPPEL, T. A. (2001) Perspectives on roadmaps: how organizations talk about the future. Journal of Product Innovation Management, 18, 39-50.

179. KELLER, M. & KLJUN, N. (2007) ARTEMIS road emission model - Model Description, Berne, Germany, INFRAS, Workpackage 1100 – Model Version 04c - Deliverable 13.

180. KEMPTON, W. & LETENDRE, S. (1997) Electric Vehicles as a new power source for electric utilities. Transportation Research Part D, 2, 157-175.

181. KEMPTON, W. & TOMIĆ, J. (2005a) Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. Journal of Power Sources 144, 268-279.

182. KEMPTON, W. & TOMIĆ, J. (2005b) Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. Journal of Power Sources 144, 280-294.

183. KEOLEIAN, G. A. & MENEREY, D. (1993) Life Cycle Design Guidance Manual: Environmental Requirements and the Product System Washington, D. C. , Centre for Sustainable Systems - University of Michigan for the Enviromental Protection Agency, EPA600/R-92/226.

184. KIM, H. C. (2003) Shaping sustainable vehicle fleet conversion policies based on life cycle optimization and risk analysis.PhD from the. Michigan, University of Michigan.

185. KIM, H. C., KEOLEIAN, G. A., GRANDE, D. E. & BEAN, J. C. (2003) Life Cycle Optimization of Automobile Replacement: Model and Application. Environmental Science and Technology, 37, 5407-5413.

186. KIM, H. C., ROSS, M. H. & KEOLEIAN, G. A. (2004) Optimal fleet conversion policy from a life cycle perspective. Transportation Research Part D, 9, 229-249.

187. KOBAYASHI, O., TEULON, H., OSSET, P. & MORITA, Y. (1998) Life Cycle Analysis of a Complex Product, Application of ISO 14040 to a Complete Car, Total Life Cycle Conference and Exposition, Graz, Austria, SAE Technical Paper Series nº 982187.

188. LAWLESS, J. F. (1982) Statistical Models and Methods for Lifetime Data, USA, John Whiley and Sons, Inc.

189. LIPMAN, T. & DELUCCHI, M. (2003) Hybrid-Electric Vehicle Design Retail and Lifecycle Cost Analysis, Davis, California, Institute of Transportation Studies - University of California, UCD-ITS-RR-03-01.

190. LIPMAN, T. E., CALIFORNIA, AIR RESOURCES, B., INSTITUTE OF TRANSPORTATION, S. & DAVIS UNIVERSITY OF, C. (1999) The Cost of Manufacturing Electric Vehicle Batteries, Institute of Transportation Studies, University of California.

191. LITMAN, T. (2002) Mobility Management and Sustainable Transport: A Sourcebook for Policy-makers in Developing Cities, Eschborn, Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ).

192. LONDON ECONOMICS (2006) Developments in car retailing and after-sales markets under Regulation N° 1400/2002, London, European Comission Directorate-General for Competition.

193. LOUVIERE, J. J., HENSHER, D. A. & SWAIT, J. D. (2000) Stated Choice Methods: Analysis and Applications, Cambridge, UK, Cambridge University Press.

194. LOVINS, A. B. & CRAMER, D. R. (2004) Hypercars, hydrogen, and the automotive transition. Int. J. Vehicle Design, 35, 50-85.

195. M.A.I. (2007) Lei n.º 22-A/2007 de 29/06 (Série I nº 124) -Código do Imposto sobre Veículos e o Código do Imposto Único de Circulação, Ministério da Administração Interna.

196. MACLEAN, H. L. & LAVE, L. B. (2003) Evaluating automobile fuel/propulsion system technologies. Progress in Energy and Combustion Science, 29, 1-69.

197. MANSKI, C. F. & GOLDIN, E. (1983) An econometric analysis of automobile scrappage. Transportation science, 17, 365-375.

198. MAXTON, G. P. & WORMALD, J. (2004) Time for a Model Change: Re-engineering the Global Automobile Industry, Cambridge University Press.

199. MCDONALD, A. & SCHRATTENHOLZER, L. (2002) Learning curves and technology assessment. International Journal of Technology Management, 23, 718-745.

200. MCFADDEN, D. (2001) Economic Choices, Nobel Prize Lecture, December 8, 2000. The American Economic Review, 91, 351-378.

201. MEADOWS, D. H., MEADOWS, D. L., RANDERS, J. & BEHRENS, W. W. (1972) The Limits to Growth, New York, Universe Books.

202. MEEKER, W. Q. & ESCOBAR, L. A. (1998) Statistical Methods for Reliability Data, USA, John Wiley & Sons, Inc.

203. MERCER MANAGEMENT CONSULTING (2003) Automotive retailing 2010: Trends, fields of action and recommendations for OEM and retailers, Mercer Concultant.

204. MERRIAM-WEBSTER ONLINE DICTIONARY (2006). Merriam&Webster, http://www.m-w.com/, (20.06.2006).

205. MILLER, J. A. (1995) Implementing Activity-based management in daily operations, USA, John Whiley & Sons.

206. MINDALI, O., RAVEH, A. & SALOMON, I. (2004) Urban density and energy consumption: a new look at old statistics. Transportation Research Part A: Policy and Practice, 38, 143-162.

207. MODIS, T. (2007) Strengths and weaknesses of S-curves. Technological Forecasting and Social Change, 74, 866-872.

208. MOGRIDGE, M. J. H. (1967) Prediction of car ownership. Journal of Transport Economics and Policy, 1, 52-74.

209. MOORS, E. H. M. (2006) Technology strategies for sustainable metals production systems: a case study of primary aluminium production in The Netherlands and Norway. Journal of Cleaner Production, 14, 1121-1138.

210. MOURA, F. (2006) Driving energy system transformation with "vehicle-to-grid" power, Laxemburg, IIASA, IR-06-025.

211. MOURA, F., DUARTE, A. & VIEGAS, J. (2007) CAReFUL - Car fleet renewal as a key role for atmospheric emission reduction, Lisbon, CESUR, Instituto Suprior Técnico.

212. MURPHY, T. D. (1908) British Highways and Byways From a Motor Car, L.C. Page & Company.

213. NAKIĆENOVIĆ, N. (1985) The automotive road to technological change: diffusion of the automobile as a process of technological substitution. IIASA.

214. NEEFT, J. P. A., MAKKEE, M. & MOULIJN, J. A. (1996) Diesel particulate emission control. Fuel Processing Technology, 47, 1-69.

215. NEWMAN, P. W. G. & KENWORTHY, J. R. (1989) Cities and Automobile Dependence: An International Sourcebook, UK, Avebury Technical.

216. NIEUWENHUIS, P. & WELLS, P. (2003) The automotive industry and the environment: A technical, business and social future, Cambridge, UK, Woodhead Publishing.

217. NTZIACHRISTOS, L. & SAMARAS, Z. (Eds.) (2000) COPERT III - Computer programme to Calculate Emissions from Road Transport Methodology and Emission Factors (version 2.1), Copenhagen, EEA.

218. NTZIACHRISTOS, L., TOURLOU, P. M., SAMARAS, Z., GEIVANIDIS, S. & ANDRIAS, A. (2002) National and central estimates for air emissions from road transport, Copenhagen, European Environmental Agency.

219. O'MAHONY, M. & ARK, B. V. (Eds.) (2003) EU Productivity and Competitiveness: An Industry Perspective Can Europe Resume the Catching-up Process?, Luxembourg, Office for Official Publications of the European Communities.

220. OECD (1996a) Environmental Criteria for Sustainable Transport: Report on Phase 1 of the Project on Environmentally Sustainable Transport (EST) - Pollution Prevention and Control Programme, Paris, Organization For Economic Co-Operation And Development, OCDE/GD(96)136.

221. OECD (1996b) Pollution Prevention and Control Extended Producer Responsibility in the OECD Area Phase 1 Report, Paris, Organization For Economic Co-Operation And Development, OCDE/GD(96)48, (http://www.olis.oecd.org/olis/1996doc.nsf/LinkTo/NT00000C6A/$FILE/03E65226.PDF access in 26/10/2008).

222. OECD (2000) Synthesis Report of the OECD project on Environmentally Sustainable Transport (EST): futures, strategies and best practices Druck, Austria, Organization For Economic Co-Operation And Development.

223. OECD/IEA (2001) Toward a sustainable energy future, Paris, France, OECD/IEA.

224. OGDEN, J., WILLIAMS, R. & LARSON, E. (2004) Societal lifecycle costs of cars with alternative fuels/engines. Energy Policy, 32, 7-27.

225. OICA (2008) World production statistics - passenger car sales. International Organization of Motor Vehicle Manufacturers, http://oica.net/category/production-statistics/.

226. ORSATO, R. J. & WELLS, P. (2007) U-turn: the rise and demise of the automobile industry. Journal of Cleaner Production, 15, 994-1006.

227. ORTÚZAR, J. D. D. & WILLUMSEN, L. G. (2002) Modeling Transport, England, John Wiley and Sons.

228. OSTENWALDER, A. (2004) The Business Model Ontology-a proposition in a design science approach.PhD from the Ecole des Hautes Etudes Commerciales. Lausane, Université de Lausanne.

229. OTE (2008) Specialty Equipment Market Association. Europe, Specialty Equipment Market Association, http://www.sema.org.

230. PALISSADE CORP. (2008) Sensitivity Analysis. @Risk Technical Notes. London, UK, Palisade Corporation, http://helpdesk.palisade.com/kb/repository/%7BD0810C53-84D8-4E05-9735-E301766862BD%7D_TornadoCoefficients.zip, (December, 12th 2008).

231. PARKER'S - EMAP AUTOMOTIVE (2007) Parker's Car Price Guide. IN LTD, E. A. (Ed.). London, UK, http://www.parkers.co.uk.

232. PARTIDÁRIO, M. R. & MOURA, F. (1999) Strategic Sustainability Appraisal - One way of using SEA in the move toward sustainability. IN PARTIDÁRIO, M. R. & CLARK, R. (Eds.) Perspectives on Startegic Environmental Assessment. London, UK, CRC Press.

233. PHAAL, R., FARRUKH, C. J. P. & PROBERT, D. R. (2004) Technology roadmapping--A planning framework for evolution and revolution. Technological Forecasting and Social Change, 71, 5-26.

234. PLOTKIN, S. E. (2008) The Cost and Effectiveness of Policies to Reduce Vehicle Emissions: Examining Fuel Economy and Carbon Standards for Light Vehicles. Argonne National Laboratory Prepared for the Round Table of 31 January - 1 February 2, http://www.climateforchange.ca/files/climateforchange.ca/Public_Files53/TFIpaper.pdf, (04'03'2008).

235. POKHAREL, S. S., BISHOP, G. A. & STEDMAN, D. H. (2001) On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 2, Denver,, Department of Chemistry and Biochemistry, University of Denver.

236. POKHAREL, S. S., BISHOP, G. A. & STEDMAN, D. H. (2002) On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 3, Denver,, Department of Chemistry and Biochemistry, University of Denver.

237. PRICEWATERHOUSECOOPERS (2005) Block exemption: Bar room brawl spills onto the streets. Autofacts, Part 1, 9.

238. PSA PEUGEOT (2007) Our Action Plan 2007. France, PSA Peugeot, http://www.sustainability.psa-peugeot-citroen.com/vision/commitment/action-plan.htm, (22/04/2008).

239. RAC (2006a) RAC Report on Motoring 2006 - The Future of Motoring: A clear road map or collision course?, Norwich, Royal Automobile Club.

240. RAC (2006b) Running costs - RAC's Motoring Index. Norwich, RAC, http://www.rac.co.uk/web/knowhow/owning_a_car/running_costs/motoring_index.

241. REBITZER, G. & HUNKELER, D. (2003) Life Cycle Costing in LCM: Ambitions, Opportunities, and Limitations, Discussing a Framework. International Journal of Life Cycle Assessment, 8, 253-256.

242. REIS, I. (1999) Avaliação do Ciclo de Vida de um automóvel: aplicação à VW-Sharan.MSc from the Dpt. Mechanical Engineering. Lisbon, Instituto Superior Técnico.

243. RENAULT (2007) Renault's technological factsheets - Environment. France, RENAULT, http://www.renault.com/renault_com/en/main/50_INOVATION_ET_TECHNOLOGIE/40_Environnement/10_Reduire_la_consommation/.

244. RÖDER, A. (2001) Integration of Life-Cycle Assessment and Energy Planning Models for the Evaluation of Car Powertrains and Fuels.PhD from the Swiss Federal Institute of Technology. Würzburg (Germany).

245. ROGERS, E. (2003) Diffusion of Innovations, New York, Free Press.

246. ROGNER, H. H. (1997) An Assessment of World Hydrocarbon Resources. Annual Review of Energy and the Environment, 22, 217-262.

247. ROGNER, H. H. (1998) Hydrogen technologies and the technology learning curve. International Journal of Hydrogen Energy, 23, 833-840.

248. ROSS, M., GOODWIN, R., WATKINS, R., WENZEL, T. & WANG, M. Q. (1995) Real-world emissions from model year 1993, 2000, and 2010 passenger cars, Berkeley, California, Lawrence Berkeley Lab./Energy and Environment Division, LBL--37977.

249. ROSS, M., WENZEL, T. & WANG, M. Q. (1998) Real-World Emissions from Conventional Passenger Cars. J. Air & Waste Manage. Assoc., 48, 502-515.

250. RUPF, I. & GRIEF, S. (2002) Opportunities for Action in the Automotive Industry - Automotive Components: New Business Models, New Strategic Imperatives Boston, USA, The Boston Consulting Group, Inc., (www.bcg.com/impact_expertise/publications/files/Automotive_Components_Business_Models_Strategic_Imperatives_May2002.pdf access in November 10th, 2008).

251. RUSSELL, A., EKVALL, T. & BAUMANN, H. (2005) Life cycle assessment - introduction and overview. Journal of Cleaner Production, 13, 1207-1210.

252. SAKO, M. & MURRAY, F. (1999) Modular Strategies in Cars and Computers. Cambridge, USA, IMVP.

253. SAKO, M. & WARBURTON, M. (1999) MIT International Motor Vehicle Programme: Modularization and Outsourcing Project: Preliminary Report of European Research Team, Cambridge, USA, MIT International Motor Vehicle Programme, #w-0209a.

254. SAMARAS, Z., ZACHARIADIS, T., JOUMARD, R., VERNET, I., HASSEL, D., WEBER, F. J. & RIJKEBOER, R. (1998) Alternative short tests for inspection and maintenance of in-use cars with respect to their emissions performance. International Journal of Vehicle Design, 20, 292-303.

255. SAMARAS, Z., ZACHARIADIS, T., TOURLOU, E., GIANNOULI, M. & MPAMPATZIMOPOULOS, A. (2002) Development of a Database System for the Calculation of Indicators of Environmental Pressure Caused by Transport (TRENDS), Thessaloniki, Greece, Lab. of Applied Thermodynamics, Mechanical Engineering Dept., Aristotle University Thessaloniki, B2000-B27040B-SI2.198159-SER ARISTOTLE.

256. SAMUELSON, P. A., NORDHAUS, W. D. & MANDEL, M. J. (1992) Economics, McGraw-Hill New York.

257. SAN JOAQUIN VALLEY AIR POLLUTION CONTROL DISTRICT (2006) Heavy-Duty Engine Program - On-road vehicle component / Engine repowering and retrofit option: Eligibility criteria and application guidelines. San Joaquim, Sacramento, USA, San Joaquin Valley Air Pollution Control District, http://www.valleyair.org/transportation/materials.htm#On-Road_Vehicle_Component_.

258. SCHAFER, A. & VICTOR, D. G. (2000) The future mobility of the world population. Transportation Research Part A: Policy and Practice 34, 171-205.

259. SCHIPPER, L. & NG, W.-S. (2004) Rapid motorization in China: Environmental and Social Challenges, World Resources Institute, EMBARQ, ADB-JBIC-World Bank East Asia and Pacific Infrastructure Flagship Study.

260. SCHMIDHEINY, S. (1992) Changing Course: A Global Business Perspective on Development and the Environment, Cambridge, Massachussetts, World Business Council for Sustainable Development/MIT Press.

261. SCHUKERT, M., BEDDIES, H., GEDIGA, J., FLORIN, H., EYERER, P. & SCHWEIMER, G. W. (1997) Life cycle inventories - New experiences to save environmental loads and costs, Total life cycle meeting, Auburn Hills, Michigan, USA, SAE Technical Paper Series

262. SCHUMPETER, J. A. (1934) The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle, USA, Harvard University Press, Cambridge MA.

263. SCHWEIMER, G. W. & LEVIN, M. (2000) Life Cycle Inventory for the Golf A4, Germany, Research, Environment and Transport, Volkswagen AG, Wolfsburg / Center of Environmental Systems Research, University of Kassel, (http://www.volkswagen-environment.de/_download/sachbilanz_golf_a4_englisch.pdf access in 04/04/2008).

264. SEIDEL, M., LOCH, C. H. & CHAHIL, S. (2005) Quo Vadis, Automotive Industry? A Vision of Possible Industry Transformations. European Management Journal, 23, 439-449.

265. SEIXAS, J. & ALVES, B. (2006a) PNAC - Avaliação do Estado de Cumprimento do protocolo de Quioto / Anexo técnico dos Transportes, Lisbon, E-value for the Agência Portuguesa do Ambiente (Portuguese Enviromental Agency).

266. SEIXAS, J. & ALVES, B. (2006b) Portuguese National Programme for Climate Change (PNAC) - Transport Technical Annex, Lisbon, Portuguese Environmental Agency (Agência Portuguesa de Ambiente - APA).

267. SEMA (2001) 2001 Market Study, Diamond Bar, California, Specialty Equipment Market Association, (http://www.sema.org/main/semaorghome.aspx?ID=59891#International_Research access in November 7, 2008).

268. SEMA (2008) Specialty Equipment Market Association. USA, Specialty Equipment Market Association, http://www.sema.org.

269. SHERIF, Y. S. & KOLARIK, W. J. (1981) Life cycle costing: concept and practice. Omega, 9, 287-296.

270. SLOTT, R. S. (2007) E-23 Remote Sensing in Four Cities to Determine the Change in On-Road Vehicle Fleet Emissions Over Time, Alpharetta, Georgia, Coordinating Research Council, CRC Contract No. E-23.

271. SMITH, V. M. & KEOLEIAN, G. A. (2004) The Value of Remanufactured Engines: Life-Cycle Environmental and Economic Perspectives. Journal of Industrial Ecology, 8, 193-221.

272. SMMT (2002) Foresight vehicle technology roadmap: technology and research directions for future road vehicles, Cambridge, Society of Motor Manufacturers and Traders, V1.

273. SMMT (2004) Foresight Vehicle Technology Roadmap - Technology and Research Directions for Future Road Vehicles (Version 2), Cambridge, Society of Motor Manufacturers and Traders.

274. SMOKERS, R., VERMEULEN, R., MIEGHEM, R. V., GENSE, R., SKINNER, I., FERGUSSON, M., MACKAY, E., BRINK, P. T., FONTARAS, G. & SAMARAS, Z. (2006) Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars, Delft, The Netherlands, TNO Science and Industry, IEEP - Institute for European Environmental Policy and Laboratory of Applied Thermodynamics, Contract nr. SI2.408212.

275. SPIELMANN, M. & ALTHAUS, H.-J. (2007) Can a prolonged use of a passenger car reduce environmental burdens? Life Cycle analysis of Swiss passenger cars. The Automobile Industry & Sustainability, 15, 1122.

276. SPITZLEY, D. V., GRANDE, D. E., GRUHL, T., KEOLEIAN, G. A. & BEAN, J. C. (2004) Automotive Life Cycle Economics and Replacement Intervals, Ann Arbor, Michigan, Center for Sustainable Systems, CSS04-01.

277. SPITZLEY, D. V., GRANDE, D. E., KEOLEIAN, G. A. & KIM, H. C. (2005) Life cycle optimization of ownership costs and emissions reduction in US vehicle retirement decisions. Transportation Research Part D: Transport and Environment, 10, 161-175.

278. STEDMAN, D. H., BISHOP, G. A., BEATON, S. P., PETERSON, J. E., GUENTHER, P. L., MCVEY, I. F. & ZHANG, Y. (1994) On-road remote sensing of CO and HC emissions in California, Sacramento, California, CARB - California Air Resources Board.

279. STORCHMANN, K. (2004) On the Depreciation of Automobiles: An International Comparison. Transportation, 31, 371-408.

280. SULLIVAN, J. L. & COBAS-FLORES, E. (2001) Full Vehicle LCAs: A Review. 2001 Environmental Sustainability Conference and Exhibition. Graz, Austria, Society of Automotive Engineering (SAE).

281. SULLIVAN, J. L., WILLIAMS, R. L., YESTER, S., COBAS-FLORES, E., CHUBBS, S. T., HENTGES, S. G. & POMPER, S. D. (1998) Life Cycle Inventory of a Generic U.S. Family Sedan: Overview of Results USCAR AMP Project, Society of Automotive Engineering (SAE), 982160.

282. T&E (2006) How Clean is Your Car Brand ? The car industry's commitment to the EU to reduce CO2 emissions: a brand-by-brand progress report, Brussels, T&E – European Federation for Transport and Environment.

283. TAKEISHI, A. & FUJIMOTO, T. (2001) Modularisation in the auto industry: interlinked multiple hierarchies of product, production and supplier systems. International Journal of Automotive Technology and Management 1, 379-396.

284. THE AUTOCHANNEL (2008) Total Ownership Costs Guide. http://db.theautochannel.com/db/tocdb.phtml.

285. TODD, J. A. & CURRAN, M. A. (1999) Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup, Pensacola, Society of Environmental Toxicology and Chemistry (SETAC).

286. TOYOTA EUROPE (2001) Toyota European Environmental Report 2001, Toyota Europe, (http://www.toyotaeurope.com access in.

287. TRAIN, K. (1986) Qualitative Choice Analysis, Cambridge, MIT Press.

288. TRAIN, K. (2003) Discrete Choice Methods with Simulation, Cambridge, UK, Cambridge University Press.

289. TSUCHIYA, H. & KOBAYASHI, O. (2004) Mass production cost of PEM fuel cell by learning curve. International Journal of Hydrogen Energy, 29, 985-990.

290. TURTON, H. (2006a) Scenario and policy analysis of sustainable energy systems and automobile transportation.PhD from the. Zurich, Switzerland, Swiss Federal Institute of Technology.

291. TURTON, H. (2006b) Sustainable global automobile transport in the 21st century: An integrated scenario analysis. Technological Forecasting & Social Change, 73, 607-629.

292. TURTON, H. & BARRETO, L. (2006) Long-term security of energy supply and climate change. Energy Policy, 34, 2232-2250.

293. TURTON, H. & MOURA, F. (2008) Vehicle-to-grid systems for sustainable development: an integrated energy analysis. Technological Forecasting and Social Change, 75, 1091-1108

294. UNFCCC (1992) United Nations Framework Convention on Climate Change, NY, USA, United Nations, FCCC/INFORMAL/84.

295. US DEPARTMENT OF DEFENSE (2003) Manager's guide to technology transition in an evolutionary acquisition environment, Washington DC, USA, US Department of Defense.

296. US DEPARTMENT OF DEFENSE (2004) Chapter 3 - Affordability and Life-Cycle Resource Estimates, USA, US Department of Energy.

297. UTIGARD, T. A. (2005) Aluminium versus steel production trends – past, present and future. Aluminium International Today, Jan/Feb, 26-31.

298. VALORCAR (2007) Annual Report, Lisbon, VALORCAR, (http://www.valorcar.pt/biblioteca_documentos.asp access in November, 19th 2008).

299. VAN DEN BRINK, R. M. M. & VAN WEE, B. (2001) Why has car-fleet specific fuel consumption not shown any decrease since 1990? Quantitative analysis of Dutch passenger car-fleet specific fuel consumption. Transportation Research Part D: Transport and Environment, 6, 75-93.

300. VAN WEE, B., MOLL, H. C. & DIRKS, J. (2000) Environmental impact of scrapping old cars. Transportation Research Part D: Transport and Environment, 5, 137-143.

301. VERHULST, P.-F. (1838) Notice sur la loi que la population suit dans son accroissement. Correspondance mathématique et physique, 10, 113-121.

302. VIEGAS, J. (2003) Transport Policy development in Europe 1950-2020. IN ECMT (Ed.) 50 years of Transport Policy. Paris, European Conference of Ministers of Transport.

303. VIEGAS, J. (2008) Lecture Notes of the Transportation Course - 3rd year of the Graduation in Civil Engeneering. Department of Civil Engineering and Architecture / Instituto Superior Técnico.

304. VIEGAS, J. & LU, B. (2004) The Intermittent Bus Lane signals setting within an area. Transportation Research Part C: Emerging Technologies, 12, 453-469.

305. VIEGAS, J. & MOURA, F. (2006) A Procura e Eficiência Energética nos Transportes. Gazeta de Física - Sociedade Portuguesa de Física (http://nautilus.fis.uc.pt/gazeta/), Fascículo 1 e 2, 74-80.

306. VIEIRA, J., MOURA, F. & VIEGAS, J. (2007) Transport policy and environmental impacts: The importance of multi-instrumentality in policy integration. Transport Policy, 14, 421-432.

307. VTPI (2003) TDM Encyclopedia. Energy Conservation and Emissions Reduction Strategies., Victoria Transport Policy Institute, http://www.vtpi.org/.

308. VW AG (2005) Sustainability Report 2005/2006. Wolfsburf, Germany, VOLKSWAGEN AG-Environment and Industrial Safety, www.volkswagen-sustainability.com.

309. WALLACE, D. (1995) Environmental Policy and Industrial Innovation: Strategies in Europe, the USA and Japan, London, UK, Earthscan.

310. WANG, M., WEBER, T., FINIZZA, A., ARMSTRONG, A., SIMNICK, J., ROBBINS, G. J., CADU, J., BRINKMAN, N. & SANTINI, D. (2001) Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - North American Analysis., USA, General Motors Corp., Argonne National Laboratory, BP, Exxon Mobil, and Shell.

311. WANG, M. Q. (1999) GREET 1.5-Transportation fuel cycle model. Volume 2: Appendices of Data and Results, Argonne, Illinois, Center for Transportation Research - Argonne National Laboratory, ANL/ESD-39.vol2.

312. WARE, C. (1982) Durable car ownership: New approach to low cost motoring, Bath, UK, The Morris Minor Centre.

313. WATSON, R. T. & THE CORE WRITING TEAM (Eds.) (2001) Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of theIntegovernmental Panel on Climate Change, Cambridge,United Kingdom, and New York, NY, USA,, Cambridge University Press.

314. WBCSD (2001) Mobility 2001, Switzerland, World Business Council for Sustainable Development.

315. WBCSD (2004) Mobility 2030: Meeting the Challenges to Sustainability - The sustainable mobility project, Hertfordshire, England, World Business Council for Sustainable Development.

316. WEIBULL, W. (1951) A Statistical Distribution Function of Wide Applicability. Journal of Applied Mechanics, 293-297.

317. WEISS, M. A., HEYWOOD, J. B., DRAKE, E. M., SCHAFER, A. & AUYEUNG, F. F. (2000) On the road in 2020: A life-cycle analysis of new automobile technologies, Cambridge, Massachusetts, Energy Laboratory, Massachusetts Institute of Technology, Energy Laboratory Report # MIT EL 00-003, (http://web.mit.edu/energylab/www).

318. WHITNEY, D. E. (2003) Physical limits to modularity. MIT Engineering Systems Division, http://esd.mit.edu/symposium/pdfs/papers/whitney.pdf.

319. WHO (2004) Transport-related Health Effects with a Particular Focus on Children Towards an Integrated Assessment of their Costs and Benefits - State of the Art Knowledge, Methodological Aspects and Policy - Directions (Synthesis Report), Vienna, Austria, World Health Organization.

320. WOMACK, J. P., JONES, D. T. & ROOS, D. (2007) The machine that changed the world - How lean production revolutionized the global car wars, London, UK, Simon&Schuster UK, ltd.

321. WOODWARD, D. G. (1997) Life cycle costing-theory, information acquisition and application. International Journal of Project Management, 15, 335-344.

322. WORRELL, E. & BIERMANS, G. (2004) Move over! Stock turnover, retrofit and industrial energy efficiency. Energy Policy, 33, 949-962.

323. WORRELL, E., PRICE, L., MARTIN, N., FARLA, J. & SCHAEFFER, R. (1997) Energy intensity in the iron and steel industry: a comparison of physical and economic indicators. Energy Policy, 25, 727-744.

324. XU, B. (2000) Multinational enterprises, technology diffusion, and host country productivity growth. Journal of Development Economics, 62, 477-493.

325. ZACHARIADIS, T. (2006) On the baseline evolution of automobile fuel economy in Europe. Energy Policy, 34, 1773-1785.

326. ZACHARIADIS, T., SAMARAS, Z. C. & ZIEROCK, K.-H. (1995) Dynamic Modeling of Vehicle Populations: An Engineering Approach for Emissions Calculations. Technological Forecasting and Social Change, 50, 135-149.

327. ZELENKA, P., CARTELLIERI, W. & HERZOG, P. (1996) Worldwide diesel emission standards, current experiences and future needs. Applied Catalysis B: Environmental, 10, 3-28.

328. ZITTEL, W., SCHINDLER, J. & GMBH, L. B. S. (2002) Future world oil supply. International Summer School on the Politics and Economics of Renewable Energy at the University of Salzburg.

Annexes

A.1. Sources, impacts, and exceedances of the principal motor-vehicle-related air pollutants

Table 55. Sources, impacts, and exceedances of the principal motor-vehicle-related air pollutants (OECD, 1996a)

Type of impact	Local	Regional		Global			Source of emission	Health effects of pollutant	Exceedances of ambient air quality guidelines
Pollutant	High Concen-trations	Acidi-fication	Photoche-mical oxidants	Indirect Greenhouse Effect	Direct Greenhouse Effect	Stratospheric Ozone Depletion			
Suspended particulate matter (SPM)	X		X				Products of incomplete combustion of fuels; also from wear of brakes and tires	Irritates mucous membranes; increased respiratory symptoms, pulmonary effects; carcinogenic	WHO guidelines are exceeded by up to or more than a factor of two in 17 of 21 cities considered in one survey; in another, the guidelines were exceeded in 20 of 37 cities, with only 5 cities having concentrations within both annual and daily guidelines; the US EPA has designated 82 in 1994 areas as non-attainment areas.
Lead (Pb)	X						Added to gasoline to enhance engine performance	Affects circulatory, reproductive, and nervous systems	People in about one third of the world's cities are exposed to levels above WHO guidelines.
Carbon monoxide (CO)	X		X	X			Incomplete combustion product of carbon-based fuels	Reduced oxygen-carrying capacity of red blood cells	Short-term WHO guideline values are often exceeded in many urban areas in Europe and in southern California; in the USA, the EPA designated 36 regions as non-attainment areas for CO in 1994, with Los Angeles being classified as serious.
Nitrogen oxides (NOx)	X	X	X	X		X	Formation from fuel combustion at high temperatures	Irritates lungs; increases susceptibility to viruses	Major cities and metropolitan areas in Europe, the USA, and Japan continue to experience high episodic values exceeding applicable standards; concentrations exceeding WHO guidelines by a factor of 2-4 have been measured in some non-OECD megacities.
Volatile organic compounds (VOCs)	X		X	X			Combustion of petroleum products; also evaporation of unburnt fuel	Irritates eyes, causes intoxication; carcinogenic	Emissions and exceedances vary according to the compound. Acceptable emission levels for carcinogens may be zero, as in the case of two of the most important VOCs, 1,3- butadiene and benzene, which respectively account for 32 and 5 per cent of US cancer cases related to air pollution and of which transport is responsible for 94 and 85 per cent of all emissions.
Tropospheric ozone (O_3)		X	X	X			Not exhaust gas; product of photochemical reaction of NOx and VOCs in the presence of sunlight	Irritates mucous membranes of respiratory system; impairs immunities	WHO guidelines for short- and long-term exposure are frequently exceeded in large areas of OECD Europe, North America, and Japan; the US EPA has designated 77 areas as nonattainment areas in 1994.
Methane (CH_4)				X	X		Leakage during production, transport, filling and use of natural gas		
Carbon dioxide (CO_2)					X		Combustion product of carbon based fuels		
Nitrous oxide (N2O)					X	X	Combustion product of fuel and biomass; also formed in catalytic converters		
Chlorofluorocarbons (CFCs)				X	X	X	Leakage of coolant from air conditioning systems		

A.2. Emission standards in force in the EU countries

Emissions from passenger cars differ significantly according to the age of the vehicle. This is due to the fact that since the early 70s the legislation tried to improve air quality by setting emission standards for those vehicles. As a result, and in order to conform to more stringent standards, vehicle manufacturers developed new technologies for improved emission performance. From 1970 and until 1985 all EC member states followed the UN ECE R15 amendments (United Nations Economic Committee for Europe Regulation 15) as regards the emissions of pollutants from vehicles less than 3.5 tonnes. According to the relevant EC Directives, the implementation dates of these regulations were as follows:

Table 56. Implementation periods of UN-ECE regulations (EEA, 2007b)

UN-ECE standards	Implementation period
pre-ECE	<1971
ECE 15 00/01	1972 - 1977
ECE 15 02	1978 - 1980
ECE 15 03	1981 - 1985
ECE 15 04	1986 – 1992
Improved conventional	
Open loop	>1992
Closed loop	

The implementation dates were different depending on the member state. Importantly, these regulations were applicable to vehicles either produced in the member state or imported from elsewhere in the world. UN-ECE standards are not compulsory. Thus, the countries that adopted those regulations did it on a voluntary basis. This was not the case of Portugal. Portugal adopted the directive 91/441/EEC (Euro 1) and implemented it in 1993. Thereafter, the new emission standards (Euro 2) for passenger cars have been adopted in the EU (including Portugal) to be effective after 1.1.1997 (Directive 94/12/EEC). The following table lists all Euro standards including the post 2000 emission standards, where Euro 5 and 6 standards and implementation dates are still under negotiation.

Table 57. Emission standards (passenger cars) and implementation periods of Euro Regulation (http://ec.europa.eu/environment/air/transport/road.htm)

Standard	Directives	Date	CO	HC	HC+NOx	NOx	PM
					Diesel		
Euro 1	91/441/EEC	1992	2.72	n.a.	0.97	n.a.	0.140
Euro 2	94/12/EC or 96/69/EC	1996	1.00	n.a.	0.90	n.a.	0.100
Euro 3	98/69/EC, further amendments in 2002/80/EC	2000	0.64	n.a.	0.56	0.50	0.050
Euro 4		2005	0.50	n.a.	0.30	0.25	0.025
Euro 5[a]	Regulation 715/2007] of 20 June 2007d	2009	0.50	n.a.	0.23	0.18	0.005
Euro 6[a]		2014	0.50	n.a.	0.17	0.08	0.005
					Gasoline		
Euro 1	91/441/EEC	1992	2.72	n.a.	0.97	n.a.	n.a.
Euro 2	94/12/EC or 96/69/EC	1996	2.20	n.a.	0.50	n.a.	n.a.
Euro 3	98/69/EC, further amendments in 2002/80/EC	2000	2.30	0.20	n.a.	0.15	n.a.
Euro 4		2005	1.00	0.10	n.a.	0.08	n.a.
Euro 5[a]	Regulation 715/2007] of 20 June 2007d	2009	1.00	0.10[b]	n.a.	0.06	0.005[c]
Euro 6[a]			1.00	0.10[b]	n.a.	0.06	0.005[c]

a) The implementing part of the regulation (which will cover test procedures, deterioration factors and, if agreed by Member States, revised PM requirements) was to be finalized by 2 July 2008.

b) NMHC = 0.068 g/km.

c) Applicable only to vehicles using Direct Ignition engines.

A.3. Incremental technologies to promote energy and environmental efficiency

Environmental control technologies through the increase of engine efficiency (EE), vehicle efficecny (VE) or cleaning up emissions (C)

- (VE) Aerodynamic design of the car makes it possible to bring down its resistance to air at high speeds. The better the car penetrates the air, the less the call on the engine to maintain speed, and therefore the lower its fuel consumption.
- (VE) Downsizing – It consists of reducing the cubic capacity of an engine while maintaining its level of performance. This can be done with a turbocharger and direct injection technology.
- (VE) Reducing friction - By reducing friction, it is possible to increase the overall efficiency of the car and thus to minimise its exhaust emissions. This can be done in the engine (contact between surfaces), in valve sliding, in the gearbox, through aerodynamics (as referred above) and with tires (optimise the balance between grip and rolling resistance).
- (VE) Shedding weight – Substitute metallic components (e.g. bumpers, wings, hatch doors, spare wheel well, etc.) with lighter (less dense) materials such as polymers and composites. Cast iron engine components can also be substituted with lighter aluminum. For the chassis and body structures, very high yield-point steel and ultra-high yield-point steel have meant that it is possible to make components that are both lighter and better able to absorb impact energy.
- (EE) Engine managenemt unit – The EMU is one of many supervisor units in the vehicle and it provides real-time management of some fifty engine function parameters. To achieve this, it permanently analyses signals sent by the various sensors (accelerator position, engine mode, occurrence of knock, pressures, temperatures, etc.), decides the optimal engine adjustment and acts on the numerous actuators (fuel throttle, fuel injectors, exhaust gas recirculation valves, turbocharger blade positions, etc.), which will place the engine in the condition the supervisor has chosen. Among other operating parameters, the engine management unit acts on the richness (air/fuel mass ratio present in the combustion chamber), the key parameter that, under optimal conditions, will allow the catalytic converter of a petrol engine to convert polluting exhaust emissions of CO (carbon monoxide), HC (unburned hydrocarbons) and NOx (nitrogen oxides) into non-toxic gases – water vapour and CO2. In the case of a diesel engine equipped with a particulate filter, it is also an accurate control of the mix richness which controls the increase in exhaust gas temperatures during the periodic phases of filter regeneration (combustion of soot).
- HCCI and CAI engines – The phenomenon of auto-ignition is used here to cause instant ignition of the whole air fuel mixture in the combustion chamber. Whether it be gasoline (through Controlled Auto Ignition – CAI) or diesel (through Homogeneous Charge Compression Ignition – HCCI) engine, this type of operation no longer requires ignition. The mixture is auto-ignited either by the pressure and temperature of the predetermined diesel mixture (HCCI) or by residual burned gases (CAI). In this case, traditional heterogeneous hot combustion by propagation of a flame front is replaced with overall homogeneous combustion which is “colder” (the temperature remains less than 1,300° C). These two points result in the absence of formation of soot particles and NOx.

- (EE) The stratified charge engine - The principle of stratified charge applies to direct injection petrol engines. It involves concentrating spraying of the fuel close to the spark plug rather than throughout the whole of the combustion chamber. This method of operation delivers a reduction in fuel consumption that can reach 40% when the engine is running at very low charge.
- (EE) Turbochargers - By compressing air at the level of the engine air intake, the turbocharger provides a virtual increase in cubic capacity. It therefore makes it possible to greatly increase the specific power which it is capable of delivering while maintaining a much lower weight than a naturally aspirated engine with much greater cubic capacity. This alternative method has the advantage of simultaneously reducing a vehicle's fuel consumption and the level of polluting emissions.
- (EE) Camless engine - The opening and closing of the valves is commanded by electromechanical actuators that replace the camshaft. They give the valves great flexibility in opening and closing, which in turn makes it possible to adapt the intake and exhaust emissions to each phase of engine operation and to optimize its running.
- (EE) Camshaft angle variator - By adjusting the opening and closing of valves according to engine speed and load, the camshaft angle variator optimizes the operation of the engine, giving it more torque at low rpm and more power at high rpm, at the same time as reducing polluting emissions.
- (EE) Common rail - This technology is able to place fuel under extremely high pressure and send it through very small diameter nozzle holes thus giving micro-vaporization of fuel, which improves combustion and therefore provides greater engine efficiency while lowering polluting exhaust emissions.
- (EE) Multi-injection diesel engines -The speed of reaction of electronic injectors allows the use of multi-injection. The overall amount of diesel vaporized in the engine combustion chambers is divided into several squirts to optimize combustion while the piston is moving. This technology enables some engines on smaller vehicles to meet the requirements of the Euro 4 standard, without the need for a particulate filter.
- (EE) Piezoelectric injectors – They are controlled by the injection computer and behave like solenoid valves, letting fuel through or retaining it. They operate very rapidly, making it possible to adjust the quantity of fuel to optimize engine efficiency.
- (EE) The robotized gearbox - A robotized gearbox is a "manual" gearbox fitted with electromechanical actuators which shift gears according to instructions communicated by the gearbox computer, taking account of pre-established criteria.
- Continuously variable transmission – A CVT is a transmission which can change steplessly through an infinite number of effective gear ratios between maximum and minimum values. This contrasts with other mechanical transmissions that only allow a few different discrete gear ratios to be selected. The flexibility of a CVT allows the driving shaft to maintain a constant angular velocity over a range of output velocities. This can provide better fuel economy than other transmissions by enabling the engine to run at its most efficient revolutions per minute (RPM) for a range of vehicle speeds.

- (C) Catalytic converters for petrol engines - A three-way catalytic converter has three simultaneous tasks: reduction of nitrogen oxides to nitrogen and oxygen ($2NOx \rightarrow xO_2 + N_2$); oxidation of carbon monoxide to carbon dioxide ($2CO + O_2 \rightarrow 2CO_2$); and, oxidation of unburned hydrocarbons to carbon dioxide and water ($2CxHy + (2x+y/2)O_2 \rightarrow 2xCO_2 + yH_2O$). These three reactions occur most efficiently when the catalytic converter receives exhaust from an engine running slightly above the stoichiometric point. It is composed by a ceramic honeycomb structure coated a mixture of silica and alumina. The catalyst itself is most often a precious metal. Platinum is the most active catalyst and is widely used. However, it is not suitable for all applications because of unwanted additional reactions and/or cost. Palladium and rhodium are two other precious metals that are used. Platinum and rhodium are used as a reduction catalyst, while platinum and palladium are used as an oxidization catalyst
- Particulate filter - The particulate filter consists of a porous cellular substrate, with pores the diameter of which is smaller than that of the particulates rejected by the engine. By retaining these, it purifies the exhaust gas. To achieve this, the substrate is directly impregnated with catalytic materials. The particulate filter is fitted to the exhaust line, downstream from the catalytic converter, and supplements it without replacing it completely. However, like any filter, the particulate filter gets clogged quickly. So that it remains effective and does not block evacuation of exhaust gas, it must regularly (300 to 500 kilometres) be regenerated, an operation which is carried out automatically and is undetectable to the driver. The regeneration phase consists of bringing the particulate filter up to a very high temperature. To achieve this, the calculator adds to the injection cycle one, or even two, post-injections that are not present in the normal injection cycle.
- (C) NOx filter – It fulfills the role of both the conventional oxidation catalytic converter (HC/CO oxidation) and NOx trap. It captures NOx and stores them in a microporous structure. The operating principle is similar to that of the particulate filter and requires NOx traps to have regular phases of regeneration. To regenerate the catalytic converter, the lean-burn engine must operate in rich-burn so that the unburned hydrocarbons and the carbon monoxide emitted in large quantities reduce the stored NOx.
- Selective catalytic reduction – SCR is a means of converting NOx with the aid of a catalyst into N_2 and H_2O. A gaseous reductant, typically anhydrous ammonia, aqueous ammonia or urea, is added to the exhaust gas and is absorbed onto a catalyst. CO_2 is a reaction product when urea is used as the reductant. These are applied to large diesel engines, such as those found on large ships, diesel locomotives, combustion turbines, but more recently they are used in heavy duty vehicles and possibly in automobiles.
- (C) Exhaust Gas Recirculation- EGR works through a solenoid valve that re-injects some of the exhaust gases into the engine air intake circuit. By lowering combustion temperature, EGR reduces the formation of NOx.

A.4. Emission factors for the up and downstream lifecycle phases to car use

Table 58. LCI parameters for the materials production and manufacturing phases of cars (based on Sullivan *et al.*, 1998, Kim, 2003)

	Materials production						Manufacturing					
Year	Energy	CO_2	CO	NMVOC	NO_X	PM	Energy	CO_2	CO	NMVOC	NO_X	PM
1985	0.0651	3.6236	0.0458	0.0044	0.0095	0.0191	0.0256	1.6759	0.0038	0.0091	0.0054	0.0050
1990	0.0624	3.4040	0.0435	0.0042	0.0092	0.0181	0.0257	1.6869	0.0038	0.0091	0.0054	0.0050
1995	0.0588	3.1640	0.0404	0.0040	0.0089	0.0173	0.0274	1.7971	0.0041	0.0097	0.0058	0.0054
2000	0.0551	2.9192	0.0384	0.0037	0.0086	0.0163	0.0260	1.7068	0.0039	0.0092	0.0055	0.0051
2005	0.0531	2.7415	0.0369	0.0036	0.0083	0.0155	0.0248	1.6234	0.0037	0.0088	0.0052	0.0048
2010	0.0528	2.6685	0.0365	0.0037	0.0083	0.0149	0.0229	1.5017	0.0034	0.0081	0.0048	0.0044
2015	0.0510	2.5399	0.0351	0.0036	0.0080	0.0145	0.0209	1.3721	0.0031	0.0074	0.0044	0.0041
2020	0.0487	2.4305	0.0346	0.0033	0.0077	0.0141	0.0194	1.2697	0.0029	0.0069	0.0041	0.0037
2025	0.0487	2.4305	0.0346	0.0033	0.0077	0.0141	0.0194	1.2697	0.0029	0.0069	0.0041	0.0037
2030	0.0487	2.4305	0.0346	0.0033	0.0077	0.0141	0.0194	1.2697	0.0029	0.0069	0.0041	0.0037

Note: Energy consumption is expressed in $GJ/kg_{vehicle}$ and emissions in $kg_{pollutant}/kg_{vehicle}$.

Table 59. LCI parameters for the maintenance phase of cars (based on Sullivan *et al.*, 1998, Kim, 2003)

	MY	Vehicle Age																				
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
FC	1990	0.076	0.076	0.076	0.078	0.079	0.081	0.081	0.081	0.079	0.079	0.078	0.076	0.076	0.075	0.074	0.073	0.072	0.071	0.069	0.068	0.067
	1995	0.086	0.086	0.086	0.084	0.084	0.083	0.081	0.081	0.080	0.079	0.078	0.076	0.075	0.074	0.073	0.071	0.070	0.069	0.068	0.067	0.066
	2000	0.078	0.078	0.078	0.076	0.075	0.074	0.073	0.071	0.070	0.069	0.068	0.067	0.066	0.064	0.064	0.063	0.061	0.061	0.059	0.059	0.058
	2005	0.068	0.068	0.067	0.066	0.064	0.064	0.063	0.062	0.061	0.060	0.059	0.058	0.057	0.056	0.055	0.054	0.053	0.053	0.053	0.053	0.053
	2010	0.058	0.058	0.057	0.056	0.055	0.054	0.053	0.053	0.051	0.051	0.050	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
	2015	0.049	0.049	0.048	0.048	0.047	0.046	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
	2020	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
	2025	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
	2030	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
CO_2	1990	3.381	3.381	3.413	3.481	3.556	3.625	3.600	3.594	3.519	3.513	3.469	3.419	3.413	3.350	3.313	3.275	3.206	3.150	3.100	3.044	3.000
	1995	3.838	3.838	3.831	3.744	3.744	3.700	3.644	3.638	3.569	3.525	3.488	3.419	3.356	3.306	3.244	3.194	3.144	3.094	3.044	3.000	2.950
	2000	3.463	3.463	3.456	3.388	3.350	3.313	3.250	3.188	3.138	3.081	3.038	2.988	2.938	2.894	2.850	2.800	2.756	2.713	2.669	2.625	2.581
	2005	3.050	3.050	2.988	2.944	2.894	2.850	2.806	2.756	2.713	2.675	2.631	2.588	2.544	2.506	2.463	2.419	2.381	2.381	2.381	2.381	2.381
	2010	2.581	2.581	2.538	2.494	2.463	2.419	2.381	2.344	2.306	2.263	2.225	2.188	2.188	2.188	2.188	2.188	2.188	2.188	2.188	2.188	2.188
	2015	2.194	2.194	2.163	2.125	2.088	2.056	2.019	2.019	2.019	2.019	2.019	2.019	2.019	2.019	2.019	2.019	2.019	2.019	2.019	2.019	2.019
	2020	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863
	2025	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863
	2030	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863	1.863
CO	1990	0.179	0.179	0.181	0.185	0.189	0.193	0.191	0.191	0.187	0.186	0.184	0.181	0.181	0.178	0.176	0.174	0.171	0.167	0.164	0.162	0.159
	1995	0.204	0.204	0.203	0.199	0.199	0.196	0.193	0.193	0.189	0.188	0.185	0.181	0.178	0.176	0.173	0.169	0.167	0.164	0.162	0.159	0.157
	2000	0.184	0.184	0.184	0.180	0.178	0.176	0.173	0.169	0.167	0.164	0.161	0.159	0.156	0.154	0.151	0.149	0.146	0.144	0.142	0.139	0.137
	2005	0.162	0.162	0.159	0.156	0.154	0.151	0.149	0.146	0.144	0.142	0.139	0.138	0.135	0.133	0.131	0.129	0.126	0.126	0.126	0.126	0.126
	2010	0.137	0.137	0.135	0.133	0.131	0.128	0.126	0.124	0.123	0.120	0.118	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116	0.116
	2015	0.116	0.116	0.114	0.113	0.111	0.109	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108
	2020	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099
	2025	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099
	2030	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099
NMVOC	1990	0.010	0.010	0.010	0.010	0.011	0.011	0.011	0.011	0.010	0.010	0.010	0.010	0.010	0.010	0.009	0.009	0.009	0.009	0.009	0.009	0.009
	1995	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.010	0.010	0.010	0.010	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
	2000	0.010	0.010	0.010	0.010	0.010	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008
	2005	0.009	0.009	0.009	0.009	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.007	0.007	0.007	0.007
	2010	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
	2015	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
	2020	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
	2025	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
	2030	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
NO_X	1990	0.013	0.013	0.013	0.013	0.013	0.014	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.012	0.012	0.012	0.011	0.011	0.011
	1995	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.013	0.013	0.013	0.013	0.013	0.013	0.012	0.012	0.012	0.011	0.011	0.011	0.011

	MY	Vehicle Age																				
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	2000	0.013	0.013	0.013	0.013	0.013	0.013	0.012	0.012	0.012	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.010	0.010	0.010	0.010	0.009
	2005	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.010	0.010	0.010	0.010	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
	2010	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
	2015	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
	2020	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
	2025	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
	2030	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
PM	1990	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	1995	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
	2000	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	2005	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	2010	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
	2015	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
	2020	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
	2025	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
	2030	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007

Notes: to Energy Intensity is expressed in (MJ/km) and emission factors in (g/km). 'FC' refers to fuel consumption.

Table 60. LCI parameters for the end-of-life phase of cars (based on Sullivan *et al.*, 1998, Kim, 2003)

	MY	Vehicle Age																				
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
FC	1990	0.470	0.470	0.470	0.470	0.470	0.470	0.470	0.470	0.470	0.470	0.482	0.484	0.497	0.495	0.501	0.501	0.501	0.509	0.515	0.510	0.510
	1995	0.469	0.469	0.469	0.469	0.469	0.482	0.485	0.497	0.495	0.501	0.501	0.501	0.509	0.514	0.511	0.509	0.507	0.506	0.502	0.504	0.502
	2000	0.484	0.484	0.496	0.495	0.501	0.501	0.501	0.509	0.514	0.511	0.509	0.507	0.506	0.502	0.505	0.503	0.502	0.501	0.496	0.494	0.492
	2005	0.507	0.507	0.516	0.521	0.517	0.516	0.514	0.512	0.509	0.511	0.510	0.508	0.507	0.503	0.501	0.498	0.496	0.496	0.496	0.496	0.496
	2010	0.516	0.516	0.515	0.511	0.514	0.512	0.511	0.510	0.506	0.504	0.501	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499
	2015	0.506	0.506	0.505	0.502	0.499	0.497	0.495	0.495	0.495	0.495	0.495	0.495	0.495	0.495	0.495	0.495	0.495	0.495	0.495	0.495	0.495
	2020	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497
	2025	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497
	2030	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497
CO_2	1990	98	98	98	98	98	98	98	98	98	98	101	102	104	104	105	105	105	107	108	107	107
	1995	98	98	98	98	98	101	102	104	104	105	105	105	107	108	107	107	107	106	105	106	105
	2000	101	101	104	104	105	105	105	107	108	107	107	107	106	105	106	105	105	105	104	104	103
	2005	107	107	108	109	109	108	108	107	107	107	107	107	107	106	105	105	104	104	104	104	104
	2010	109	109	108	107	108	108	107	107	106	106	105	105	105	105	105	105	105	105	105	105	105
	2015	106	106	106	105	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	2020	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	2025	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	2030	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
CO	1990	1.487	1.487	1.487	1.487	1.487	1.487	1.487	1.487	1.487	1.487	1.525	1.535	1.574	1.568	1.587	1.587	1.587	1.612	1.629	1.617	1.614
	1995	1.487	1.487	1.487	1.487	1.487	1.526	1.535	1.574	1.568	1.587	1.587	1.587	1.612	1.629	1.618	1.614	1.607	1.602	1.590	1.598	1.592
	2000	1.535	1.535	1.574	1.569	1.587	1.587	1.587	1.612	1.629	1.618	1.614	1.607	1.602	1.590	1.598	1.593	1.589	1.585	1.574	1.568	1.559
	2005	1.608	1.608	1.634	1.651	1.639	1.635	1.628	1.623	1.612	1.619	1.614	1.610	1.606	1.595	1.588	1.580	1.573	1.573	1.573	1.573	1.573
	2010	1.637	1.637	1.632	1.620	1.628	1.623	1.620	1.615	1.604	1.597	1.588	1.581	1.581	1.581	1.581	1.581	1.581	1.581	1.581	1.581	1.581
	2015	1.605	1.605	1.600	1.589	1.583	1.574	1.567	1.567	1.567	1.567	1.567	1.567	1.567	1.567	1.567	1.567	1.567	1.567	1.567	1.567	1.567
	2020	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574
	2025	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574
	2030	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574	1.574
NMVOC	1990	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.121	0.121	0.124	0.124	0.126	0.126	0.126	0.127	0.128	0.128	0.128
	1995	0.118	0.118	0.118	0.118	0.118	0.120	0.121	0.124	0.124	0.125	0.125	0.125	0.127	0.129	0.128	0.128	0.127	0.126	0.126	0.126	0.126
	2000	0.121	0.121	0.124	0.124	0.125	0.125	0.125	0.127	0.129	0.128	0.127	0.127	0.127	0.125	0.126	0.126	0.125	0.125	0.124	0.124	0.123
	2005	0.127	0.127	0.129	0.130	0.129	0.129	0.129	0.128	0.127	0.128	0.127	0.127	0.127	0.126	0.125	0.125	0.125	0.125	0.125	0.125	0.125
	2010	0.130	0.130	0.129	0.128	0.129	0.128	0.128	0.127	0.127	0.126	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
	2015	0.127	0.127	0.127	0.125	0.125	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124
	2020	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
	2025	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
	2030	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
NO_X	1990	0.554	0.554	0.554	0.554	0.554	0.554	0.554	0.554	0.554	0.554	0.568	0.571	0.586	0.584	0.591	0.591	0.591	0.600	0.607	0.602	0.601
	1995	0.554	0.554	0.554	0.554	0.554	0.568	0.572	0.586	0.584	0.591	0.591	0.591	0.601	0.607	0.603	0.601	0.599	0.597	0.592	0.595	0.593

	MY	Vehicle Age																				
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	2000	0.572	0.572	0.586	0.584	0.591	0.591	0.591	0.600	0.607	0.602	0.601	0.598	0.596	0.592	0.595	0.593	0.592	0.590	0.586	0.584	0.580
	2005	0.599	0.599	0.609	0.615	0.611	0.609	0.606	0.604	0.600	0.603	0.601	0.600	0.598	0.594	0.592	0.588	0.586	0.586	0.586	0.586	0.586
	2010	0.610	0.610	0.608	0.604	0.607	0.604	0.603	0.602	0.597	0.595	0.591	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589
	2015	0.598	0.598	0.596	0.592	0.589	0.586	0.584	0.584	0.584	0.584	0.584	0.584	0.584	0.584	0.584	0.584	0.584	0.584	0.584	0.584	0.584
	2020	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587
	2025	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587
	2030	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587
PM	1990	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161
	1995	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161
	2000	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166
	2005	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172
	2010	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174
	2015	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172
	2020	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168
	2025	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168
	2030	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168

Notes: Energy Intensity is expressed in (MJ/kg) and emission factors in (kg/kg). 'FC' refers to fuel consumption.

A.5. Exhaust emission factors for regulated pollutants

Table 61. Exhaust emission factors for regulated pollutants (source: author based on EEA, 2007b)

Pollutant	VT	MY between...		Emission factors varying with age (or equivalent cumulative mileage that depends on vehicle type)																				
		Low	High	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
CO	PCGS	1900	1971	26.26	26.26	26.26	28.46	31.56	34.50	37.29	39.97	42.56	45.05	47.47	49.82	52.10	54.32	56.48	58.60	60.67	62.69	63.76	63.76	63.76
CO	PCGS	1972	1977	21.27	21.27	21.27	23.04	25.53	27.88	30.12	32.27	34.34	36.34	38.27	40.15	41.98	43.76	45.50	47.19	48.85	50.47	51.32	51.32	51.32
CO	PCGS	1978	1980	15.71	15.71	15.71	16.99	18.79	20.49	22.11	23.66	25.16	26.61	28.01	29.37	30.69	31.98	33.23	34.46	35.66	36.83	37.45	37.45	37.45
CO	PCGS	1981	1985	16.14	16.14	16.14	17.46	19.31	21.06	22.73	24.33	25.87	27.36	28.80	30.20	31.56	32.89	34.18	35.44	36.68	37.88	38.52	38.52	38.52
CO	PCGS	1986	1992	9.70	9.70	9.70	10.45	11.51	12.50	13.45	14.37	15.24	16.09	16.91	17.71	18.49	19.24	19.98	20.70	21.40	22.09	22.45	22.45	22.45
CO	PCGS	1993	1995	3.92	3.92	3.92	4.04	4.21	4.37	4.52	4.67	4.81	4.94	5.07	5.20	5.32	5.45	5.56	5.68	5.79	5.90	5.96	5.96	5.96
CO	PCGS	1996	1999	3.08	3.08	3.08	3.06	3.11	3.15	3.20	3.24	3.28	3.32	3.36	3.39	3.43	3.47	3.50	3.53	3.57	3.60	3.61	3.61	3.61
CO	PCGS	2000	2004	3.09	3.09	3.09	3.06	3.11	3.16	3.21	3.25	3.29	3.33	3.37	3.41	3.44	3.48	3.51	3.55	3.58	3.61	3.63	3.63	3.63
CO	PCGS	2005	2008	2.80	2.80	2.80	2.79	2.81	2.83	2.85	2.87	2.89	2.91	2.93	2.94	2.96	2.98	2.99	3.01	3.02	3.04	3.04	3.04	3.04
CO	PCGS	2009	2013	2.80	2.80	2.80	2.79	2.81	2.83	2.85	2.87	2.89	2.91	2.93	2.94	2.96	2.98	2.99	3.01	3.02	3.04	3.04	3.04	3.04
CO	PCGS	2014	2050	2.80	2.80	2.80	2.79	2.81	2.83	2.85	2.87	2.89	2.91	2.93	2.94	2.96	2.98	2.99	3.01	3.02	3.04	3.04	3.04	3.04
CO	PCGM	1900	1971	26.26	26.26	26.26	25.28	27.29	29.19	31.00	32.73	34.41	36.02	37.59	39.11	40.59	42.02	43.43	44.80	46.14	46.67	46.67	46.67	46.67
CO	PCGM	1972	1977	21.27	21.27	21.27	20.49	22.10	23.62	25.07	26.46	27.80	29.10	30.35	31.57	32.76	33.91	35.03	36.13	37.20	37.63	37.63	37.63	37.63
CO	PCGM	1978	1980	15.71	15.71	15.71	15.15	16.31	17.41	18.46	19.47	20.44	21.37	22.28	23.16	24.02	24.85	25.67	26.46	27.23	27.55	27.55	27.55	27.55
CO	PCGM	1981	1985	16.14	16.14	16.14	15.56	16.76	17.89	18.97	20.01	21.01	21.97	22.91	23.81	24.69	25.55	26.39	27.21	28.01	28.33	28.33	28.33	28.33
CO	PCGM	1986	1992	9.87	9.87	9.87	9.53	10.23	10.89	11.52	12.12	12.70	13.26	13.80	14.33	14.84	15.34	15.83	16.30	16.76	16.95	16.95	16.95	16.95
CO	PCGM	1993	1995	3.68	3.68	3.68	3.63	3.74	3.84	3.94	4.04	4.13	4.22	4.30	4.38	4.47	4.54	4.62	4.70	4.77	4.80	4.80	4.80	4.80
CO	PCGM	1996	1999	2.84	2.84	2.84	2.76	2.79	2.82	2.84	2.87	2.89	2.92	2.94	2.96	2.98	3.01	3.03	3.05	3.07	3.07	3.07	3.07	3.07
CO	PCGM	2000	2004	2.86	2.86	2.86	2.78	2.81	2.84	2.87	2.90	2.92	2.95	2.97	3.00	3.02	3.04	3.06	3.08	3.10	3.11	3.11	3.11	3.11
CO	PCGM	2005	2008	2.56	2.56	2.56	2.53	2.54	2.55	2.57	2.58	2.59	2.60	2.61	2.62	2.63	2.64	2.65	2.66	2.67	2.68	2.68	2.68	2.68
CO	PCGM	2009	2013	2.56	2.56	2.56	2.53	2.54	2.55	2.57	2.58	2.59	2.60	2.61	2.62	2.63	2.64	2.65	2.66	2.67	2.68	2.68	2.68	2.68
CO	PCGM	2014	2050	2.56	2.56	2.56	2.53	2.54	2.55	2.57	2.58	2.59	2.60	2.61	2.62	2.63	2.64	2.65	2.66	2.67	2.68	2.68	2.68	2.68
CO	PCGB	1900	1971	26.26	26.26	26.26	25.07	26.00	26.89	27.73	28.54	29.32	30.08	30.81	31.51	32.20	32.87	33.53	34.17	34.75	34.75	34.75	34.75	34.75
CO	PCGB	1972	1977	21.27	21.27	21.27	20.32	21.07	21.78	22.46	23.11	23.73	24.33	24.92	25.49	26.04	26.58	27.10	27.61	28.08	28.08	28.08	28.08	28.08
CO	PCGB	1978	1980	15.71	15.71	15.71	15.02	15.57	16.08	16.57	17.04	17.49	17.93	18.35	18.76	19.16	19.55	19.93	20.30	20.64	20.64	20.64	20.64	20.64
CO	PCGB	1981	1985	16.14	16.14	16.14	15.43	15.99	16.52	17.02	17.51	17.97	18.42	18.86	19.28	19.69	20.09	20.48	20.86	21.21	21.21	21.21	21.21	21.21

Pollutant	VT	MY between...		Emission factors varying with age (or equivalent cumulative mileage that depends on vehicle type)																				
		Low	High	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
CO	PCGB	1986	1992	9.87	9.87	9.87	9.46	9.79	10.09	10.39	10.67	10.94	11.20	11.45	11.70	11.93	12.17	12.39	12.62	12.82	12.82	12.82	12.82	12.82
CO	PCGB	1993	1995	3.33	3.33	3.33	3.26	3.32	3.37	3.42	3.48	3.52	3.57	3.62	3.66	3.71	3.75	3.79	3.83	3.87	3.87	3.87	3.87	3.87
CO	PCGB	1996	1999	2.37	2.37	2.37	2.34	2.36	2.38	2.40	2.42	2.44	2.46	2.48	2.49	2.51	2.53	2.54	2.56	2.57	2.57	2.57	2.57	2.57
CO	PCGB	2000	2004	2.43	2.43	2.43	2.34	2.35	2.36	2.37	2.38	2.39	2.39	2.40	2.41	2.42	2.43	2.43	2.44	2.45	2.45	2.45	2.45	2.45
CO	PCGB	2005	2008	2.07	2.07	2.07	2.02	2.03	2.03	2.04	2.04	2.05	2.05	2.06	2.06	2.06	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08
CO	PCGB	2009	2013	2.07	2.07	2.07	2.02	2.03	2.03	2.04	2.04	2.05	2.05	2.06	2.06	2.06	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08
CO	PCGB	2014	2050	2.07	2.07	2.07	2.02	2.03	2.03	2.04	2.04	2.05	2.05	2.06	2.06	2.06	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08
CO	PCDM	1900	1992	1.32	1.32	1.32	1.64	1.77	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
CO	PCDM	1993	1995	1.12	1.12	1.12	1.33	1.41	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
CO	PCDM	1996	1999	1.04	1.04	1.04	1.21	1.28	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
CO	PCDM	2000	2004	0.83	0.83	0.83	0.85	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
CO	PCDM	2005	2008	0.82	0.82	0.82	0.84	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
CO	PCDM	2009	2013	0.82	0.82	0.82	0.84	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
CO	PCDM	2014	2050	0.82	0.82	0.82	0.84	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
CO	PCDB	1900	1992	1.32	1.32	1.32	1.45	1.51	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
CO	PCDB	1993	1995	1.12	1.12	1.12	1.20	1.24	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
CO	PCDB	1996	1999	1.04	1.04	1.04	1.11	1.14	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
CO	PCDB	2000	2004	0.83	0.83	0.83	0.82	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
CO	PCDB	2005	2008	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
CO	PCDB	2009	2013	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
CO	PCDB	2014	2050	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
NO_X	PCGS	1900	1971	2.19	2.19	2.19	1.92	2.09	2.25	2.40	2.54	2.68	2.81	2.94	3.07	3.19	3.31	3.43	3.54	3.65	3.76	3.82	3.82	3.82
NO_X	PCGS	1972	1977	2.19	2.19	2.19	1.92	2.09	2.25	2.40	2.54	2.68	2.81	2.94	3.07	3.19	3.31	3.43	3.54	3.65	3.76	3.82	3.82	3.82
NO_X	PCGS	1978	1980	2.41	2.41	2.41	2.11	2.30	2.48	2.65	2.82	2.97	3.13	3.27	3.42	3.56	3.69	3.82	3.95	4.08	4.20	4.26	4.26	4.26
NO_X	PCGS	1981	1985	2.58	2.58	2.58	2.25	2.46	2.65	2.84	3.02	3.19	3.36	3.52	3.67	3.82	3.97	4.12	4.26	4.39	4.53	4.59	4.59	4.59
NO_X	PCGS	1986	1992	2.36	2.36	2.36	2.07	2.25	2.43	2.59	2.75	2.90	3.05	3.20	3.33	3.47	3.60	3.73	3.86	3.98	4.10	4.16	4.16	4.16
NO_X	PCGS	1993	1995	1.18	1.18	1.18	1.15	1.17	1.19	1.20	1.22	1.23	1.24	1.26	1.27	1.28	1.30	1.31	1.32	1.33	1.34	1.35	1.35	1.35
NO_X	PCGS	1996	1999	1.09	1.09	1.09	1.07	1.07	1.08	1.09	1.09	1.10	1.10	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.14	1.14	1.14	1.14

Pollutant	VT	MY between...		Emission factors varying with age (or equivalent cumulative mileage that depends on vehicle type)																				
		Low	High	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
NO_X	PCGS	2000	2004	1.04	1.04	1.04	1.03	1.04	1.04	1.04	1.04	1.05	1.05	1.05	1.05	1.05	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
NO_X	PCGS	2005	2008	1.03	1.03	1.03	1.02	1.03	1.03	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
NO_X	PCGS	2009	2013	1.03	1.03	1.03	1.02	1.02	1.02	1.02	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04
NO_X	PCGS	2014	2050	1.03	1.03	1.03	1.02	1.02	1.02	1.02	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04
NO_X	PCGM	1900	1971	2.71	2.71	2.71	2.41	2.64	2.86	3.06	3.26	3.45	3.64	3.82	3.99	4.16	4.32	4.48	4.64	4.79	4.86	4.86	4.86	4.86
NO_X	PCGM	1972	1977	2.71	2.71	2.71	2.41	2.64	2.86	3.06	3.26	3.45	3.64	3.82	3.99	4.16	4.32	4.48	4.64	4.79	4.86	4.86	4.86	4.86
NO_X	PCGM	1978	1980	2.66	2.66	2.66	2.36	2.58	2.80	3.00	3.19	3.38	3.56	3.73	3.90	4.07	4.23	4.38	4.53	4.68	4.75	4.75	4.75	4.75
NO_X	PCGM	1981	1985	2.71	2.71	2.71	2.41	2.64	2.86	3.07	3.26	3.46	3.64	3.82	3.99	4.16	4.33	4.49	4.65	4.80	4.86	4.86	4.86	4.86
NO_X	PCGM	1986	1992	2.84	2.84	2.84	2.52	2.76	2.99	3.21	3.42	3.62	3.82	4.01	4.19	4.37	4.54	4.71	4.88	5.04	5.11	5.11	5.11	5.11
NO_X	PCGM	1993	1995	1.18	1.18	1.18	1.16	1.18	1.19	1.21	1.23	1.24	1.26	1.27	1.28	1.30	1.31	1.32	1.34	1.35	1.35	1.35	1.35	1.35
NO_X	PCGM	1996	1999	1.09	1.09	1.09	1.07	1.08	1.08	1.09	1.10	1.10	1.11	1.11	1.12	1.12	1.13	1.13	1.14	1.14	1.14	1.14	1.14	1.14
NO_X	PCGM	2000	2004	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.05	1.05	1.05	1.05	1.05	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
NO_X	PCGM	2005	2008	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.05	1.05	1.05	1.05	1.05	1.05
NO_X	PCGM	2009	2013	1.03	1.03	1.03	1.02	1.02	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04
NO_X	PCGM	2014	2050	1.03	1.03	1.03	1.02	1.02	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04
NO_X	PCGB	1900	1971	3.81	3.81	3.81	3.39	3.74	4.08	4.39	4.70	4.99	5.28	5.55	5.82	6.08	6.33	6.57	6.81	7.04	7.04	7.04	7.04	7.04
NO_X	PCGB	1972	1977	3.81	3.81	3.81	3.39	3.74	4.08	4.39	4.70	4.99	5.28	5.55	5.82	6.08	6.33	6.57	6.81	7.04	7.04	7.04	7.04	7.04
NO_X	PCGB	1978	1980	2.92	2.92	2.92	2.61	2.87	3.11	3.35	3.57	3.78	3.99	4.19	4.38	4.57	4.76	4.94	5.11	5.27	5.27	5.27	5.27	5.27
NO_X	PCGB	1981	1985	3.69	3.69	3.69	3.28	3.62	3.94	4.25	4.54	4.83	5.10	5.36	5.62	5.87	6.11	6.35	6.58	6.79	6.79	6.79	6.79	6.79
NO_X	PCGB	1986	1992	3.11	3.11	3.11	2.78	3.05	3.32	3.57	3.81	4.04	4.26	4.48	4.69	4.89	5.09	5.28	5.47	5.64	5.64	5.64	5.64	5.64
NO_X	PCGB	1993	1995	1.06	1.06	1.06	1.04	1.05	1.07	1.09	1.10	1.12	1.14	1.15	1.16	1.18	1.19	1.20	1.22	1.23	1.23	1.23	1.23	1.23
NO_X	PCGB	1996	1999	0.97	0.97	0.97	0.96	0.96	0.97	0.98	0.99	0.99	1.00	1.01	1.02	1.02	1.03	1.03	1.04	1.05	1.05	1.05	1.05	1.05
NO_X	PCGB	2000	2004	0.92	0.92	0.92	0.91	0.91	0.92	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.94
NO_X	PCGB	2005	2008	0.91	0.91	0.91	0.90	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
NO_X	PCGB	2009	2013	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
NO_X	PCGB	2014	2050	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
NO_X	PCDM	1900	1992	1.15	1.15	1.15	1.52	1.69	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73
NO_X	PCDM	1993	1995	1.22	1.22	1.22	1.64	1.82	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87

Pollutant	VT	MY between...		Emission factors varying with age (or equivalent cumulative mileage that depends on vehicle type)																				
		Low	High	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
NO_X	PCDM	1996	1999	1.26	1.26	1.26	1.71	1.91	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96
NO_X	PCDM	2000	2004	1.30	1.30	1.30	1.58	1.74	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78
NO_X	PCDM	2005	2008	1.20	1.20	1.20	1.43	1.57	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61
NO_X	PCDM	2009	2013	1.02	1.02	1.02	1.19	1.29	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
NO_X	PCDM	2014	2050	0.76	0.76	0.76	0.83	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
NO_X	PCDB	1900	1992	1.48	1.48	1.48	2.10	2.36	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
NO_X	PCDB	1993	1995	1.11	1.11	1.11	1.47	1.63	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
NO_X	PCDB	1996	1999	1.15	1.15	1.15	1.54	1.71	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73
NO_X	PCDB	2000	2004	1.17	1.17	1.17	1.41	1.54	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56
NO_X	PCDB	2005	2008	1.20	1.20	1.20	1.45	1.59	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61
NO_X	PCDB	2009	2013	1.02	1.02	1.02	1.20	1.30	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
NO_X	PCDB	2014	2050	0.76	0.76	0.76	0.84	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
NMVOC	PCGS	1900	1971	3.05	3.05	3.05	3.15	3.28	3.40	3.52	3.63	3.74	3.84	3.95	4.04	4.14	4.23	4.32	4.41	4.50	4.58	4.63	4.63	4.63
NMVOC	PCGS	1972	1977	2.59	2.59	2.59	2.66	2.76	2.86	2.95	3.04	3.12	3.21	3.28	3.36	3.44	3.51	3.58	3.65	3.72	3.78	3.81	3.81	3.81
NMVOC	PCGS	1978	1980	2.52	2.52	2.52	2.59	2.69	2.78	2.87	2.95	3.03	3.11	3.18	3.26	3.33	3.40	3.47	3.53	3.60	3.66	3.69	3.69	3.69
NMVOC	PCGS	1981	1985	2.52	2.52	2.52	2.59	2.69	2.78	2.87	2.95	3.03	3.11	3.18	3.26	3.33	3.40	3.47	3.53	3.60	3.66	3.69	3.69	3.69
NMVOC	PCGS	1986	1992	2.23	2.23	2.23	2.29	2.37	2.44	2.51	2.58	2.65	2.71	2.77	2.83	2.89	2.95	3.00	3.06	3.11	3.16	3.19	3.19	3.19
NMVOC	PCGS	1993	1995	3.52	3.52	3.52	3.52	3.53	3.54	3.55	3.55	3.56	3.56	3.57	3.58	3.58	3.59	3.59	3.60	3.60	3.61	3.61	3.61	3.61
NMVOC	PCGS	1996	1999	3.44	3.44	3.44	3.44	3.44	3.45	3.45	3.45	3.45	3.45	3.46	3.46	3.46	3.46	3.46	3.46	3.47	3.47	3.46	3.46	3.46
NMVOC	PCGS	2000	2004	3.41	3.41	3.41	3.41	3.41	3.41	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
NMVOC	PCGS	2005	2008	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
NMVOC	PCGS	2009	2013	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
NMVOC	PCGS	2014	2050	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
NMVOC	PCGM	1900	1971	3.05	3.05	3.05	2.97	3.14	3.31	3.47	3.62	3.76	3.90	4.04	4.17	4.30	4.43	4.55	4.67	4.78	4.84	4.84	4.84	4.84
NMVOC	PCGM	1972	1977	2.59	2.59	2.59	2.52	2.66	2.79	2.91	3.03	3.14	3.25	3.36	3.46	3.56	3.66	3.75	3.85	3.94	3.98	3.98	3.98	3.98
NMVOC	PCGM	1978	1980	2.52	2.52	2.52	2.46	2.59	2.71	2.83	2.94	3.05	3.15	3.26	3.35	3.45	3.54	3.64	3.72	3.81	3.85	3.85	3.85	3.85
NMVOC	PCGM	1981	1985	2.52	2.52	2.52	2.46	2.59	2.71	2.83	2.94	3.05	3.15	3.26	3.35	3.45	3.54	3.64	3.72	3.81	3.85	3.85	3.85	3.85
NMVOC	PCGM	1986	1992	2.23	2.23	2.23	2.18	2.29	2.39	2.48	2.57	2.66	2.75	2.83	2.91	2.99	3.07	3.14	3.21	3.28	3.32	3.32	3.32	3.32

Pollutant	VT	MY between...		Emission factors varying with age (or equivalent cumulative mileage that depends on vehicle type)																				
		Low	High	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
NMVOC	PCGM	1993	1995	4.03	4.03	4.03	4.02	4.03	4.04	4.04	4.05	4.06	4.06	4.07	4.08	4.08	4.09	4.09	4.10	4.10	4.11	4.11	4.11	4.11
NMVOC	PCGM	1996	1999	3.96	3.96	3.96	3.96	3.96	3.96	3.96	3.96	3.96	3.96	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.98	3.98	3.98	3.98
NMVOC	PCGM	2000	2004	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.95	3.95	3.95	3.95	3.95
NMVOC	PCGM	2005	2008	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94
NMVOC	PCGM	2009	2013	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94
NMVOC	PCGM	2014	2050	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94	3.94
NMVOC	PCGB	1900	1971	3.05	3.05	3.05	2.88	3.02	3.15	3.27	3.38	3.50	3.60	3.71	3.81	3.91	4.01	4.10	4.19	4.27	4.27	4.27	4.27	4.27
NMVOC	PCGB	1972	1977	2.59	2.59	2.59	2.46	2.56	2.66	2.76	2.85	2.93	3.02	3.10	3.18	3.26	3.33	3.40	3.48	3.53	3.53	3.53	3.53	3.53
NMVOC	PCGB	1978	1980	2.52	2.52	2.52	2.39	2.49	2.59	2.68	2.77	2.85	2.93	3.01	3.08	3.16	3.23	3.30	3.37	3.42	3.42	3.42	3.42	3.42
NMVOC	PCGB	1981	1985	2.52	2.52	2.52	2.39	2.49	2.59	2.68	2.77	2.85	2.93	3.01	3.08	3.16	3.23	3.30	3.37	3.42	3.42	3.42	3.42	3.42
NMVOC	PCGB	1986	1992	2.23	2.23	2.23	2.13	2.21	2.29	2.36	2.43	2.50	2.57	2.63	2.69	2.75	2.81	2.87	2.92	2.97	2.97	2.97	2.97	2.97
NMVOC	PCGB	1993	1995	3.12	3.12	3.12	3.11	3.11	3.12	3.13	3.13	3.14	3.14	3.15	3.15	3.15	3.16	3.16	3.17	3.17	3.17	3.17	3.17	3.17
NMVOC	PCGB	1996	1999	3.06	3.06	3.06	3.05	3.05	3.06	3.06	3.06	3.06	3.06	3.06	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07
NMVOC	PCGB	2000	2004	3.04	3.04	3.04	3.03	3.03	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04
NMVOC	PCGB	2005	2008	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03
NMVOC	PCGB	2009	2013	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03
NMVOC	PCGB	2014	2050	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03
NMVOC	PCDM	1900	1992	1.01	1.01	1.01	1.08	1.10	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
NMVOC	PCDM	1993	1995	0.92	0.92	0.92	0.95	0.95	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
NMVOC	PCDM	1996	1999	0.91	0.91	0.91	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
NMVOC	PCDM	2000	2004	0.90	0.90	0.90	0.90	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
NMVOC	PCDM	2005	2008	0.89	0.89	0.89	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
NMVOC	PCDM	2009	2013	0.89	0.89	0.89	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
NMVOC	PCDM	2014	2050	0.89	0.89	0.89	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
NMVOC	PCDB	1900	1992	1.01	1.01	1.01	1.05	1.07	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
NMVOC	PCDB	1993	1995	0.94	0.94	0.94	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
NMVOC	PCDB	1996	1999	0.97	0.97	0.97	1.00	1.01	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
NMVOC	PCDB	2000	2004	0.92	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93

Pollutant	VT	MY between...		Emission factors varying with age (or equivalent cumulative mileage that depends on vehicle type)																				
		Low	High	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
NMVOC	PCDB	2005	2008	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
NMVOC	PCDB	2009	2013	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
NMVOC	PCDB	2014	2050	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
PM	PCDM	1900	1992	1.00	1.00	1.00	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDM	1993	1995	0.88	0.88	0.88	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDM	1996	1999	0.85	0.85	0.85	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDM	2000	2004	0.84	0.84	0.84	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDM	2005	2008	0.84	0.84	0.84	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDM	2009	2013	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDM	2014	2050	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDB	1900	1992	1.00	1.00	1.00	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDB	1993	1995	0.88	0.88	0.88	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDB	1996	1999	0.85	0.85	0.85	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDB	2000	2004	0.84	0.84	0.84	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDB	2005	2008	0.84	0.84	0.84	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDB	2009	2013	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
PM	PCDB	2014	2050	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81

Note: We used the same emissions of PCDM for PCDS vehicles as the methodology from EMEP/CORINAIR we used does not include smaller diesel vehicles (EEA, 2007b). As such, our estimates are conservative in this respect.

A.6. Weight and material composition evolution of cars

Table 62. Material composition of cars from 1990 to 2020 (Source: author based on several sources (refer to section 4.4.5) and time variation based on Kim, 2003)

Materials	1990	1991	1992	1993	1994	1995	USAMP	1996	1997	1998	1999	2000	2004	2009	2020
Regular steel [a]	44.7%	43.8%	44.0%	43.7%	43.8%	43.6%	44.7%	43.5%	43.4%	43.2%	42.7%	41.8%	41.4%	40.3%	39.7%
High- and Medium strength steel	7.6%	7.9%	7.9%	8.2%	8.3%	8.7%	8.2%	8.9%	9.1%	9.8%	10.0%	10.3%	9.4%	9.1%	8.1%
Stainless Steel	1.1%	1.2%	1.3%	1.4%	1.4%	1.4%	1.2%	1.4%	1.5%	1.5%	1.5%	1.6%	1.4%	1.4%	1.3%
Other Steel	1.3%	1.4%	1.3%	1.5%	1.3%	1.4%	1.1%	1.1%	1.0%	0.8%	0.7%	1.0%	0.9%	0.9%	0.0%
Iron	14.5%	14.1%	13.7%	13.1%	12.9%	12.4%	10.1%	12.0%	11.6%	11.2%	10.9%	10.7%	10.7%	10.4%	11.0%
Ferrous Total	69.1%	68.4%	68.3%	67.9%	67.7%	67.5%	64.3%	67.0%	66.7%	66.7%	66.0%	65.1%	64.0%	62.3%	61.1%
Aluminium	5.0%	5.4%	5.5%	5.6%	5.7%	5.8%	6.3%	6.1%	6.3%	6.9%	7.2%	7.5%	7.6%	8.1%	8.8%
Copper and Brass [b]	1.5%	1.5%	1.4%	1.4%	1.3%	1.4%	1.7%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.7%
Lead	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.8%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	1.1%
Powdered Metal	0.8%	0.8%	0.8%	0.8%	0.8%	0.9%	0.8%	0.9%	1.0%	1.0%	1.1%	1.1%	1.1%	1.1%	1.1%
Zinc Die Casting	0.6%	0.6%	0.5%	0.5%	0.5%	0.5%	0.0%	0.5%	0.4%	0.4%	0.4%	0.3%	0.4%	0.4%	0.6%
Magnesium Casting	0.1%	0.1%	0.1%	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.4%
Non-ferrous metals	9.0%	9.3%	9.3%	9.4%	9.5%	9.6%	9.9%	9.9%	10.2%	10.8%	11.1%	11.4%	11.6%	12.2%	13.7%
Plastics/Composites	7.3%	7.8%	7.7%	7.8%	7.7%	7.7%	9.3%	7.6%	7.5%	7.5%	7.5%	7.6%	8.3%	8.9%	8.9%
Fluids and Lubricants	5.8%	5.7%	5.6%	6.0%	6.0%	5.9%	4.8%	6.1%	6.1%	6.1%	5.9%	6.0%	6.1%	6.3%	5.3%
Rubber	4.3%	4.4%	4.3%	4.3%	4.2%	4.2%	4.4%	4.3%	4.3%	4.3%	4.3%	4.4%	4.5%	4.6%	4.9%
Glass	2.8%	2.8%	2.8%	2.8%	2.8%	2.9%	2.7%	2.9%	3.0%	2.9%	3.0%	3.0%	3.1%	3.1%	3.5%
Other Materials	2.7%	2.6%	2.9%	2.8%	3.0%	3.1%	2.9%	3.1%	3.1%	2.7%	3.1%	3.3%	3.4%	3.5%	3.7%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

[a] Tube, bar and rod; [b] Electrical Components.

Table 63. Average curb-weight evolution by vehicle type (Source: Average curb weight of 2000 model years based on http://www.parkers.co.uk and time variation based on Kim, 2003)

Model Year	PCDB	PCDM	PCDS	PCGB	PCGM	PCGS
1990	1,300	1,125	915	1,258	1,024	732
1991	1,337	1,141	932	1,297	1,040	749
1992	1,375	1,158	949	1,336	1,057	767
1993	1,414	1,175	967	1,377	1,074	785
1994	1,454	1,192	985	1,419	1,091	803
1995	1,495	1,209	1,003	1,462	1,108	822
1996	1,538	1,227	1,022	1,507	1,126	841
1997	1,581	1,245	1,041	1,553	1,144	861
1998	1,626	1,263	1,060	1,601	1,162	881
1999	1,673	1,281	1,080	1,650	1,181	902
2000	1,720	1,300	1,100	1,700	1,200	923
2001	1,780	1,345	1,138	1,759	1,242	955
2002	1,761	1,331	1,126	1,741	1,229	945
2003	1,743	1,317	1,114	1,722	1,216	935
2004	1,724	1,303	1,103	1,704	1,203	925
2005	1,706	1,290	1,091	1,687	1,191	916
2006	1,689	1,276	1,080	1,669	1,178	906
2007	1,671	1,263	1,069	1,652	1,166	897
2008	1,653	1,250	1,057	1,634	1,154	887
2009	1,636	1,237	1,046	1,617	1,142	878
2010	1,619	1,224	1,035	1,600	1,130	869
2011	1,602	1,211	1,025	1,584	1,118	860
2012	1,585	1,198	1,014	1,567	1,106	851
2013	1,569	1,186	1,003	1,551	1,095	842
2014	1,553	1,173	993	1,534	1,083	833
2015	1,536	1,161	983	1,518	1,072	824
2016	1,520	1,149	972	1,503	1,061	816
2017	1,504	1,137	962	1,487	1,050	807
2018	1,489	1,125	952	1,471	1,039	799
2019	1,473	1,113	942	1,456	1,028	790
2020	1,458	1,102	932	1,441	1,017	782
2021	1,443	1,090	923	1,426	1,006	774
2022	1,427	1,079	913	1,411	996	766
2023	1,413	1,068	903	1,396	985	758
2024	1,398	1,056	894	1,382	975	750
2025	1,383	1,045	885	1,367	965	742
2026	1,369	1,035	875	1,353	955	734
2027	1,354	1,024	866	1,339	945	727
2028	1,340	1,013	857	1,325	935	719
2029	1,326	1,002	848	1,311	925	712
2030	1,312	992	839	1,297	916	704

Note: PC - Passenger car; D/G – Diesel/Gasoline; B/M/S – Big/Medium/Small

A.7. Average weights of transplanting kits for different car types

Table 64. Average weights of transplanting kits for different car types (source: author based on several sources – refer to section 4.4.5)

Parts and Components	Model Year	Weight by car type (kg)					
		PCDB	PCDM	PCDS	PCGB	PCGM	PCGS
Engine	2008	200	151	128	198	149	107
	2010	196	148	125	194	137	105
	2015	186	141	119	184	130	100
	2020	176	133	113	174	123	95
	2025	167	127	107	165	117	90
	2030	159	120	102	157	111	85
Transmission	All	33	33	33	33	33	33
Engine electrical	All	12	12	12	12	12	12
Heating system	All	7.4	7.4	7.4	7.4	7.4	7.4
Air conditioning	All	30	30	30	30	30	30
Other climate control	All	27	27	27	27	27	27
Catalytic converter	All	1.6	1.6	1.6	1.6	1.6	1.6
Exhaust system	All	10	10	10	10	10	10
Engine emission and elect. Controls	All	18	18	18	18	18	18
Accessories equipment	All	0.8	0.8	0.8	0.8	0.8	0.8
Retrofitting adaptation equipment	All	5.0	5.0	5.0	5.0	5.0	5.0
Transplanting Kit	2008	345	296	273	343	284	252
	2010	341	293	270	338	282	250
	2015	331	285	264	329	275	245
	2020	321	278	258	319	268	239
	2025	312	271	252	310	262	235
	2030	304	265	246	302	256	230

A.8. Parts/components composition and manufacturing cost of generic ICEV

Table 65. Parts/components composition and manufacturing cost of generic gasoline ICEV (Delucchi *et al.*, 2000)

	Finished weight (kg)		Material used (kg)		Material cost[a]		Labour time (hrs.)		Overhead[b]
Parts and components	Escort[c]	Taurus[d]	Escort	Taurus	Escort	Taurus	Escort	Taurus	(%)
Body in white	261	375	299	420	0.78	0.78	5.42	10.84	250
Hardware	10	15	10	15	1.17	0.82	0.33	0.59	100
Electrical components	9	10	9	10	1.52	1.52	0.4	0.52	100
Moulding & ornaments	7	14	7	15	2.15	2.15	0.25	0.37	150
Trim & insulation	57	94	59	95	1.95	1.95	1.93	4.03	150
Seats	34	49	36	50	2.15	2.15	1.05	1.73	150
Glass	27	37	27	37	2.15	2.15	1.04	1.37	200
Convenience items	7	10	7	10	2.54	1.95	0.38	0.55	100
Paint & coatings	3	5	3	5	0.98	0.98	0.06	0.07	200
Total Body	415	607	457	656	n.e.	n.e.	10.86	20.07	n.e.
Base engine	102	201	104	210	1.17	1.17	2.41	13.11	250
Other engine	27	64	29	72	0.78	0.78	0.87	2.2	150
Engine assembly	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4	6	250
Total engine	129	265	134	282	n.a.	n.e.	7.28	21.31	n.e.
Clutch & controls	15	3	16	4	0.78	0.78	0.29	0.05	150
Transmission	23	61	24	64	0.78	0.78	0.48	4.3	150
Transmission assembly	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2.87	3.47	250
Total transmission	38	64	40	67	n.e.	n.e.	3.64	7.82	n.e.
Engine electrical	14	17	14	17	1.47	1.47	0.41	0.53	100
Engine emission, elect.	9	14	9	15	5.86	5.86	0.38	0.7	100
Final drive	40	50	41	52	0.78	0.78	0.78	1.52	150
Frame	48	45	50	50	0.63	0.63	0.84	1.3	150
Suspension	44	69	41	73	2.73	2.73	0.77	2	150
Steering	13	27	14	29	0.78	0.78	0.3	1.17	150
Brakes	47	70	50	73	1.07	1.07	0.9	3.2	150
Wheels tires tools	78	82	86	86	0.98	1.07	4.59	6.4	200
Exhaust system	21	15	23	16	0.98	1.17	0.49	1.4	100
Catalytic converter	11	14	12	15	5.86	5.86	0.3	0.6	250
Fuel tank & fuel lines	14	11	15	12	0.59	0.59	0.28	0.5	150
Fenders & bumpers	34	41	34	42	1.76	1.76	0.87	1.8	150
Chassis electrical exc.	4	5	5	5	0.59	0.59	0.5	1.6	100
Battery	14	14	14	14	0.59	0.59	0.05	0.16	100
Paint, cleaners, sealants,	2	4	2	4	7.81	7.81	0.29	2	150
Oil and grease	3	3	3	3	1.56	1.56	0.03	0.6	150
Fuel	27	45	27	45	0	0	0	0	150
Air conditioning	31	31	31	31	5.7	5.7	0.49	1.4	150
Heating system	5	7	5	7	0.78	0.78	0.07	0.15	150
Other climate control	2	2	2	10	1.17	1.17	0.03	0.05	150
Accessories equipment	1	2	1	2	2.15	2.15	0.06	0.1	150
Total chassis	430	536	447	562	n.e.	n.e.	12.46	26.28	n.e.
Vehicle assembly	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	30	35	250
Total Vehicle	1,042	1,502	1,119	1,598	n.e.	n.e.	64.14	110.48	n.e.

[a] Parts and components costs (2000€/kg) on a weight-basis were converted to euros at the 2000 exchange rate (US$=0.886 €);

[b] The overhead rate on labour includes: all employee benefits (i.e., health benefits, paid vacations), full salary-plus-benefits of working supervisors; base-salary of plant managers; all perishable tools, operating and maintenance costs of the plant;

[c] Ford Escort (gasoline, 70kW, 8.7 lt/100 km);

[d] Ford Taurus (gasoline, 100kW, 11.8 lt/100 km);

n.a. - not applicable; n.e. - not estimated.

A.9. Main differences between car loan, lease and renting

Table 66. Main differences between car loan, lease and renting(adapted from FRB, 2008)

	Buying with a loan	Car leasing	Car renting
Ownership	You own the vehicle and get to keep it at the end of the financing term.	You do not own the vehicle. You get to use it but must return it at the end of the lease unless you choose to buy it.	You do not own the vehicle. You get to use it but must return it at the end unless you choose to buy it.
Up-front costs	Up-front costs include the cash price or a down payment, taxes, registration and other fees, and other charges.	Up-front costs may include the first month's payment, a refundable security deposit, a capitalized cost reduction (like a down payment), taxes, registration and other fees, and other charges.	There are no up-front costs, unless agreed upon between both parties.
Monthly payments	Monthly loan payments are usually higher than monthly lease payments because you are paying for the entire purchase price of the vehicle, plus interest and other finance charges, taxes, and fees.	Monthly lease payments are usually lower than monthly loan payments because you are paying only for the vehicle's depreciation during the lease term, plus rent charges (like interest), taxes, and fees.	Monthly loan payments are usually the highest because you are paying for the vehicle's depreciation during the lease term, plus rent charges (like interest), taxes and fees (including operation and circulation taxes), insurance, maintenance and repair costs, on-road support services.
Early termination	You are responsible for any pay-off amount if you end the loan early.	You are responsible for any early termination charges if you end the lease early.	You are responsible for any pay-off amount if you end the loan early.
Vehicle return	You may have to sell or trade the vehicle when you decide you want a different vehicle.	You may return the vehicle at lease-end, pay any end-of-lease costs, and "walk away."	You may return the vehicle at rental-end and "walk away."
Future value	You have the risk of the vehicle's market value when you trade or sell it.	The lesser has the risk of the future market value of the vehicle.	The rental agent has the risk of the future market value of the vehicle.
Mileage	You may drive as many kilometres as you want, but higher mileage will lower the vehicle's trade-in or resale value.	Most leases limit the number of kilometres you may drive (often 12,000-15,000 per year). You can negotiate a higher mileage limit and pay a higher monthly payment. You will likely have to pay charges for exceeding those limits if you return the vehicle.	Most rentals limit the number of kilometres you may drive (often 12,000-15,000 per year). You can negotiate a higher mileage limit and pay a higher monthly payment. You will likely have to pay charges for exceeding those limits if you return the vehicle.
Excessive wear	There are no limits or charges for excessive wear to the vehicle, but excessive wear will lower the vehicle's trade-in or resale value.	Most leases limit wear to the vehicle during the lease term. You will likely have to pay extra charges for exceeding those limits if you return the vehicle.	There are no limits or charges for excessive wear to the vehicle as the maintenance and repair costs are included in the monthly payments.
End of term	At the end of the loan term (typically 4-6 years), you have no further loan payments.	At the end of the lease (typically 2-4 years), you may have a new payment either to finance the purchase of the existing vehicle or to lease another vehicle.	At the end of the rental (typically up to 4-5 years), you have no further rent payments.

A.10. Synthetic data distribution and regression curves

Table 67. Parameters of the p.d.f. for the generation of synthetic data for the attributes "age" and "horsepower" (source: author)

Attribute	Distribution type	Vehicle type	Parameter values					
			α	β	Min	Max		
Age	Beta (α, β, Min, Max)	PCGS	1.11	2.70	2.00	19.22		
		PCGM	68.95	100.33	-27.99	59.41		
		PCGB	1.07	2.61	2.00	19.49		
		PCDS	1.05	2.92	2.00	9.97		
		PCDM	1.20	3.47	2.00	16.36		
		PCDB	2.21	701.20	1.29	1393.89		
			μ_1	σ_1	μ_2	σ_2	μ_3	σ_3
Horsepower (HP)	Trimodal normal (μ_1, σ_1; μ_2, σ_2; μ_3, σ_3)	PCGS	59.06	2.34	60.94	3.68	73.14	7.77
		PCGM	85.49	0.4	94.68	16.28	105.32	8.24
		PCGB	162.63	1.79	167.45	30.68	528.63	8.85
		PCDS	38.48	5.03	65	0.26	74.04	3.92
		PCDM	71.33	4.34	71.76	33.47	108.24	7.47
		PCDB	141.76	3.99	175	79.15	225	3.84
			μ	σ				
Engine Size (ES)	Normal (μ, σ)	PCGS	1,076	120				
		PCGM	1,476	120				
		PCGB	2,624	743				
		PCDS	1,118	191				
		PCDM	1,661	201				
		PCDB	2,235	423				

Table 68. Parameters of the regression curves for the generation of synthetic data for the attributes "engine size", "fuel economy" and "cumulative kilometrage"

Attribute	Regression curve	Vehicle type	Parameter values			
Fuel Economy (FE)	$y = a.HP + b.ES + c.Age + \varepsilon$; where $\varepsilon \sim Unif(-\sigma;\sigma)$		a	b	c	σ
		PCGS	0.01	0.005	0.03	0.65
		PCGM	0.01	0.005	0.03	0.89
		PCGB	0.02	0.002	0.09	2.03
		PCDS	0.03	0.002	0.11	0.59
		PCDM	0.01	0.002	0.07	0.64
		PCDB	0.0001	0.0024	0.09	1.11
Cumulative Kilometrage (km)	$y = m.\ln(AGE) - b$		m	b		
		PCGS	45,232	-6,920		
		PCGM	57,663	-13,290		
		PCGB	59,914	-12,352		
		PCDS	51,200	-16,848		
		PCDM	77,502	-26,122		
		PCDB	83,051	-29,056		

Table 69. Normal pdf parameters (generation of synthetic data for the attribute car price) (source: author)

		Car type					
Age class	Normal pdf Parameter	PCGS	PCGM	PCGB	PCDS	PCDM	PCDB
<3	μ	13,603	18,319	21,747	23,897	67,392	48,671
<3	σ	2,426	3,008	6,576	6,486	31,409	16,189
3-5	μ	10,824	12,540	17,018	19,465	51,808	35,363
3-5	σ	2,250	3,921	5,032	8,677	34,799	11,300
5-8	μ	7,217	8,371	10,849	15,004	32,114	23,526
5-8	σ	1,622	1,652	3,852	5,731	20,018	8,939
>9	μ	3,755	3,637	6,359	7,861	25,988	12,260
>9	σ	2,172	1,953	3,652	4,098	20,730	5,488

A.11. Used-car prices curves

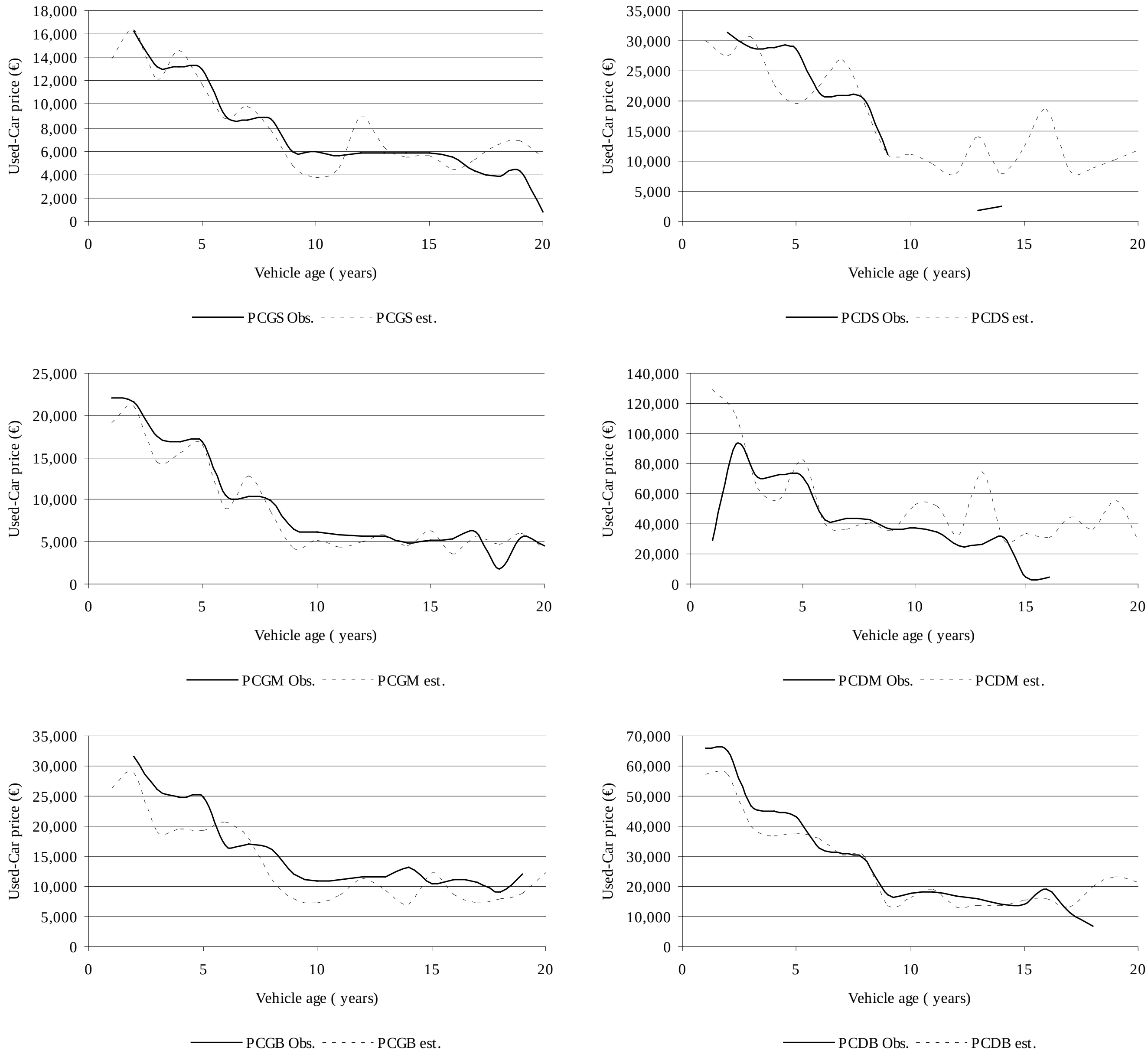


Figure 147. Comparison between observed and estimated (normal pdf) used-car prices (source: autor)

A.12. Circulation taxes for the Portuguese passenger cars

Since our case study refers to the Portuguese car fleet, we used the on-going law (Decree-Law n.º 22-A/2007 de 29/06 - Série I nº 124) to determine the circulation taxes. In 2007, this law suffered a structural modification whereby the annual tax is dependent not only on the fuel type of the vehicle, engine size – expressed in cm^3 – and model year (likewise the previous version of the law), but also on its CO_2 emission factor – expressed in gCO_2/km. The following table refers to vehicles registered before 2008:

Table 70. Circulation taxes for vehicles registered before 2008 (Decree-Law n.º 22-A/2007 de 29/06 - Série I nº 124)

Engine Size of gasoline-fuelled cars (cm^3)	Engine Size of Diesel-fuelled cars (cm^3)	Vehicle registered ...		
		After 1995	from 1990 to 1995	from 1981 to 1989
<1,000	>1,500	16	10	7
1,000 - 1,300	1,500 - 2,000	32	18	10
1,300 - 1,7500	2,000 - 3,000	50	28	14
1,750 – 2,600	>3,000	127	68	29
2,600 – 3,500	-	202	110	56
>3,500	-	360	185	85

Note: Taxes are expressed in euros. Cars sold before 1981 are not taxed.

For vehicles registered after 2008 (included), the circulation tax is obtained by summing the Engine Size and CO_2 tax components presented in the following table.

Table 71. Circulation tax components for vehicles registered after 2007 (Decree-Law n.º 22-A/2007 de 29/06 - Série I nº 124)

Engine Size (cm^3)	Tax	CO_2 emissions (g/km)	Tax
<1,250	25	<120	50
1,250 - 1,750	50	120 - 180	75
1,750 - 2,500	100	180 - 250	150
>2,500	300	>250	250

Note: Taxes are expressed in euros.

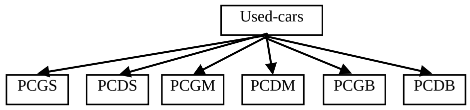
A.13. Results of the Hausman-tests to the MNL model IIA assumption (one example)

Box 5. Hausman-test with restricted model, where the PCGS alternative is excluded (source: author)

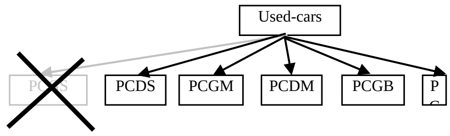
Haussman-test

Case-Study: MNL model of the Portuguese used-car fleet

Unrestricted Complete MNL model layout



Restricted MNL model layout



Unrestricted model (i.e. Complet choice set)

Parameters - bu	
ESCST	1.78E-03
AGECST	-1.73E-01
CPCST	-9.82E-05
TCCST	-2.01E-05
RUNTCST	-1.26E-02
NBRMODCS	7.22E-03

VARCOV-Vu	ESCST	AGECST	CPCST	TCCST	RUNTCST	NBRMODCS
ESCST	8.26E-09	-4.53E-07	-2.42E-10	-6.65E-12	-3.84E-08	-2.71E-08
AGECST	-4.53E-07	1.11E-04	2.58E-08	1.24E-09	2.34E-06	-8.96E-08
CPCST	-2.42E-10	2.58E-08	1.26E-11	8.25E-13	1.01E-09	3.19E-10
TCCST	-6.65E-12	1.24E-09	8.25E-13	5.14E-13	-1.09E-10	-1.06E-10
RUNTCST	-3.84E-08	2.34E-06	1.01E-09	-1.09E-10	8.13E-07	4.78E-08
NBRMODCS	-2.71E-08	-8.96E-08	3.19E-10	-1.06E-10	4.78E-08	2.83E-07

Restricted model (i.e. Choice set without the PCDB alternative)

Parameters - br	
ESCST	1.82E-03
AGECST	-1.88E-01
CPCST	-9.08E-05
TCCST	-1.50E-05
RUNTCST	-1.30E-02
NBRMODCS	6.29E-03

VARCOV-Vr	ESCST	AGECST	CPCST	TCCST	RUNTCST	NBRMODCS
ESCST	9.19E-09	-5.79E-07	-2.74E-10	-8.59E-12	-4.13E-08	-2.71E-08
AGECST	-5.79E-07	1.55E-04	3.29E-08	1.52E-09	2.86E-06	-1.99E-07
CPCST	-2.74E-10	3.29E-08	1.40E-11	8.85E-13	1.15E-09	3.65E-10
TCCST	-8.59E-12	1.52E-09	8.85E-13	5.50E-13	-1.34E-10	-1.23E-10
RUNTCST	-4.13E-08	2.86E-06	1.15E-09	-1.34E-10	8.26E-07	8.08E-08
NBRMODCS	-2.71E-08	-1.99E-07	3.65E-10	-1.23E-10	8.08E-08	3.08E-07

Difference of the parameters matrices

[bu-br]	
ESCST	-4.45E-05
AGECST	1.47E-02
CPCST	-7.42E-06
TCCST	-5.02E-06
RUNTCST	3.43E-04
NBRMODCS	9.32E-04

Difference of the VARCOV matrices

[Vr-Vu]	ESCST	AGECST	CPCST	TCCST	RUNTCST	NBRMODCS
ESCST	9.36E-10	-1.26E-07	-3.16E-11	-1.93E-12	-2.89E-09	6.12E-11
AGECST	-1.26E-07	4.42E-05	7.06E-09	2.82E-10	5.12E-07	-1.09E-07
CPCST	-3.16E-11	7.06E-09	1.46E-12	5.97E-14	1.42E-10	4.65E-11
TCCST	-1.93E-12	2.82E-10	5.97E-14	3.67E-14	-2.57E-11	-1.71E-11
RUNTCST	-2.89E-09	5.12E-07	1.42E-10	-2.57E-11	1.27E-08	3.30E-08
NBRMODCS	6.12E-11	-1.09E-07	4.65E-11	-1.71E-11	3.30E-08	2.50E-08

Transposed Matrix of the difference of parameters

[bu-br]'	-4.45E-05	1.47E-02	-7.42E-06	-5.02E-06	3.43E-04	9.32E-04

Inverse of the Matrix of the difference of VARCOV matrices

$[Vr\text{-}Vu]^{-1}$	ESCST	AGECST	CPCST	TCCST	RUNTCST	NBRMODCS
ESCST	-9.60E+08	2.82E+07	-2.09E+11	4.69E+11	9.89E+07	7.04E+08
AGECST	2.82E+07	-1.48E+05	1.70E+09	-2.99E+09	-1.11E+06	-4.45E+06
CPCST	-2.09E+11	1.70E+09	-1.57E+13	2.92E+13	1.20E+10	4.13E+10
TCCST	4.69E+11	-2.99E+09	2.92E+13	-1.04E+13	-3.12E+10	-3.44E+10
RUNTCST	9.89E+07	-1.11E+06	1.20E+10	-3.12E+10	-3.08E+07	-8.17E+06
NBRMODCS	7.04E+08	-4.45E+06	4.13E+10	-3.44E+10	-8.17E+06	-7.06E+07

Calculation of the Test-Statistic

$q1=[bu - br]' * [Vr - Vu]^{-1}=$	3.42E+05	-5.55E+03	4.71E+07	-2.72E+08	2.87E+04	-2.99E+05

q =q1* [bu - br]=	**649.705**

p-value	**df**	**q**	**t-test**
0.000	6	649.705	12.592

As $q > \chi^2_{(df = 6 ,a=0.05)}$=12,592, then we reject the null hypothesis and the IIA assumption is not verified for our MNL model.

A.14. 2-levels Nested Logit model: utility and probability functions

The following expressions were used to calculate the utilities and probabilities of each alternative considered in the present NL model, which was estimated by normalizing the scale parameters at level one of the model (i.e., $\mu_j = 1$).

"Leaf" level 1 - The utility functions for all elemental alternatives j (PCGS, PCGM, PCGB, PCDS, PCDM, PCDB) are:

$$V_j = 0.0016 \times ES - 0.1971 \times AAGE - 0.0001 \times CP - 0.0002 \times CIRCT + 0.00931684 \times NBRMOD \tag{10-1}$$

The conditional probabilities at the lowest level are:

$$\begin{aligned}
P_{PCGS|G} &= e^{V_{PCGS}} / \left(e^{V_{PCGS}} + e^{V_{PCGM}} + e^{V_{PCGB}}\right) \\
P_{PCGM|G} &= e^{V_{PCGM}} / \left(e^{V_{PCGS}} + e^{V_{PCGM}} + e^{V_{PCGB}}\right) \\
P_{PCGB|G} &= e^{V_{PCGB}} / \left(e^{V_{PCGS}} + e^{V_{PCGM}} + e^{V_{PCGB}}\right) \\
P_{PCDS|D} &= e^{V_{PCDS}} / \left(e^{V_{PCDS}} + e^{V_{PCDM}} + e^{V_{PCDB}}\right) \\
P_{PCDM|D} &= e^{V_{PCDM}} / \left(e^{V_{PCDS}} + e^{V_{PCDM}} + e^{V_{PCDB}}\right) \\
P_{PCDB|D} &= e^{V_{PCDB}} / \left(e^{V_{PCDS}} + e^{V_{PCDM}} + e^{V_{PCDB}}\right)
\end{aligned} \tag{1-2}$$

"Branch" level 2 - The upper level utilities are:

$$\begin{aligned}
V_G &= 1.0000 \times \ln\left(e^{V_{PCGS}} + e^{V_{PCGM}} + e^{V_{PCGB}}\right) \\
V_D &= 0.4736 \times \ln\left(e^{V_{PCDS}} + e^{V_{PCDM}} + e^{V_{PCDB}}\right)
\end{aligned} \tag{1-3}$$

The upper level probabilities are:

$$\begin{aligned}
P_G &= e^{V_G} / \left(e^{V_G} + e^{V_D}\right) \\
P_D &= e^{V_D} / \left(e^{V_G} + e^{V_D}\right)
\end{aligned} \tag{1-4}$$

The final marginal probabilities are:

$$\begin{aligned}
P_{PCGS} &= \left[e^{V_{PCGS}} / \left(e^{V_{PCGS}} + e^{V_{PCGM}} + e^{V_{PCGB}}\right)\right] \times \left[e^{V_G} / \left(e^{V_G} + e^{V_D}\right)\right] \\
P_{PCGM} &= \left[e^{V_{PCGM}} / \left(e^{V_{PCGS}} + e^{V_{PCGM}} + e^{V_{PCGB}}\right)\right] \times \left[e^{V_G} / \left(e^{V_G} + e^{V_D}\right)\right] \\
P_{PCGB} &= \left[e^{V_{PCGB}} / \left(e^{V_{PCGS}} + e^{V_{PCGM}} + e^{V_{PCGB}}\right)\right] \times \left[e^{V_G} / \left(e^{V_G} + e^{V_D}\right)\right]
\end{aligned} \tag{1-5}$$

$$P_{PCDS} = \left[e^{V_{PCDS}} / \left(e^{V_{PCDS}} + e^{V_{PCDM}} + e^{V_{PCDB}} \right) \right] \times \left[e^{V_D} / \left(e^{V_G} + e^{V_D} \right) \right]$$

$$P_{PCDM} = \left[e^{V_{PCDM}} / \left(e^{V_{PCDS}} + e^{V_{PCDM}} + e^{V_{PCDB}} \right) \right] \times \left[e^{V_D} / \left(e^{V_G} + e^{V_D} \right) \right]$$

$$P_{PCDB} = \left[e^{V_{PCDB}} / \left(e^{V_{PCDS}} + e^{V_{PCDM}} + e^{V_{PCDB}} \right) \right] \times \left[e^{V_D} / \left(e^{V_G} + e^{V_D} \right) \right]$$

A.15. Age distribution of used cars

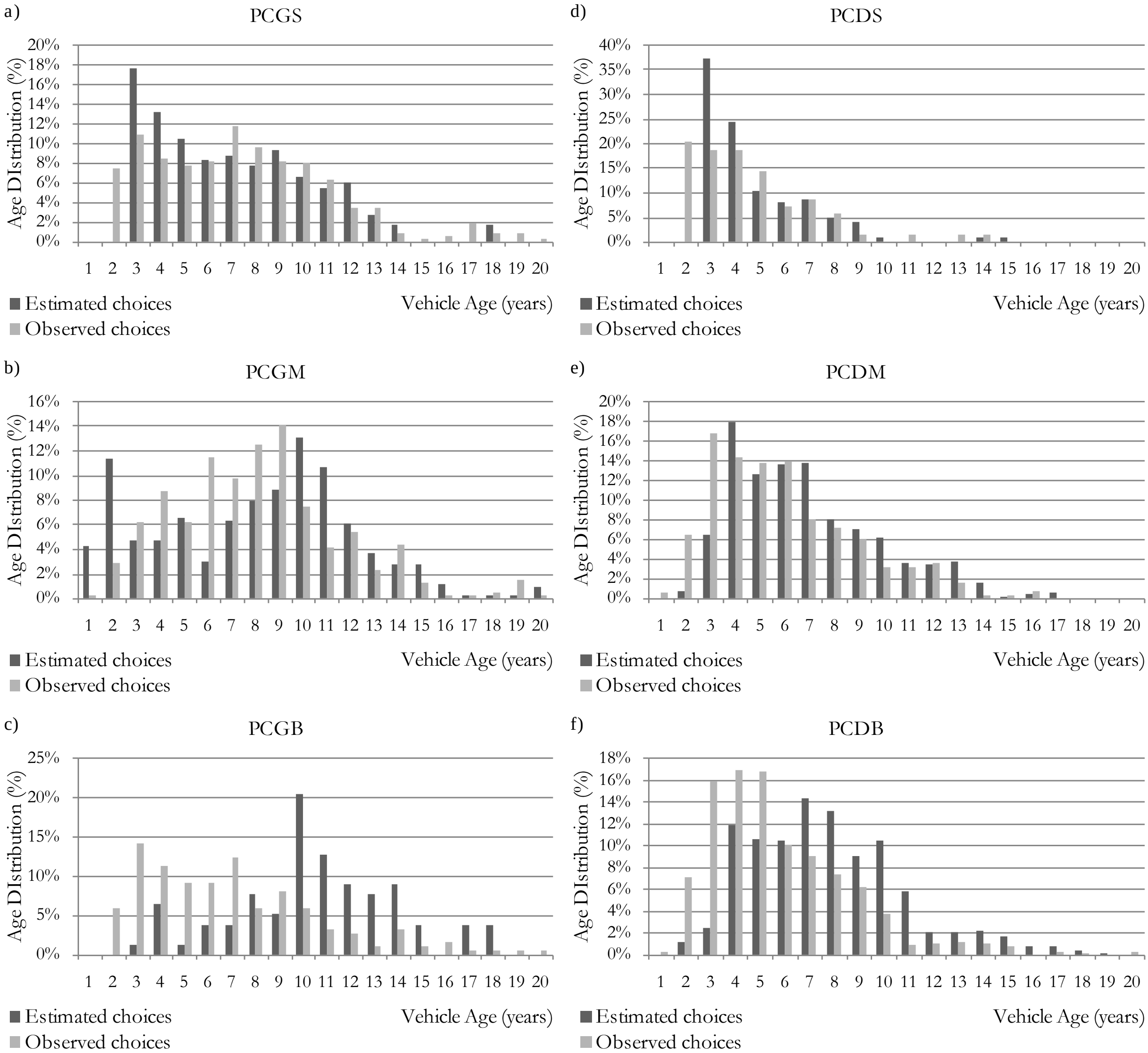


Figure 148. Observed and estimated age distribution of used cars, by vehicle type (source: author)

A.16. Portuguese transport policy measures for the reduction of carbon footprint

Table 72. Portuguese transport policy measures for the reduction of carbon footprint (Seixas and Alves, 2006a)

Code	Transport Policy Measure	CO_2 emissions (Gg)
MRt1	Expected impact of the agreement between the EU and the automotive industry	175.0
MRt2-5	Expansion of the light rail and underground network in urban areas of Portugal	58.0
MRt6-7	Reorganization of the rail service supply by CP (national operator) [a)]	78.0
MRt8	Increase of the CNG-fuelled fleet of Lisbon and Oporto bus operators	1.2
MRt9	Reduction of the average speed in the Portuguese network of highways	1.0
MRt 10	Introduction of biofuels in Portugal	1,243.0
Sub-total		1,556 (70% of total)
MAt1	Reduction of the maximum service days for taxis' operation in Lisbon	3.9
MAt2	Increase of the CNG-fuelled fleet of taxis in Lisbon and Oporto	0.2
MAt3	Increase of the average fuel economy of the national car stock	7.7
MAt4-5	Transfer of 5% of the urban mobility from private car use to public transport [b)]	347.0
MAt6	Incentive program for the scrappage of End-of-Live Vehicles	0.4
MAt7	Enforcement of the regulation of energy management for the transport sector	18.1
MAt8	Development of railway accessibility to the Port of Aveiro	40.0
MAt9	Integration of the motorways of the see in the national maritime network	150.0
MAt11	Reorganization of rail service supply (CP - national operator)	44.4
Sub-total		612 (30% of total)
Total		2,168

Notes: 'MRt' refers to undergoing policies that are not directly related to the PNAC; 'MAt' refers to additional measures determined by the Portuguese governments in the context of the national climate change policy; [a)] The reduction of the time-distance between several cities in Portugal is expected to shift passengers from private car and other public transportation; [b)] Induced by the creation of Transport Authorities in Lisbon and Oporto.