UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

Peer-to-Peer Autonomous Car-Sharing: a system architecture and impact assessment for Lisbon

ANA RITA MONTEIRO ROCHA DE SOUSA MARTINS

Supervisor: **Doctor Filipe Manuel Mercier Vilaça e Moura**

Co-Supervisor: **Doctor Carlos Miguel Lima de Azevedo**

Thesis approved in public session to obtain the PhD Degree in

TRANSPORTATION SYSTEMS

Jury final classification: ***Pass with Distinction***

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Abstract

The future landscape of autonomous mobility on-demand (AMOD) has predominantly focused on business-to-consumer (B2C) solutions. However, the future might mirror the current trend where vehicle ownership remains significant. The peer-to-peer autonomous car-sharing (P2P ACS) solution emerges as an opportunity to optimize the use of idling private autonomous vehicles (AV), fostering sustainability in the transportation system.

To contextualize the P2P ACS solution within the future mobility framework, an extensive literature review was conducted, and a business model was developed, pinpointing the solution's market value. This solution was also examined from an operational standpoint, with an agent-based model (ABM) constructed for the Greater Lisbon area and the AnyLogic software employed to simulate impacts across different supply-demand scenarios.

This thesis posits that the P2P ACS solution has a place in the future. It aims to address urban mobility needs, offering benefits to its users, and maximizing vehicle usage with passengers, addressing environmental challenges. However, the implementation of the P2P ACS solution also presents challenges.

Operational simulation reveals that approximately 1,000 AVs (0.3% of Lisbon's current private vehicle fleet) can satisfy around 22,000 trips (2% of daily travel demand, using the current taxi modal share as a proxy), ensuring a high service level. It also indicates that the P2P ACS solution can boost daily vehicle usage to values between 23% and 54%, contingent on fleet size (0.3% and 0.1%, respectively). The simulation underscores the importance of balancing supply and demand and highlights that the vehicle owner's schedule greatly impacts supply levels, especially during peak hours when the highest dropout rates due to unmet demand occur.

Investing in operational policies related to vehicle quota imposition or empty trip fees, and public policies concerning designated waiting areas and the provision of charging and maintenance services, may be crucial to ensure the solution's success and bring benefits to urban mobility.

Keywords: *autonomous vehicle; peer-to-peer; car-sharing; business model; agent-based model.*

Resumo

O futuro da mobilidade autónoma partilhada a pedido (AMOD) tem-se centrado, maioritariamente, em soluções empresariais (B2C). No entanto, o futuro pode transparecer a tendência atual na qual a posse de veículos ainda é relevante. A solução de mobilidade autónoma partilhada entre pares (P2P ACS) surge como uma oportunidade de dar maior uso aos veículos autónomos (AVs) privados, promovendo a sustentabilidade no sistema de transportes.

Para contextualizar a solução P2P ACS no sistema de mobilidade futuro, foi realizada uma ampla revisão de literatura e desenvolvido um modelo de negócio no qual se identificou o valor da solução para o mercado. Esta solução foi também explorada numa perspectiva operacional, foi construído um modelo por agentes (ABM) para a Área Metropolitana de Lisboa (LMA) e usado o *software* AnyLogic para simular os impactes de diferentes cenários de oferta-procura.

Esta tese mostra que a solução P2P ACS pode caber no futuro. A solução foca-se em dar resposta às necessidades de mobilidade urbana, trazendo beneficios para os seus utilizadores, e potenciar o maior uso dos veículos com passageiros, respondendo aos desafios ambientais. Mas o sucesso da solução P2P ACS também acarreta desafios.

A simulação da operação mostra que aproximadamente 1.000 AVs (0,3% da atual frota de veículos privados em Lisboa) conseguem satisfazer cerca de 22.000 viagens (2% da procura diária de viagens, usando como *proxy* a quota modal atual do táxi), assegurando um bom nível de serviço. Também aponta que a solução P2P ACS contribui para aumentar o uso diário do veículo para valores entre 23% e 54%, dependendo do tamanho da frota (0,3 e 0,1%, respectivamente). A simulação realça a importância do equilíbrio entre a oferta e procura e sublinha que a agenda do dono do veículo tem um grande impacte no nível de oferta nomeadamente em horas de ponta, quando se verificam os maiores níveis de desistência por falta de resposta.

A aposta em políticas operacionais relacionadas com a imposição de quotas de veículos ou taxas de viagem em vazio e políticas públicas relacionadas com a localização de pontos de espera e fornecimento de serviços de carregamento e manutenção, podem ser essenciais para garantir o sucesso da solução e trazer benefícios à mobilidade urbana.

Palavras-chave: veículos autónomos; partilha entre pares; mobilidade partilhada; modelo de negócio; modelação por agentes.

Acknowledgments

I express my deepest gratitude to my family for their unwavering presence and support throughout this journey. To my mother, my husband, my brother, and my son—who came into my life during this process—for making me smile daily, even on the toughest days. To my father, who, although no longer with us, instilled in me strength and determination.

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I'm indebted to a diverse group of researchers who offered a different perspective, instilled a critical outlook on the world, and made learning an everyday experience. I was privileged to share an office with brilliant minds and friends: Samuel Matias, Joana Cunha, Inês do Ó, and Pedro Rodrigues. Others, like Duarte Cunha, Laura Khammash, and Nuno Gregório, remained close and were instrumental along the way. Together with other transportation systems researchers, we formed the uShift group. This group provided immense learning opportunities within various transportation subfields, underscoring the unique and essential role each of us plays. From this group, special mentions to Rosa Félix, Paulo Cambra, and Mariza Motta. Beyond their expertise as researchers, their boundless generosity and warm-hearted nature stand out.

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Lastly, I am grateful for the affection shown by all those in my life. What I've gained from this journey extends beyond knowledge—it's a tapestry of experiences enriched by friends, which have profoundly influenced the person I've become today.

Disclosure

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Abbreviations and acronyms

ABM	Agent-based model
ABS	Anti-lock braking system
ABSi	Agent based simulations
AcBM	Activity-based model
ACC	Adaptive cruise control
ACS	Autonomous car-sharing
AEBS	Advanced emergency braking system
ALKS	Automated lane keeping system
AMOD	Autonomous mobility on-demand
ASI	Avoid-shift-improve
ATG	Advanced technologies group
AV	Autonomous vehicle
B2C	Business-to-consumer
BMC	Business model canvas
C2B2C	Consumer-to-business-to-consumer
C2C	Consumer-to-consumer
CAV	Connected autonomous vehicle
COP26	Conference of the parties on climate change
CS	Car-sharing
CV	Connected vehicle
DCM	Discrete choice model
DE	Discrete event
DRS	Dynamic ride-sharing
DV	Driverless vehicle

ESC	Electronic stability control
ESF	Emergency steering function
EU	European union
EV	Electric vehicle
FDAV	Framework on automated/ autonomous and connected vehicles
GHG	Greenhouse gas
GRVA	Working part on automated/ autonomous and connected vehicles
HDP	Highway driving pilot
HOV	High occupancy vehicle
IMOB	Mobility survey (in LMA)
IPCC	Intergovernmental panel on climate change
IPF	Iterative proportional fitting
LDWS	Lane departure warning system
LIDAR	Light detection and ranging system
LMA	Lisbon metropolitan area
MaaS	Mobility as a Service
OD	Origin/destination
OECD	Organization for economic co-operation and development
OEDR	Object and event detection and response
OEM	Original equipment manufacturers
P2P	Peer-to-peer
RH	Ride-haling
RMF	Risk mitigation functions
RS	Ride-sharing
RSy	Reputation system
RUM	Random utility maximization

SAE	Society of Automotive Engineers
SAV	Shared autonomous vehicle
SD	System dynamics
SDG	Sustainable development goals
SE	Sharing economy
SMART	Singapore-MIT alliance for research and technology
SUMP	Sustainable urban mobility plan
SWOT	Strengths, weaknesses, opportunities and threats
TCO	Total cost of ownership
THM	Theory of human motivation
TNC	Transport network companies
TPB	Theory of planned behavior
TRA	Theory of reasoned action
U.K.	United Kingdom
U.S.	United States of America
UN	United Nations
UNECE	United Nations Economic Commission for Europe
VKT	Vehicle kilometres travelled
VOT	Value of time
WTP	Willingness to pay

Chapter 1. Introduction

1.1 Research context and motivation

Lisbon's road infrastructure remains heavily populated with cars. In Portugal, the number of passenger cars has been on the rise; from 4.5 million cars on the roads in 2007, the number grew to 5.2 million just 9 years later (ASF, 2020). Despite Lisbon's extensive public transportation options, people still prefer using their cars for commuting (INE, 2017). Surface parking spaces are frequently full, and in areas with high parking demand, even underground parking lots struggle to meet the demand at certain times of the day. Cars dominate, and the data (INE, 2017) over the years doesn't indicate any significant decline in car usage. The same narrative can be found often in similar or bigger cities throughout the world.

Technological advancements in recent years have fueled a renewed interest in cars. Modern vehicles offer increased comfort, in-car features that reduce the perceived cost of time, and new functionalities that assist driving. These are just a fraction of what major car manufacturers promise for the future. Electrification, driven by fossil fuel scandals or global pressure for transportation decarbonization, has also rejuvenated the image of cars. Over the past decade, nearly $330 billion has been invested in mobility technologies, with 2/3 of that amount directed towards autonomous and/or smart mobility (Holland-Letz et al., 2021). However, the projected investment for the coming years is also substantial. A study of 37 global automakers reveals plans to invest nearly $1.2 trillion solely in electric vehicles and batteries by 2030 (Paul Lienert, 2022).

This investment is backed by the expectation that cars will remain a preferred mode of transportation. The forecasted use of private vehicles in major U.S. cities for 2030 is expected to be similar to that of 2019, largely because there aren't significant incentives in the country promoting change (Heineke, Kampshoff, et al., 2020). Even if cities begin to introduce affordable shared fleets of autonomous vehicles (SAV), a significant portion of the population remains interested in retaining their private vehicles. This sentiment is reflected in a survey of 7,000 individuals across 7 countries, where 70% of Germans and 76% of Americans expressed a desire to keep their private cars (Heineke, Holland-Letz, et al., 2020).

On the other side of the equation are European policies aiming for countries to reduce their reliance on private vehicles in the coming years to address environmental challenges. The transportation sector is at the forefront of the debate on harmful atmospheric emissions. Between 1990 and 2021, emissions from fuel combustion rose from 4.6 $GtCO_2$ to 7.6 $GtCO_2$ (EDGAR/JRC, 2022); the sector now accounts for 20 percent of global CO_2 emissions, making it the second-largest carbon-polluting sector worldwide. In 2020 alone, road transportation contributed to 12% of global greenhouse gas emissions (Rhodium Group, 2022).

To avert the most severe climate impacts, global greenhouse gas (GHG) emissions must be nearly halved by 2030 and ultimately reach 'net zero'. 'Net zero' will be realized when emissions produced by human activities are offset by carbon removal from the atmosphere. Achieving this balance between 2050 and 2060 is crucial. Recognizing the urgency, countries globally signed the Paris Agreement in 2016, followed by the Glasgow Climate Pact in 2021. As of 2023, 93 parties (out of 198) representing around 80% of global emissions have committed to a net-zero target, with 23 of these embedding the net-zero target in their laws (Levin et al., 2023).

In 2019, Stephen Bennett, the Chair of the Transport Planning Society, identified five strategies to address this issue and accelerate the transition to low-carbon transport (Bennett, 2019): phase out petrol and diesel cars; invest in technology; emphasize skills; construct infrastructure for sustainable travel; and develop policies. The first two strategies relate to vehicle evolution, while the last three focus on behavior change, which will be the emphasis of the next paragraph.

The drive for change must resonate with everyone involved. It's essential to involve citizens and stakeholders and engage communities in transport decision-making, as highlighted in the principles for successful Sustainable Urban Mobility Plans (SUMP)[1]. Action is also necessary. Building more infrastructure is a public policy designed to promote the increase in public transport – together with biking and walking – key solutions to combat climate change (Levin et al., 2023). The desire for change can be sparked by providing users with comfortable and safe spaces. However, public policies are most effective when employing the 'carrot and stick' approach (C. Xiao et al., 2022). Offering conditions for the use of active modes should be paired with measures that penalize car usage. Transport planning plays a pivotal role in reaching the net zero target.

Cities' support has been instrumental in promoting more sustainable mobility solutions. The rise of shared mobility, encompassing bike-sharing, scooters, and car-sharing, has been particularly pronounced in recent years. In 2022, the revenue from the Shared Mobility sector was US$1.13 trillion and by 2027 it is poised to reach US$1.68 trillion[2]. Over the past decade, numerous car-

[1] https://www.eltis.org/mobility-plans/sump-concept , accessed in September 2023.
[2] https://www.statista.com/outlook/mmo/shared-mobility/worldwide , accessed in September 2023.

sharing companies have emerged worldwide. Membership numbers have been growing exponentially. By 2027, the car-sharing sector alone is projected to boast over 63.15 million users[3] (excluding P2P CS and carpooling options). Car-sharing is increasingly seen as a viable alternative to private car ownership, especially in urban areas. And it's anticipated that its reach will expand even further with the introduction of autonomous vehicles (AVs) to the market.

Technology supporting fully autonomous driving is available. Numerous companies have deployed autonomous shared fleets in typical urban settings (*e.g.*, Waymo[4], Cruise[5], Baidu[6], among others). For instance, Waymo One offers autonomous ride-hailing services in cities like Phoenix, San Francisco, and Los Angeles, even operating without safety drivers under specific conditions. The platform bridging supply and demand is well-established among two-sided market enterprises, a topic garnering heightened interest from both researchers (Antonialli et al., 2019; K. Münzel et al., 2019; Taipale-Erävala et al., 2020) and tech industry leaders (Lladós-Masllorens et al., 2020). Given the persistence of private car ownership and the rising trend of sharing, the existing P2P CS model presents a promising avenue for exploration with AVs.

A search within article titles, abstracts, and keywords for the terms "peer-to-peer AND autonomous AND car AND sharing" on the SCOPUS platform reveals only nine published articles. The most recent article, which aligns closely with the theoretical aspect of this dissertation, is from 2023 (Jahan et al., 2023). Another article, not referenced on the platform, that attempts to explore the practical application of a similar solution is from September 2023, coinciding with the submission date of this dissertation (Zhou et al., 2023). These facts underscore the topic's relevance within the academic community.

1.2 Gaps and research objectives

AVs have garnered significant media attention in recent years. Reports highlighted an impending revolution in automotive technology that could transform mobility as we know it today.

The academic community has keenly followed this topic. Early comprehensive reviews identified the main features of AVs and discussed the potential benefits and drawbacks of this technology (Fagnant & Kockelman, 2015). Spurred by the rapid growth of mobility solutions, such as car-

[3] https://www.statista.com/outlook/mmo/shared-mobility/shared-rides/car-sharing/worldwide , accessed in September 2023.
[4] https://waymo.com/waymo-one/, accessed in September 2023.
[5] https://getcruise.com/ , accessed in September 2023.
[6] https://www.reuters.com/business/autos-transportation/baidu-wins-permit-offer-driverless-robotaxi-service-beijing-city-2023-03-17/ , accessed in September 2023.

sharing and ride-hailing, scholars began to envision the future of AVs as part of shared fleets (Jing et al., 2020; Spieser et al., 2013). Research into autonomous mobility-on-demand (AMOD) fleets, using modeling and simulation of their operations (Bischoff & Maciejewski, 2016; Boesch et al., 2016; Martinez & Viegas, 2017, among others), showcased the benefits such a solution could offer to all stakeholders.

The proposed research line explores a different approach to the future of mobility. There are varied perspectives in the literature regarding the perception of vehicle use and purchase. Some authors argue that younger generations are increasingly adopting shared mobility services and do not feel the need to own a vehicle (Delbosc and Currie, 2013; Chatterjee et al., 2018) for urban commuting. However, others emphasize that cars are still seen as a symbol of status, comfort, and personal achievement (Audi, 2022; Hartoyo et al., 2023; Verma et al., 2017). Mobility data also indicates that cars remain the most popular mode of transport in many countries (ECA, 2020), and car sales show no signs of declining. Past decisions often predict future ones and given that purchasing a vehicle is a long-term commitment, there are arguments challenging a future scenario that dismisses car ownership.

Despite the focus on AMOD solutions as company-fleets, some authors consider other business models (Berrada et al., 2017). Stocker & Shaheen (2017) introduces the Peer-to-Peer Autonomous Car-Sharing (P2P ACS) as a viable mobility scenario, where fully AVs navigate urban roads without a driver while they are not being used by their owners. The primary goal of this research is to spotlight this new solution and position it within the future mobility system.

While P2P solutions are gaining more attention from the public, there's a gap in academic research (Jahan et al., 2023), especially concerning the vehicle owner's perspective (Hazee et al., 2020). These owners, by their individual choice to share their vehicles, collectively ensure a supply fleet that meets demand. Balancing this is of paramount interest to all parties, as indicated by de Lorimier & El-Geneidy (2012) and Habib et al. (2012) for Business-to-Consumer Car-Sharing (B2C CS) solutions. This study primarily focuses on the supply and operational aspects rather than demand. Bridging this research gap becomes even more crucial as we consider the broader implications of P2P ACS within the evolving landscape of urban mobility.

It's anticipated that the P2P ACS service, like other autonomous mobility services, will have both positive and negative impacts on its environment. While the industry leads in the technological knowledge of AVs, there's a need for more active involvement from other stakeholders (Rebalski et al., 2022). The onus is on academia to advance system analysis and develop frameworks that harmonize technology advancement with urban and transport planning (Legado et al., 2019).

Further research is needed on how policies and measures can be introduced to either promote or mitigate the disruptive impact that AVs might have in the future (Faisal et al., 2019).

The second objective of this research is to identify the impacts that the P2P ACS solution might have on stakeholders and determine the most relevant measures to ensure its success.

1.3 Research questions

This thesis introduces a new mobility solution and places it within a projected future setting. While the transportation sector has seen significant changes, driven by technology and evolving paradigms, some behaviors remain consistent. These behaviors, along with other external and internal factors, play a crucial role in shaping the future. Recognizing these elements is essential to ensure the solution's adaptability. This context leads to the first research question:

1. **How does P2P ACS solution fit urban mobility?**

Recent technological advancements have led to new solutions that change how society functions. While these innovations bring benefits and new opportunities, they also come with challenges. Often, these challenges are only addressed when their effects become clear. It's important to study and discuss these new solutions to ensure they contribute positively to sustainable growth. This leads to the next research question:

2. **What are the operational and policy implications of P2P ACS solution?**

Given the breadth of these issues, it was crucial to delineate specific sub-questions for clarity and focus. Figure 1.1 illustrates the questions designed to direct the emphasis of each block. The first two blocks, 'Literature Review' and 'P2P ACS Solution', aim to answer the first research question. The subsequent blocks, 'Simulation', 'Results' and ‘Operational and policy implications’ focus on addressing the second.

The structure of the thesis is designed to follow a funnel approach. It begins broadly, addressing questions pivotal to shaping the transportation system, such as the underlying reasons for mobility, the variety of solutions available, and usage trends. It then narrows its focus to delve into the core issues associated with the proposed solution. The thesis elucidates the primary features of the P2P ACS solution, positions it within a diverse array of solutions, emphasizes its value, and discusses potential factors that could influence its future success.

The second segment of the thesis concentrates on the operation. It begins by pinpointing the key components of the solution and models it as a stylized representation of reality, outlining the inherent constraints. This new model is then integrated into a broader framework, which undergoes certain modifications. Once the model is operational, various tests are conducted across different scenarios. The results aim to assess the impact of fluctuating user interest in the solution, gauge the service levels it can provide, and identify operational challenges that might jeopardize its functionality.

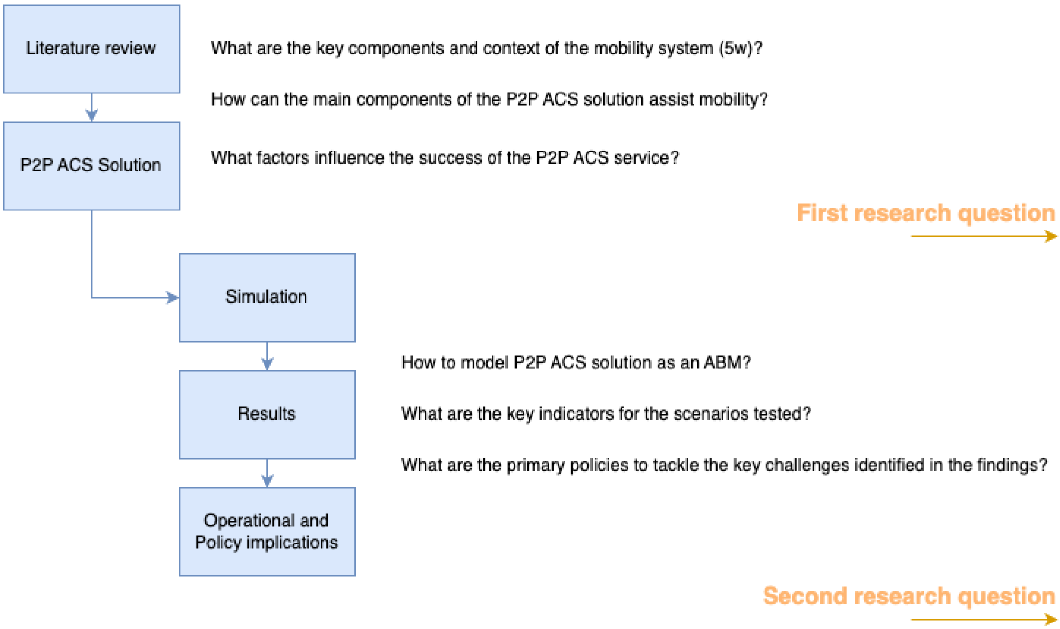


Figure 1.1 - Flowchart intended to guide the research.

1.4 Research design and methods

The research employed diverse methods to address the research questions.

The first research question required an extensive literature review, aiming to address all factors that might influence the success of this new P2P ACS service. The development of a strategic plan served as a tool to test the value of the proposed solution, especially by identifying and describing its internal strengths and its interaction with the external environment (case study research). In this context, a Canvas Business Model and a SWOT analysis were chosen. Creating an operational model would provide insights into the implications of interactions among all stakeholders and how this might influence its operation.

The answer to the second research question relied on a quantitative method. To understand the implications of the proposed mobility solution, it was necessary to identify the main components of the service, model, and simulate the solution's operation in a computational environment (experimental research). The model's framework is designed for adaptability, enabling its application for different software. For this case, we opted to utilize the AnyLogic software to simulate the P2P ACS solution. Modeling the behavior of agents related to the operation of the P2P ACS solution is new. The model would be integrated with an existing ABM that emulates mobility in the Lisbon Metropolitan Area (LMA). Demand and supply levels were scenario-based, drawing from current demand assumptions and the potential response a SAV fleet can provide to these needs, as found in the literature. The simulation aimed to evaluate different service features and understand the potential consequences this new solution might bring to the system. The results would then be analysed and recommendations could be made to mitigate any negative impacts of the solution (descriptive research).

Figure 1.2 displays the research design adopted for the thesis.

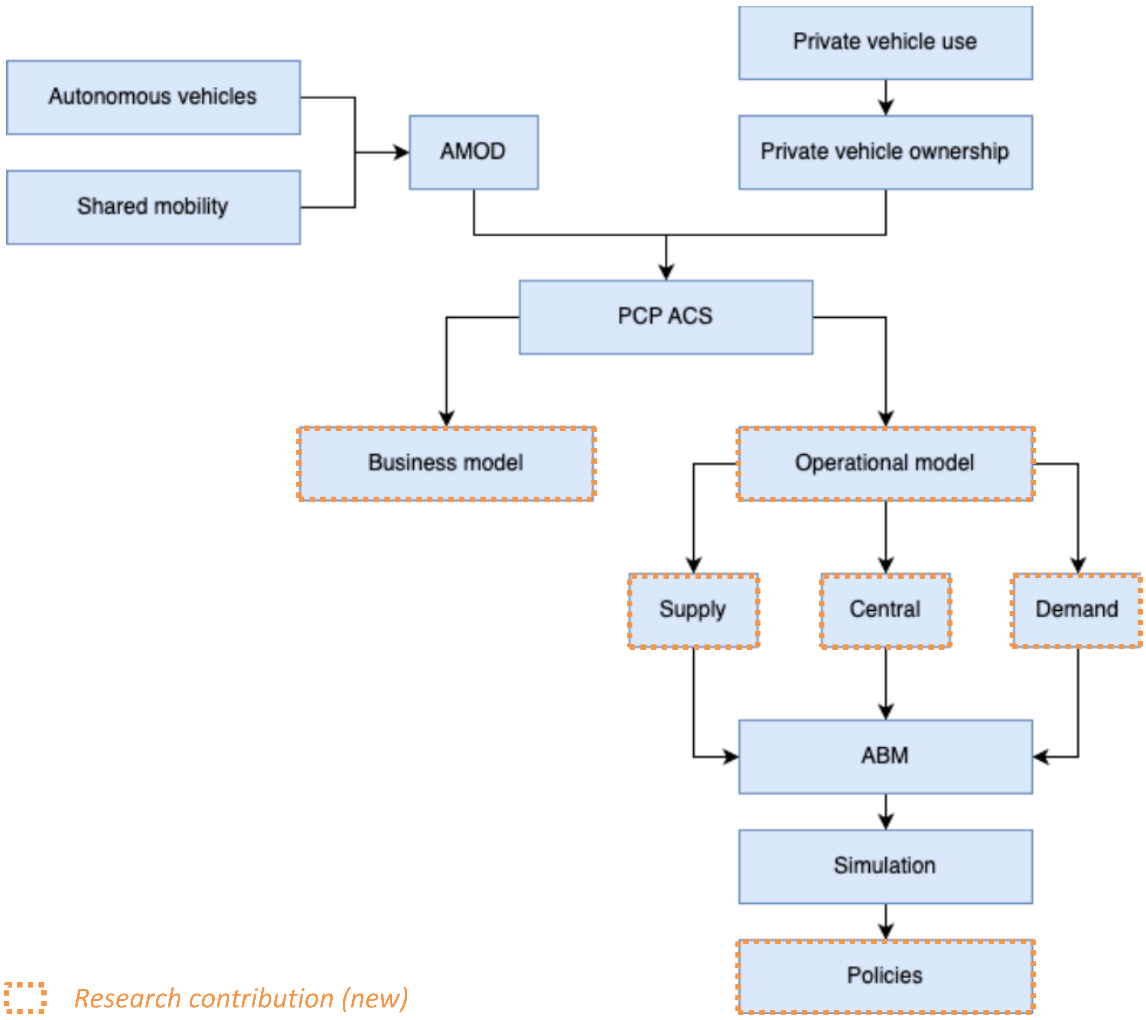


Figure 1.2 – Research design.

The literature review encompassed various aspects of automobile mobility. Evaluating current interests, trends, and potential future scenarios helped frame the context for the P2P ACS solution. This solution was examined from both a business and operational perspective. The operational aspect was delved into deeply, leading to the development of a simulation model. The model evaluated the service across various scenarios, yielding specific results. An extensive analysis of these outcomes was conducted, discussing the primary impacts on the system. Additionally, several measures were identified to ensure the successful implementation of the operation.

1.5 Thesis structure

In Chapter 1 'Introduction', the theme of the developed work is contextualized, and the rationale for pursuing this research direction is presented. After an initial literature review, certain gaps were identified and are highlighted here, along with the research questions that shaped the research. Answering these questions can add value to current knowledge in the field. At this stage, the methodology followed to address these questions and the tools required throughout the process are introduced. Lastly, steps taken to disseminate the work to the scientific community and the public are shared.

Chapter 2 'Exploring Urban Mobility' begins by framing the motivation behind people's movement within a city. It then reviews how people commute, focusing on the use of private vehicles and the intent to purchase, which seems to be unwavering. This trajectory contributes to environmental concerns. Reducing emissions is one of the primary challenges of mobility in the coming years. Exploring shared solutions might be part of the answer. This chapter introduces various shared mobility solutions, with a spotlight on peer-to-peer solutions, which have been gaining increasing traction. The future will also be shaped by the ever-growing technological advancements in the automotive industry. Thus, different levels of automation, concerns, impacts, and interest in AVs are explored. The chapter concludes by investigating future mobility trends, emphasizing shared autonomous mobility, and wraps up with the main conclusions from this literature review.

Chapter 3 'P2P ACS: proposal of a mobility solution', provides a brief introduction to the solution, explaining its essence and exploring the value of the proposed mobility service. To delve deeper into the P2P ACS solution, a business model was constructed. The Canvas Business Model tool was employed for this purpose, consisting of nine blocks representing various business facets. A

SWOT analysis was also conducted, identifying the strengths, weaknesses, opportunities, and threats that might jeopardize the success of the P2P ACS as a new urban mobility solution. After examining the business strategy, the focus shifted to the solution's functionality. The main players of the solution were identified, the impact of their long, medium, and short-term decisions was analysed, and interactions among them within the operation were defined.

Chapter 4 'An ABM to explore the P2P ACS solution' begins with a brief overview of the primary simulation models and development platforms available for simulating AV fleets. Given that the chosen simulation model is based on the mobility of the Lisbon metropolitan area, a concise introduction to the mobility system in this region is provided. The chapter then unveils the ABM model for Lisbon, originally designed to simulate a car-sharing fleet operation. A succinct theoretical context is given to the steps leading to trip generation in the LMA, demonstrating how this model is practically built in the AnyLogic software (this explanation is brief, serving merely as an introduction and framework). Modifications made to the original model, aiming to ensure the feasibility of simulating the new service, are highlighted. The implementation of the P2P ACS module, which aims to model the P2P ACS service operation and its integration with the original model, is elaborated upon. The chapter concludes with a summary of the key takeaways.

Chapter 5 'Simulation, and operational and Policy Implications of the P2P ACS' revolves around simulating the P2P ACS solution for Lisbon. It starts by presenting the assumptions considered during the operation's construction, how specific agent characteristics or decisions were approached, and the values used in assigning key parameters. Simulation results are then showcased for each proposed scenario, emphasizing the impacts a solution like P2P ACS might have on a future mobility system for all stakeholders and the system itself. A brief discussion ensues about the obtained results, focusing on the operational and policy implications this new P2P ACS solution might bring in the future.

Chapter 6 'Conclusions, Limitations, and Future Research' begins by presenting the main conclusions of this work and addressing the initially proposed research questions. It also scrutinizes the primary limitations of the study and suggests ways to overcome them, notably by introducing potential future research avenues that can delve deeper into some unresolved issues or explore the feasibility and impact of public policies.

Chapter 7 'References' concludes the thesis with a comprehensive list of all works, papers, websites, and other resources consulted throughout the PhD, which are cited throughout the text.

1.6 Thesis dissemination

Within the academic realm, several conference presentations illustrated the multifaceted, and not always linear, journey of this doctorate. At the onset of the doctoral research, various facets of shared autonomous mobility were delved into. There was a pronounced emphasis on AVs, which were heralded as the linchpin of future mobility. The research showcased at the ICTCT conference was geared towards analysing and discussing factors pertinent to road safety.

Ana Martins, Filipe Moura, Carlos Lima Azevedo (2018) Road safety in an uncertain technological future, 31st ICTCT Conference, Porto

Following the completion of the thesis project in 2018, work began on constructing a model that would emulate the operation of a P2P ACS service. My visit to the Intelligent Transportation Systems Lab at MIT, headed by Professor Moshe Ben-Akiva, under the MIT Portugal program, afforded me the chance to engage with the SimMobility MT model, which was crafted to replicate AMOD operations. The new model pinpoints the primary distinctions between solutions, specifically the agents and actions that need to be integrated to operationalize the novel P2P solution. The requisite modifications were showcased at the CRP conference.

Ana Martins, Filipe Moura, Carlos Lima Azevedo (2019) Um modelo de avaliação de sistemas de veículos autónomos partilhados: Peer-to-peer vs Fleet based systems, 9º CRP, Lisboa

The P2P ACS solution comprises three components: the central hub, demand, and supply. An opportunity arose to explore the actual taxi supply in Lisbon and to apply some findings to the developed model. During the research period, a collaboration agreement was forged with the company CoopTaxis, aiming to conduct a spatiotemporal analysis of taxi trip data. In collaboration with a master's student, we delved into the databases and modeled the demand for taxis. The findings were presented at two conferences: CRP and EWGT.

Pedro Rodrigues, Ana Martins, Sofia Kalakou, Filipe Moura (2019) Previsão espaciotemporal da procura de táxis em Lisboa (2019), 9º CRP, Lisboa

Pedro Rodrigues, Ana Martins, Sofia Kalakou, Filipe Moura (2019) Spatiotemporal Variation of Taxi Demand, 22nd EURO Working Group on Transportation Meeting, EWGT, Barcelona

The latest study was also published in the proceedings of a conference.

Pedro Rodrigues, Ana Martins, Sofia Kalakou, Filipe Moura (2019) Spatiotemporal Variation of Taxi Demand, Transportation Research Procedia 47 (2020) 664–671. DOI 10.1016/j.trpro.2020.03.145

During the research process, there was also an effort to disseminate the work to the public.

Recognizing that IST provides server space, a website[7] dedicated to AVs, titled 'popós autónomos,' was launched. Initiated in 2017, this platform featured regular articles for a year on various topics related to AVs, such as their features, benefits, risks, and impact on the system.

A few months later, in collaboration with other researchers, the UShift group was established. To promote the group and its research, a website[8] was created. This site has been consistently maintained, with regularly updated content showcasing the work of all the group's researchers.

In 2020, during an interview[9] with the Expresso newspaper, the potential role of AVs in the future of urban mobility was discussed. The research concept, described as the 'Airbnb of autonomous vehicles,' introduced the public to the primary features of this new mobility solution.

More recently, during an appearance on the '90 Seconds of Science' program[10] in 2021, the AV sharing system, which is the subject of this thesis, was once again shared with the public.

[7] https://web.tecnico.ulisboa.pt/~ist154137/pt/ , accessed in September 2023.
[8] http://ushift.tecnico.ulisboa.pt/ , accessed in September 2023.
[9] http://ushift.tecnico.ulisboa.pt/ja-nasceu-o-ultimo-condutor/ , accessed in September 2023.
[10] https://www.90segundosdeciencia.pt/episodes/ep-1083-ana-martins/ , accessed in September 2023.

Chapter 2. Exploring urban mobility

2.1 Introduction

This chapter aims to lay the groundwork for understanding how a P2P ACS solution can fit into the mobility landscape. Unlike traditional literature review chapters that delve into existing literature to identify gaps, this chapter navigates through the literature to underscore the reasons why these gaps should be addressed.

The chapter traverses various topics. It begins by examining the underlying reasons for people's mobility choices, drawing from theoretical frameworks. It then delves into the pressing context of transportation, which is largely intertwined with car usage - a factor often overlooked in future-focused discussions. Subsequently, the chapter highlights the challenges, especially those related to climate concerns, which have become pivotal in shaping transportation policies. Achieving the decarbonization objective aligns with two primary components of the P2P ACS solution: sharing and technology. The chapter delves deeper into these concepts and concludes with a vision of what future mobility might entail.

2.2 Urban mobility and Travel behavior

The intricate relationship between urban mobility and residential location choice plays a significant role in the decisions city dwellers make, with far-reaching implications. When urban mobility is effective and well-coordinated, it offers residents a broader range of residential options. Conversely, when mobility within an urban setting is hampered or inefficient, it can confine individuals to reside within the vicinity of essential services or workplaces. Understanding this dynamic is crucial for enhancing urban life quality.

The transportation system should be adept at offering solutions tailored to people's mobility needs. Understanding the key decisions governing transportation use, such as housing choices, can guide the introduction of innovative transportation solutions.

Several theories have been proposed to explain residential location decisions, theories fall into two categories: the market and non-market approach. Despite their drawbacks, older and simpler theories still hold practical value (Balchin et al., 1995), including travel-cost minimization, travel-cost/housing-cost trade-off, and maximum housing expenditure, as expounded by Balchin et al. (1995). The travel-cost/housing-cost trade-off theory is the most widely accepted and developed, suggesting that households, when given the opportunity, will opt for a residence that strikes a balance between space and commuting expenses, thus embodying a trade-off between affordability and space.

Households seeking to maximize utility choose a location with amenities specific to that location, and ample housing and land space (Phe & Wakely, 2000). The presence of location-specific amenities implies that location is an integral part of the consumption set. As commuting and land or housing costs often depend on location, residential location also impacts the budget constraint.

However, this theory has faced criticism for its inadequate address of different income groups (Phe & Wakely, 2000). The theory indicates that wealthier individuals are likely to reside on the city's outskirts, given their ability to afford larger houses and commuting expenses, a notion that Brueckner et al. (1999) demonstrates isn't always the case.

Studies estimating the impact of the built environment on travel behavior often overlook residential self-selection bias, leaving the causal relationship ambiguous (van de Coevering et al., 2015). This bias arises when individuals choose their residences based on their travel preferences, attitudes, or social inequity (Cao et al., 2009; Diez Roux, 2004). Personal preferences and attitudes towards travel behaviors may influence residential location selection, and social inequity, particularly in terms of income and vehicle ownership, can also contribute to residential self-selection.

The concept of residential self-selection is gaining attention globally, particularly in the developing world. Factors influencing housing choice include school quality (Guidon et al., 2019), mobility, travel attitude, and built environment (Ettema & Nieuwenhuis, 2017; Heinen et al., 2018; Zang et al., 2019), accessibility to jobs and services (Baraklianos et al., 2020; Hu & Wang, 2019), affordability and neighborhood quality (Lee and Waddell, 2010; Bayoh et al., 2006), and availability of public transportation services (Heinen et al. 2018; Scheiner 2014; Boone-Heinonen et al. 2010; Cao et al. 2009).

However, the importance of contextual setting in understanding variations in these results across the globe has been emphasized by some authors. For instance, factors like the availability of utility services and affordability are paramount in decision-making processes in Pakistan (Aslam et al., 2019), the availability of transportation modes is a critical factor in Egypt (Masoumi et al., 2021), and security is a significant consideration in Nigeria (Ubani et al., 2017). These factors vary considerably from those identified in high-income countries (Masoumi et al., 2021).

Various other factors also play into the decision process of choosing a residential location. These include social status (Maclennan, 1982), particularly in highly structured societies, the desire to live near family (Rapoport, 1977), and the conditioned perception of the place's significance (Bachelard, 1957). One aspect that has lessened in importance over time is the distance to work, which has been mitigated by the advent of the internet and remote work (Harvey, 1991). Today, telework allows people to choose any location in the world to settle down, giving more credence to the famous empirical dictum: "First, location; second, location; and third, location."

Car ownership also plays a key role in residential location choice (Masoumi et al., 2021). Possessing a car allows individuals to place less emphasis on the transportation network, providing a sense of 'freedom' (which can also translate into a dependency on a single mode of transportation) and allowing them to focus on other factors like neighborhood quality or affordability, which includes both the cost of housing and the cost of living in a given region.

The conclusion of the housing location selection process marks the onset of another critical decision-making phase - identifying the most suitable mode of transportation to cater to an individual's daily commute needs. This selection isn't arbitrary but is often shaped by a myriad of factors and considerations. To understand this complex decision-making process, several Travel Behavior Theories have been established over the years.

Random utility maximization (RUM), introduced by Marschak (1959), assumes that, when making a choice from a set of discrete alternatives, the decision-maker selects the best alternative for him or her-self, the one with the highest utility (a scalar measure of value). Building on the foundation of RUM, the transportation mode choice model was later formulated, primarily drawing from McFadden (1974)'s approach. RUM assumes a rational decision-maker and a reasoned decision-making process. This means that the decision-maker will tend to choose the best alternative given the information available to them at the time, and that given the same exact conditions the decision-maker will probably make the same choice.

Original RUM models made the assumption of perfect information. This means that when a decision-maker is faced with a choice, they have complete knowledge about all the possible options, including their respective attributes and potential outcomes, which may not be the case in many real-world situations. But the main criticism is that RUM models operate on the assumption of rationality, suggesting that individuals always make choices that maximize their utility. Critics argue that this assumption does not always hold true in the real world, that it does not encompass the motivation of human behavior (Talvitie, 1997), where decision-making can be influenced by a variety of factors such as emotions, habits, and cognitive biases, leading to seemingly irrational behavior.

Hägerstrand's pioneering work introduced the time-space prism and the concept of constraints to explain how individual behavior shapes aggregate patterns in regional science and geography. This insight, which has been crucial to the development of activity-based travel demand models (AcBM), views individuals as moving within time and space, bound by capability, coupling, and authority constraints (Ortúzar & Willumsen, 2011). These models prioritize feasibility, as primary choices such as the purpose and mode of a trip shape the available alternatives for secondary choices (such as the number of stops and purpose of each, and the choice of transportation for each leg of the trip).

Chapin's (1974) three-component model provides a clear framework for understanding how motivation, choice, and outcome interact to determine individual behavior. This model highlights the role of propensity and opportunity in shaping activity patterns, functioning similarly to demand and supply mechanisms. For instance, an individual may have a high propensity to use public transit due to environmental beliefs, but the opportunity to do so may be limited by the availability and quality of public transit in their area.

Recognizing that economic factors alone cannot fully explain travel behavior, there has been an increased focus on the roles of perceptions, attitudes, beliefs, and preferences. The theory of human motivation (THM) (Maslow, 1943), for instance, posits that basic needs drive behavior, suggesting a hierarchy of needs that must be met sequentially. This might explain why certain factors like safety and reliability often take precedence over environmental considerations in travel behavior.

The theory of reasoned action (TRA) (Fishbein & Ajzen, 1975) introduces the idea that attitudes and social norms influence travel behavior through their effect on intention or motivation. This theory implies that individual attitudes, societal beliefs, and perceptions play a significant role in travel choice modeling, and that positive or negative attitudes towards specific modes of travel can be powerful predictors of travel behavior. For instance, a positive attitude towards cycling and the social norm of environmental consciousness might result in an intention to cycle more often.

Building on the TRA, the theory of planned behavior (TPB) (Ajzen, 1991) incorporates perceived behavioral control into the equation, accounting for behaviors that are not entirely within an individual's control. According to TPB, behavioral intention is a function of attitudes, subjective norms, and perceived behavioral control, offering a comprehensive framework for understanding how different factors might influence a person's decision to use certain modes of transport. For example, a person might intend to use a car less often due to environmental concerns, but this intention may be influenced by their belief about their ability to use alternative modes of transport.

Finally, Singleton (2013)´s conceptual framework presents a comprehensive theory of travel decision-making, with a particular emphasis on active travel modes. This theory, which includes seven components ranging from the type of activity to the feedback from previous decisions, offers a comprehensive approach to understanding why individuals might choose active modes of travel, considering factors such as the type of activity, travel needs, and perceived control over the behavior.

These theories shed light on the multifaceted role of motor vehicles in daily life. The AcBM highlight how cars provide the flexibility essential for individuals to juggle their multiple activities and commitments. Concerns about journey time often influence their transportation mode choices (Gardner, 2007). Many people's daily routines involve extensive trip-chains, such as dropping off their children at school on their way to work or picking them up afterward. This is a significant reason why car usage is more prevalent among households with children (Bergstad et al., 2011; Fyhri et al., 2011). The TRA posits that individuals are more likely to have strong intentions to carry out an action if they view it favorably and believe that significant others expect them to do so. However, certain behaviors require specific skills or external resources. This is why giving up private cars can be challenging, particularly when public transportation isn't up to the mark (Staats, 2004).

The successor of the TRA, the TPB, suggests that perceived behavior and habit play a significant role in shaping individuals' intentions and subsequent actions, as demonstrated by the studies of Forward (2004) and Mann & Abraham (2012). When individuals perceive reducing their car usage as challenging, they are less inclined to want to cut back on it (Abrahamse, 2019). Chapin (1974) posits that activity patterns are influenced by opportunities, which relate to the availability and quality of facilities. This perspective underscores the intricate relationship between infrastructure and behavior, where car ownership can influence short-term decisions, such as the daily car usage of individuals and households (Van Acker & Witlox, 2010).

The importance of framing voluntary car reduction as a multi-tiered transition, personalized to individuals' unique circumstances, cannot be overstated. This involves proactive measures that address both intentional behavior and the availability of viable transportation alternatives, each carrying different impacts. Traditionally, a one-size-fits-all approach has been employed for all car users, as cited in Richter et al. (2010). However, given the myriad of motivations that exist, such a broad-brush approach may not yield the desired effect. The outcomes we witness, which are the direct consequences of actions or lack thereof, continue to be influenced by longer-term decisions, such as the car purchase (Van Acker & Witlox, 2010).

2.3 Private vehicles

Car ownership

The interest in automobiles continues to persist, despite being significantly influenced by socio-economic factors. Figure 2.1 presents the number of cars registered in Portugal over the past 20 years, revealing two distinct periods of lower vehicle registrations. The first period corresponds to the aftermath of the 2007-2008 financial crisis, triggered by the burst of the real estate market bubble in the United States, which had far-reaching international repercussions in subsequent years. In 2022, alongside post-pandemic conditions and political instability (such as the conflict in Ukraine), the market experienced a shortage of semiconductors, leading to constraints in the production and sale of new vehicles. However, the final months of 2022 indicate a promising recovery, although sales levels have not yet reached those observed in 2019.

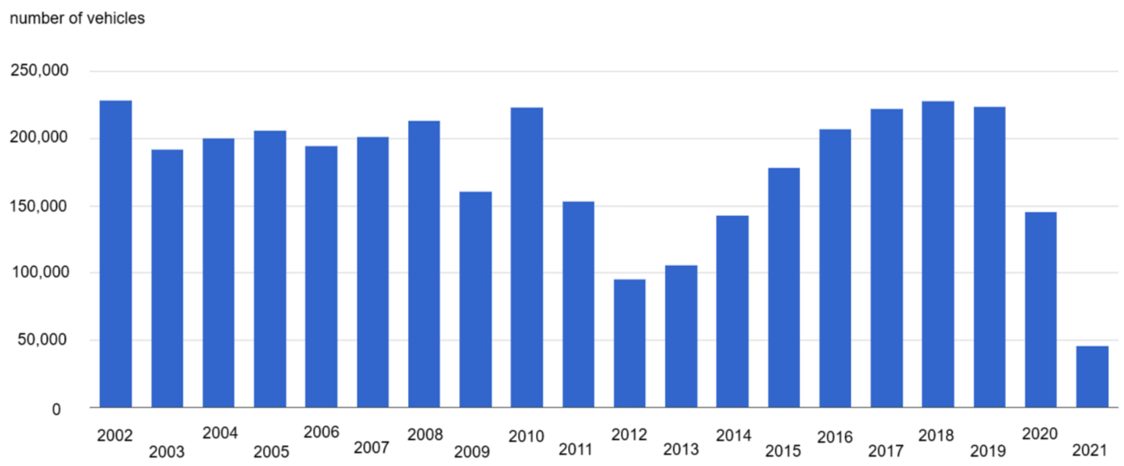


Figure 2.1 - Passenger Car Registrations in Portugal, over the years (ACAP) [11].

[11] https://www.acap.pt/pt/estatisticas/graficos , accessed in December 2022

Across the majority of EU Member States, the passenger car fleet has witnessed growth over the past five years. The total number of EU-registered passenger cars has reached 253 million, reflecting an increase of 8.6% compared to the figures in 2016 (as depicted in Figure 2.2).

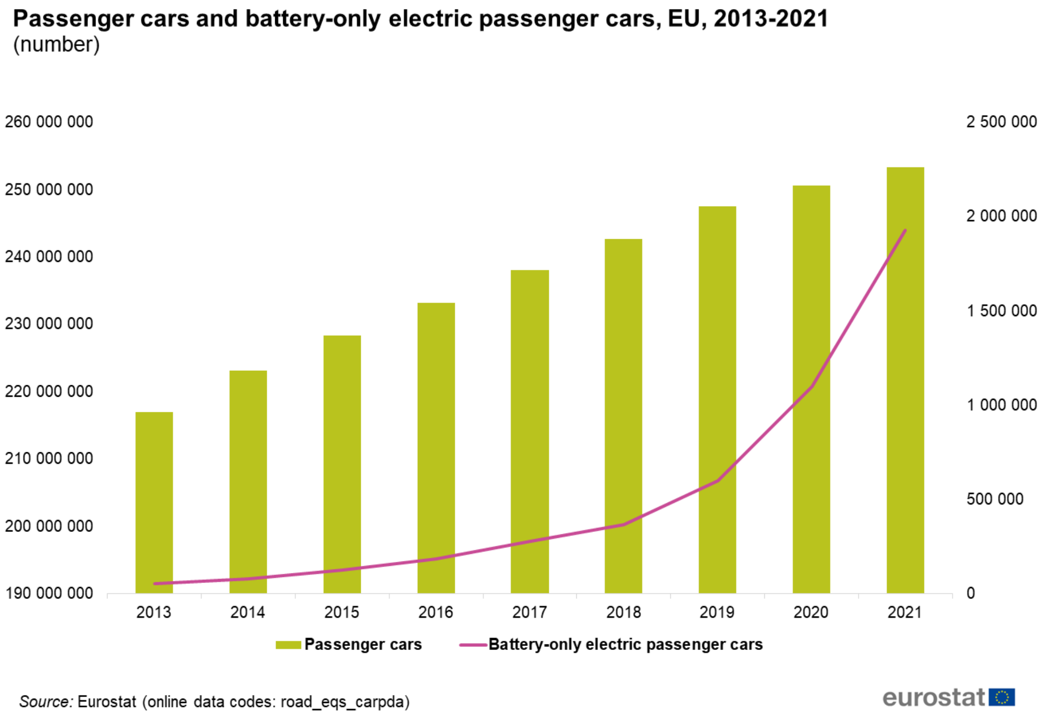


Figure 2.2 - Passenger cars and battery-only electric passenger cars EU, 2013-2021[12].

In 2021, the number of battery-only electric cars in the EU was over 1.9 million, which is 37 times more than in 2013. The share of electric cars in the overall passenger car market rose from 0.02% to 0.8%. In Portugal, there are currently 146,641 passenger cars, of which 13,546 are fully electric, showcasing the growing presence of electric vehicles in the country's automobile landscape[12].

Car ownership is a common and significant aspect of modern life for individuals and families worldwide. In the context of the Lisbon metropolitan area, data from a recent mobility survey conducted in 2017 reveals that car ownership stands at 50.2%, a figure close to the European average. However, it is notably lower than the car ownership rate in the United States, which was reported as 76.6% in 2016 according to Sivak (2018) with 0.766 vehicles per person and 1.968 vehicles per household. These statistics highlight the substantial number of passenger vehicles present on the roads or occupying public spaces. In the Lisbon metropolitan area alone,

[12] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Passenger_cars_in_the_EU#Overview:_car_numbers_grow_with_a_rapid_increase_in_electric_but_a_low_share_of_overall_alternative_fuels , accessed in September 2023.

there are over 1.4 million registered vehicles, with 332,000 of them registered specifically in Lisbon (ASF, 2020).

Many individuals still prefer the use of private cars due to their perceived advantages in terms of comfort, privacy, and flexibility, especially when compared to the perceived discontinuity in time and space often associated with transit systems (Caulfield, 2012; S. Tao et al., 2019). Despite discussions about the disutility of car ownership, the attachment to owning a vehicle remains strong, driven by instrumental and emotional motives that challenge the perception of its drawbacks (Correia et al., 2013). Cars continue to hold symbolic relevance, representing individuality, freedom, and status (Audi, 2022).

Individuals develop strong attachments to their cars and attribute various psychosocial benefits to them (Steg, 2005). Owning a car provides people with social and economic opportunities, as it eliminates constraints and allows for convenient mobility (Curl et al., 2018; Moody et al., 2021; Steg et al., 2001). In many social contexts, the automobile represents consumer identity and independence as individuals transition into adulthood (Ball & Tasaki, 1992) and signifies high social status (Moody & Zhao, 2020). Furthermore, the perceived value of car ownership and usage has increased during the Sars-Covid-2 pandemic due to concerns about virus exposure and the desire for personal security (Moody et al., 2021).

A comprehensive study on vehicle purchase decisions conducted by McCollum et al. (2017) shed light on the non-rational nature of transport mode choices. As a result, interventions solely focused on cost and price have limited effectiveness in driving transitions in passenger transport. Sjöman et al. (2020) reached a similar conclusion in their research, which involved interviewing individuals and presenting them with the actual costs of car ownership compared to the hypothetical costs of a CS service. Participants perceived the cost comparisons as too low to incentivize a switch from car ownership to CS.

People tend to assign costs in various ways, such as monetary or time-related factors, in order to balance their decision-making process (Millonig & Haustein, 2020). Andor et al. (2020) concluded that people estimate the total costs of car ownership by half and that a more rational knowledge of the costs would lead people to own fewer cars. This poses a challenge for alternative mobility solutions, as they struggle to meet the perceived benefits and values associated with car ownership. Consequently, comparisons between car ownership and other mobility options may not fully account for all the costs involved, leading to what can be perceived as "unfair" assessments (*idem*).

Contrary to somewhat optimistic reports suggesting that adolescents, often referred to as 'millennials,' are less inclined to learn to drive and own a car compared to previous generations (Chatterjee et al., 2018; Delbosc & Currie, 2013), other studies have found evidence of an ongoing preference for car-based transport and intentions to learn to drive among young urban millennials (Hopkins et al., 2021). Moreover, surveys have shown that the aspiration for car ownership among youths has not vanished (Hartoyo et al., 2023; Verma et al., 2017).

The decision to own a vehicle is not necessarily an independent choice, but one that's intricately tied to factors like the structure of the local environment and travel needs (Bhat & Guo, 2007; Cao et al., 2007; Pinjari et al., 2011; Van Acker & Witlox, 2010). Some researchers highlight that households without car ownership can be seen as transportation-disadvantaged. The absence of a car often makes it difficult to access opportunities such as employment, educational resources, and social activities, placing these households at a disadvantage (Currie & Delbosc, 2011; Shay et al., 2016). In a specific case study from the San Francisco Bay Area, it was demonstrated that significant accessibility gaps exist between car travel and public transport across all neighborhoods, further underscoring these challenges (Golub & Martens, 2014). Lucas (2019)'s research indicates that among all social groups, car owners experience the fewest limitations and benefit from greater access to various activity opportunities.

It is worth noting that car or automobile ownership exerts a significant influence on travel mode choices (Nwachukwu et al., 2023), as an increase in car ownership is associated with a higher likelihood of driving (Cervero & Kockelman, 1997). This suggests that owning a car plays a crucial role in shaping individuals' preferences and behaviors when it comes to selecting their preferred mode of transportation.

Car usage

In 2020, Portugal reported an extensive usage of passenger cars, accounting for over 92% of the passenger-kilometres travelled, surpassing the European Union's average of 86.2% as per EC (2022)´s report. This indicates a significant increase in car use since 2015 when car trips in Portugal represented about 88% of passenger-kilometres travelled (as opposed to 81.3% in the EU27). Conversely, Portugal's use of buses, coaches, and railways is less prevalent compared to the average usage across the EU.

In urban areas with a higher concentration of people, there is generally a movement towards less car usage. A relation has often been observed in research between lower automobile dependence and factors like high population density and varied land use (Buehler, 2011;

Vanoutrive, 2015). In Lisbon, car use accounts for 45.1% of the mode of transportation (INE, 2017), a figure that aligns with those from several other European cities, as shown in Figure 2.3. On the contrary, metropolitan areas tend to show a greater reliance on cars. Aspects of travel behavior, such as the number of trips taken and the distances travelled, could lead to a rise in private vehicle usage (Scheiner, 2010). The use of cars in the LMA is reported at 58.9% (INE, 2017), but it is Prague that stands out, with 80% of trips being made by car.

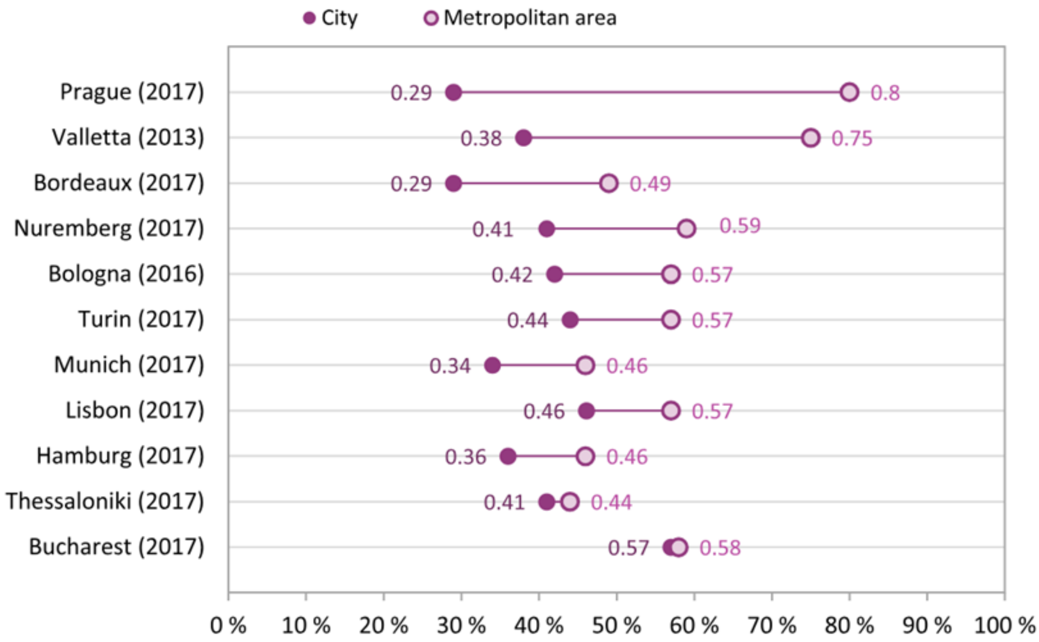


Figure 2.3 - Modal share of private vehicles in 11 cities and metropolitan areas surrounding cities. *Source*: ECA (2020)

The increase in car use from 2000 to 2019, coupled with a recent, albeit slight, rise in the carbon intensity of fossil fuels consumed by passenger cars, are the key contributors identified for escalating emissions (Harris et al., 2021). This scenario potentially jeopardizes the attainment of sustainability goals set for 2030. To understand the influence of city characteristics on the choice of primary and overall intra-city transportation modes, Lee et al. (2022) studied examples from cities around the world. Their observations suggest that factors such as high gasoline taxes and low fares for public transit and taxis often prompt individuals to reconsider the ownership of private vehicles.

TfL (2017) has classified London's inhabitants into nine segments, as displayed in Figure 2.4. These segments are based on the travel choices people make and their motivations behind those decisions. Three main groups identified as frequent car users are: detached retirees, settled suburbanites, and suburban moderates. Collectively, these groups represent 49% of London's total population.

Figure 2.4 - Transport Classification of Londoners – Segment Summary. *Source*: TfL (2017)

The detached retirees group typically consists of individuals in the "empty nest" stage or those who are retired. They generally reside in the verdant suburbs on the periphery of London and have one or more cars in their household (81%). The settled suburbanites segment is often found across outer London and usually includes families with at least one child at home, lower incomes, and minimal lifestyle changes. Lastly, the suburban moderates group is primarily located in outer London, likely to have at least one child at home, and experiences an average level of lifestyle changes.

Jacques et al. (2013) based on a comprehensive transportation survey, categorized groups according to their preferred mode of transport. The automobile cluster showed a practicality value suggesting that car travel is faster than transit times for equivalent trips. Most of these individuals were satisfied automobile users who chose to drive due to preference rather than necessity, with an average commute time. These drivers are not truly "captive" to their cars but select them out of "convenience" where both their satisfaction with the trip and its practicality are optimized. However, a subset of unsatisfied drivers continues to drive due to the longer transit times otherwise.

Further, Khan (2007)´s study, which divided car-dependent users into four distinct categories based on work-related commuting, revealed that over two-thirds of the users felt they had no viable alternative to using a car for their work trips, emphasizing the challenge of shifting behaviors from private vehicles to other transportation alternatives.

The research by O'Riordan et al. (2022) refers that work-related journeys, companion or escort trips, and shopping expeditions are the primary drivers of passenger transport demand, as illustrated in Figure 2.5. The figure also highlights that the use of private vehicles extends far beyond work commutes. In fact, non-work-related travel, encompassing activities such as accompanying others, engaging in leisure or entertainment activities, or visiting family, emerged as the leading reason for private vehicle use. This observation aligns with the conclusions drawn by Z. Xiao et al. (2022) from their assessment of driving behavior patterns.

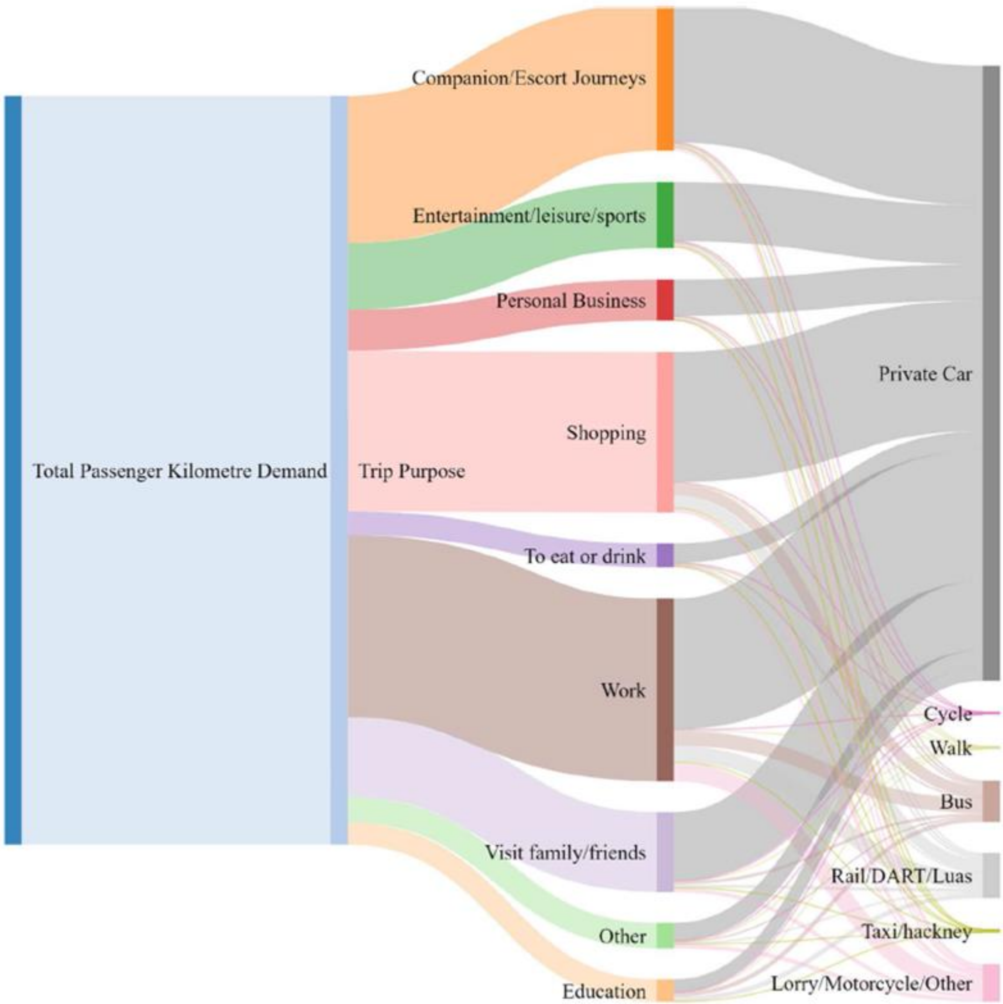


Figure 2.5 - Breakdown of Passenger Kilometer trip purpose and mode type for 2019.
Source: O'Riordan et al. (2022)

Temporal analysis by O'Riordan et al. (2022) unveils some intriguing trends. There was a substantial increase (+187%) in travel related to dining out, suggesting a shift in consumer behavior towards eating out more frequently, thereby boosting the use of cars. Simultaneously, the proportion of private car emissions linked to commuting for educational purposes saw a significant decline (-31%), indicating that more adults have opted for alternative modes of transport for educational journeys in recent years.

When individuals drive, they commonly travel between a selected Frequently Visited Places (FVPs), such as workplaces and homes (Huang et al., 2020). Z. Xiao et al. (2022) evaluated car trajectories in five Chinese cities, concluding that these standard patterns had the same type of daily mobility routines and accounted for approximately 85% of travel. Furthermore, for over 60% of private cars, the entropy (randomness of the spatial transition) is lower than 4.8, and it drops below 2 for 20% of users, which indicates user's mobility pattern is regular (at least during the period under study).

Despite traveling to the same locations, car users were found to cover greater distances, participate in a wider array of activities, and exhibit higher travel efficiency compared to transit users, as highlighted by Gao et al. (2022) and Lucas (2019).

2.4 Mobility challenges

The transportation sector, a significant contributor to global environmental concerns, accounts for a substantial quarter of greenhouse gas emissions. Road transport, in particular, accounts for the vast majority, responsible for a whopping 72% of these emissions as of 2019 (EEA, 2022). A notable rise of 5.8% in CO_2 emissions from light passenger vehicles was observed in the 27 EU Member States from 2000 to 2019. This increase was primarily driven by a 16.6% surge in passenger transport volume, which was compounded by a slightly growing dominance of car transport among various land transport modes (EEA, 2022).

In parallel, the world's population continues its upward trajectory, with projections estimating it will swell to around 8.5 billion by 2030 (UNECE, 2021). A significant portion of this population resides in urban settings, especially within the European Union, where more than 70% of its population currently lives in cities. This urban proportion is predicted to increase further, reaching an estimated 84% by 2050 (EC, 2021). By 2030, a 50% increase in annual passenger traffic is expected, and by 2050, an additional 1.2 billion cars are projected to be on the roads[13]. This transformation is accompanied by a significant shift in lifestyle and mobility expectations as half of the world's new population enters the middle class.

[13] https://www.sum4all.org/ , accessed in September 2023.

These two pivotal factors — escalating urbanization and rising greenhouse gas emissions from the transport sector — underscore the urgency for transformative solutions. As such, there's a concerted, pan-European initiative underway to reshape the future of urban mobility, aligning it with the global commitment to sustainability and emission reduction.

The European Commission has delineated six strategic priorities for the development of Europe for the period spanning 2019 to 2024. At the forefront of these priorities is the European Green Deal, an initiative that underscores the urgent need to tackle climate change. In a dedicated effort to combat global warming, the European Commission has introduced a series of proposals aimed at significantly reducing greenhouse gas emissions by the next decade (*e.g.*, electrification, greater use of renewable energy, more opportunities for innovation). The transport sector, a significant contributor to carbon emissions, is a key target area in this ambitious plan.

In 2021, as part of its commitment to spearhead a transition to cleaner, greener, and more intelligent mobility, the European Commission greenlighted four progressive proposals aimed at overhauling the transport system. These initiatives aspire to establish an interconnected network linking the largest cities in the EU, including LMA, while emphasizing intelligent mobility and enhancing urban mobility. This will be achieved through the implementation of the innovative Urban Mobility Framework.

At the heart of this framework is a commitment to emission reduction and mobility enhancement, with an emphasis on sustainable modes of transport such as public transit, walking, and cycling. This is principally driven by the development of Sustainable Urban Mobility Plans (SUMP).

In a parallel effort to improve global conditions, the United Nations (UN) has been instrumental in guiding international initiatives. Between 2000 and 2015, eight Millennium Development Goals shaped global efforts, resulting in significant enhancements in living conditions for many people worldwide. In a similar vein, the Sustainable Mobility for All (SuM4All)[13] Partnership has emerged as a robust global alliance. Comprising 57 international entities, including organizations and companies, this partnership is united in its mission to transform and elevate the sustainability of transport systems.

In 2015, the UN introduced the Sustainable Development Goals (SDGs), a collection of 17 global objectives designed to guide governments and citizens alike in the creation of a worldwide governance model (refer to Figure 2.6). The aim is to eradicate poverty, safeguard the environment, and foster prosperity and well-being for all by 2030. Transport, although not having its own specific goal, is intricately intertwined with all the SDGs. Out of the 169 SDG targets, 50 are indirectly linked to the transport sector, while 2 are directly related[13]: the target 3.6 related to road traffic accidents and the target 11.2 that aims provide access to safe, affordable, accessible, and sustainable transport systems for all. These targets are linked to 3rd SDG, good health and well-being, and 11th SDG, sustainable cities and communities, respectively.

Figure 2.6 – Sustainable development Goals (UN).

Every nation and entity across the globe are resolutely dedicated to diminishing atmospheric emissions. The Paris Agreement, which was unanimously signed and ratified by the European Union and all its Member States in 2016, binds the EU to a rigorous goal of slashing its emissions by a minimum of 55% by 2030, using 1990 levels as a benchmark (see Figure 2.7). Furthermore, it has set an ambitious target for the EU to pioneer as the first climate-neutral economy and society by the year 2050, heralding a new era of environmental responsibility. In 2022, the Conference of the Parties on Climate Change (COP26) concludes that it is necessary to work with partners around the world to accelerate implementation of the actions and initiatives agreed at COP26 and to mobilize global funds for sustainable and green investments[14]. Later that year, in the COP27, the Council approved conclusions that represent the EU's general negotiating position[14].

[14] https://www.consilium.europa.eu/pt/policies/climate-change/paris-agreement/ , accessed in September 2023.

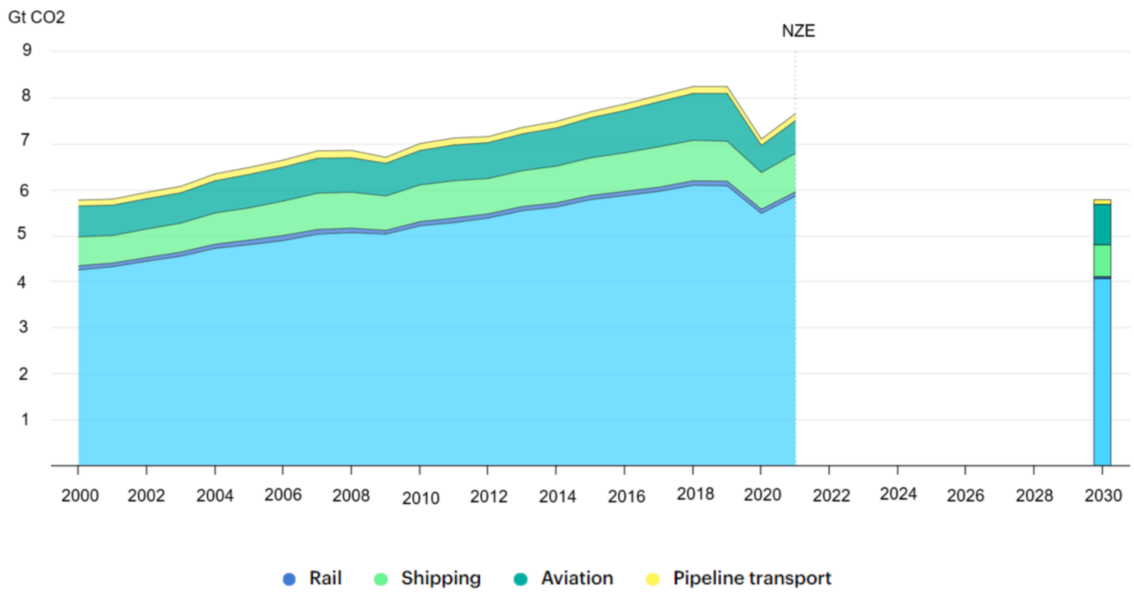


Figure 2.7 – Emissions: key targets for 2030.

To streamline transport demand and foster a transition towards more sustainable modes of transportation, an extensive portfolio of policies is employed across various levels - EU, national, regional, and local. These policies range from broad measures like 'equating all modes with their external costs', 'eliminating administrative and technical hurdles', and 'endorsing digital solutions' at the EU level, to more targeted initiatives such as 'congestion pricing schemes', 'distance-based charging', and 'car taxation' at the national level, and further to 'reallocation of road space' and 'adjustment of parking prices' at the local level (EEA, 2022).

These strategic approaches align with the 'avoid-shift-improve' (ASI) paradigm, which was first conceptualized in Germany in the early 1990s to systematically structure policy measures aimed at mitigating the environmental impact of transport (Creutzig et al., 2018). This concept has been endorsed by the Intergovernmental Panel on Climate Change (IPCC) as a holistic sustainability framework for transport[15]. It underscores reducing passenger transport emissions through a sequential order of actions: initially, 'avoid' - circumventing unnecessary journeys through inventive spatial planning and demand management; subsequently, 'shift' - transitioning to more eco-friendly travel options such as walking, cycling, and public transport; and finally, 'improve' - enhancing the energy and carbon efficiency of the chosen mode of transport (O'Riordan et al., 2022).

The 'Avoid-Shift-Improve' paradigm implies that addressing long-term climate goals requires not just a focus on transport demand policy measures, but also a harmonious integration with

[15] https://www.ipcc.ch/report/ar5/syr/ , accessed in September 2023.

infrastructure progression and new technologies (as telecommuting technologies, e-Commerce platforms, ride-sharing apps, EVs, AVs, among others). The potential of these approaches is amplified when they are symbiotically aligned. For example, the electrification of passenger cars has not yet played a significant role in reducing emissions (EEA, 2022) but a larger uptake of shared vehicles could make it easier to manage the problem of finding enough raw materials for EV batteries if it leads to fewer cars per capita (Harris et al., 2021).

Shared vehicles can also play a pivotal role in amplifying the utility potential of a car. Although these statistics are not novel, they have been recently repeated by a report from the (Nagler, 2021), which stated that in England over the past quarter-century, cars and vans were immobile, parked up to 96% of the time. Further research into mobility patterns by (Z. Xiao et al., 2022) discovered that the proportion of total driving days within a 0-10 day range (out of a 31-day month) accounted for over 40% of responses. This suggests that private cars are utilized less frequently by some individuals.

Despite this low frequency of use, when cars operate, their occupancy rate is often low. Across the European Union, the average occupancy rate for most common car trips was found to be 1.7 persons per car (Fiorello et al., 2016). This rate varied from country to country, reaching a low of 1.4 in Denmark and peaking at 2.7 in Romania (*idem*). Therefore, it becomes clear that the automobile, despite its ubiquity and centrality to modern life, is a significantly underutilized asset. There is potential for more effective usage of this resource, benefiting not only individual car owners but the wider community as well.

The main challenge in mobility in the coming years revolves around decarbonizing the sector while ensuring that mobility is equitable (both horizontally and vertically) and inclusive. However, with the increasing demand for transportation, especially in large cities, it is difficult to respond positively to this challenge if mobility patterns do not change, and the car continues to be at the centre of mobility. New AMOD solutions, especially P2P, can help move toward sustainable development. Sharing used resources can reduce carbon emissions throughout the vehicle's life cycle, as it avoids the creation of more cars and tends to reduce the number of miles travelled in shared fleets compared to scenarios of private AV use. Moreover, technology (and the consequent data collection) can contribute to greater efficiency in both system operation and policy decisions.

2.5 Shared Mobility

2.5.1 Shared mobility solutions

In recent years, there has been a marked transition towards the adoption of sharing systems to meet transportation needs, while simultaneously addressing environmental concerns, as shown in Dill et al. (2019), Münzel et al. (2019) and Shaheen et al. (2021). Shared mobility has not only gained public traction, but it has also captured the attention of investors over the past decade. As *per a* McKinsey (2023) report analysing annual data, the number of e-hailing trips skyrocketed from 5.5 trillion in 2016 to an astounding 16.5 trillion in 2019, generating revenues more than $130 billion.

Presently, there exists a diverse array of mobility services, including but not limited to, CS, RH, slugging, car clubs, and carpooling. Each of these systems provides users with on-demand, short-term access to vehicles, operating based on different strategies and business models (Shaheen et al., 2016).

The Organization for Economic Co-operation and Development (OECD) establishes "shared mobility" as involving an intermediary system, which differentiates it from traditional public transport services (OECD/ITF, 2016). These shared mobility services can be classified based on two primary criteria: who is driving (self-driving or chauffeured), and the business model employed (business-to-consumer or peer-to-peer) (Wilhelms et al., 2017).

Today, ride-sourcing is a crucial component of urban transportation, known by various names like on-demand ride services, e-hailing, app-based rides, or on-demand rides (Alemi et al., 2018). Ride-sourcing services are further divided into two categories: private cabs or ride-hailing and shared cabs or ridesharing (Kumar et al., 2022). Ride-hailing services provide access to a single individual, with no option for unknown co-passengers to join the ride *en* route (*idem*). Examples of ride-hailing services include Uber, Bolt, and Cabify.

Ridesharing entails the collective use of a motor vehicle by a driver and one or more passengers, either to share costs (non-profit) or to compensate the driver (*i.e.*, paid service) using billing details furnished by the participants (for profit). Carpooling is a specific variant of ride-sharing, where the driver undertakes the ride for non-profit reasons on a personal basis (Mitropoulos et al., 2021). An example of a carpooling platform is BlaBlaCar[16], operating since 2006, which has a global presence and is available in Portugal. Slugging is an informal carpooling system. In the

[16] https://www.blablacar.pt/ , accessed in September 2023.

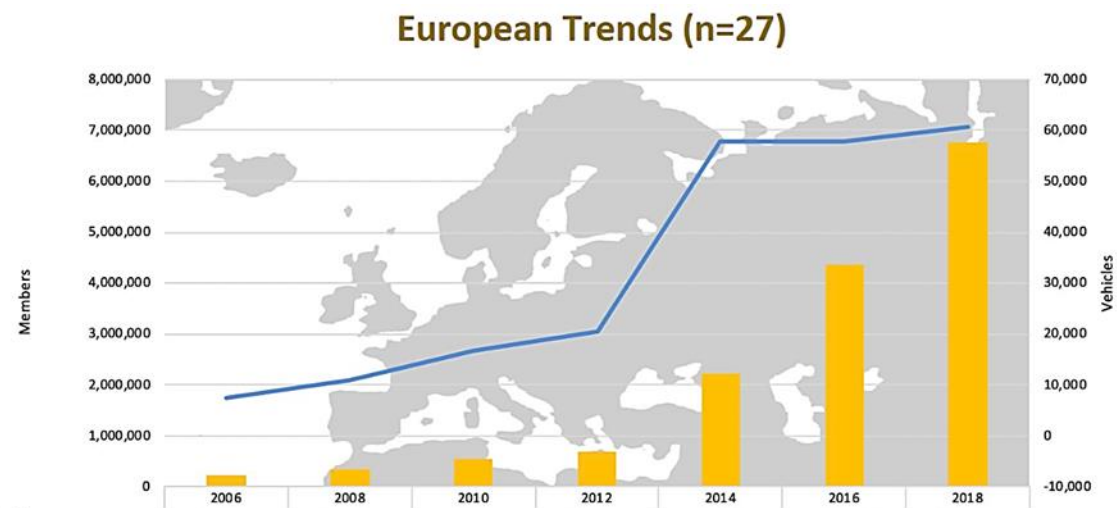
context of commuting, "slugs" are passengers picked up by drivers so that the drivers can use high-occupancy vehicle (HOV) and save time during their travel.

Dynamic ridesharing (DRS) is a singular concept. Its dynamic nature allows users to announce their availability at any time, either as a passenger seeking a ride or as a driver offering one (Nourinejad et al., 2016). The scheduling of the trip occurs on an ad hoc basis, accommodating the needs and availability of users.

Over recent decades, car-sharing has garnered significant interest. In this business structure, car-sharing entities maintain a pool of vehicles which are shared among users. B2C CS models can further be classified into round-trip and one-way services (Cohen and Kietzmann, 2014). The round-trip model requires users to return the vehicle to the same location from where it was initially rented, while the one-way model allows users to drop off the vehicle at a different location from where they started their journey (*idem*). As for the one-way model, it unfolds into two specific types: station-based, where both the pick-up and drop-off must occur at designated stations, and free-floating, which allows vehicles to be rented and returned at any parking spot within a specified operational area (Golalikhani et al., 2021).

The concept of CS, though not novel, has seen a resurgence of relevance in recent years, driven by advancements in technology and evolving economic and cultural behaviors (Belk, 2014). It was further amplified by a heightened emphasis on environmental sustainability (*idem*), bolstering the popularity of CS, particularly in Europe and several other developed nations (Hartl et al., 2018). In Europe, there has been a consistent yearly growth in CS memberships, with an impressive score of 6,761,688 members recorded in 2018 (as illustrated in Figure 2.8).

A similar trend is evident in North America. Between January 2017 and January 2018, CS membership experienced a modest 2.4% increase in the United States, contrasted by a significant 25.6% surge in Canada (Shaheen & Cohen, 2020). By the dawn of 2018, the United States boasted a substantial CS community with 1,439,399 members sharing 15,224 vehicles across 21 different operators. Notably, the three largest CS operators in the United States and Canada claimed a considerable portion of the market, accounting for 91% and 86% of total memberships respectively (these figures do not encompass P2P CS) (*idem*).



	2006	2008	2010	2012	2014	2016	2018
Members	212,124	334,168	552,868	691,943	2,206,884	4,371,151	6,761,688
Compound Annual Member Growth Rate (2 yr)	0%	26%	29%	12%	79%	41%	24%
Vehicles	7,491	10,833	16,779	20,464	57,947	57,857	60,622
Compound Annual Fleet Growth Rate (2 yr)	0%	20%	24%	10%	68%	0%	2%
Member-Vehicle Ratio	28.3	30.8	32.9	33.8	38.1	75.6	111.5

Proxies from reports and media sources were used for 12 out of 27nations in Europe.

Figure 2.8 - Regional car-sharing market trends, Europe n=27. *Source*: Shaheen & Cohen (2020)

CS presents a multitude of societal benefits, including reductions in vehicle ownership as members either eliminate their personal vehicles or refrain from acquiring one (Giesel & Nobis, 2016; Liao et al., 2020), decreases in vehicle kilometers travelled after becoming a CS member (Martin et al., 2010), which collectively contribute to decreased emissions and air pollution (Firnkorn & Müller, 2015; Nijland & van Meerkerk, 2017), and alleviation of road congestion (Shaheen and Cohen, 2013; Perboli et al., 2018). Yet, certain impacts of CS on urban transportation and sustainability remain uncertain (Wen et al., 2021; Wielinski et al., 2015) and require further research.

According to existing literature, individuals typically adopting CS services are young (Dias et al., 2017; Habib et al., 2012), male (Velazquez Romera, 2019; Hjorteset and Bocker, 2020), and reside in urban areas (Dias et al., 2017; Hjorteset & Böcker, 2020), corroborating with Prieto et al. (2017), who compared 2733 car owners across four major metropolitan areas (London, Madrid, Paris, and Tokyo). Other socioeconomic characteristics linked with higher car-sharing usage or intentions to utilize such systems include higher education levels (Lane, 2005; Becker et al., 2017) and wealth (Dias et al., 2017; Hjorteset and Bocker, 2020).

CS users often live in relatively small or non-traditional households, and their trips typically serve shopping, social-recreational purposes, or personal business such as medical appointments

(Cervero et al., 2007; Cervero & Tsai, 2004; Lane, 2005). These patterns corroborate with Burghard & Dütschke (2019) who studied car-sharing with EVs and state that it is particularly appealing to young people who live as couples without cars or are starting families and utilize car-sharing as a supplement to their own cars.

Aguilera-García et al. (2022) propose that individuals with a high propensity for sharing, a variety-seeking lifestyle, and a preference for driving are significantly more familiar with CS services. The primary factor related to attitudes towards CS is its perceived compatibility with daily life (Burghard & Dütschke, 2019). Moreover, research underscores utilitarian motives, such as parking accessibility (Paundra et al., 2017), price (Cartenì et al., 2016; Paundra et al., 2017), and convenience as critical factors influencing the decision to utilize CS services (de Luca & Di Pace, 2015). Business-to-consumer (B2C) car-sharing service users typically prioritize the attributes and offerings provided over brand loyalty, user meetings, or socialization (Bardhi & Eckhardt, 2012).

While sustainability may not be the primary motive for renters, it is perceived as an indirect benefit of engaging in CS (Merfeld et al., 2018). However, individuals with more pro-environmental behaviors reduce CS usage (Aguilera-García et al., 2022) and gravitate towards a green lifestyle, favoring environmentally friendly mobility services such as public transportation or active modes like walking or cycling (Kim et al., 2017).

Compared to other transport solutions, neighborhood and transportation characteristics play a more significant role in the success of car-sharing (Celsor & Millard-Ball, 2007). Car-sharing usage studies confirm a seasonal effect, with increased activity during the summer months. Users also tend to favor newer vehicles (de Lorimier & El-Geneidy, 2012), and most rentals typically occur on Fridays and Saturdays (Concas et al., 2013).

Nonetheless, a segment of the population remains uneasy with this service. This discomfort can be attributed to the concern of contagion, the awareness that an object has been touched by someone else (Bardhi & Eckhardt, 2012), a significant issue in disruptive events like a pandemic. As evidence of these fears, McKinsey (2020) reported that the onset of the COVID-19 pandemic resulted in a 60-70% drop in ride-hailing services within mere months, while many micromobility and carpooling services were suspended altogether.

2.5.2 Peer-to-peer car-sharing

B2C solution facilitates car sharing through fleets. While B2C solutions may have higher visibility, P2P examples have been multiplying worldwide, gaining increasing popularity as a mobility solution. In January 2017, an industry benchmarking report estimated that there were over 2,900,000 individuals participating in P2P CS, with a shared fleet of 131,336 P2P vehicles across six operators in North America (Shaheen, 2019). P2P car-sharing is particularly prevalent in certain regions of Europe, including France and the Netherlands (Shaheen, 2019).

P2P car-sharing has emerged, since it initially launched in 2010 (Shaheen, 2019), as a response to two efficiency-related issues associated with traditional B2C CS (Dill et al., 2017): first, it addresses the strategic decision of companies to avoid operating vehicles at locations that generate low profits or potential losses; second, P2P CS eliminates the need for upfront costs and ongoing maintenance expenses for new cars. While P2P CS may involve the use of older vehicles that could be more polluting than newer ones, it helps conserve the resources required for manufacturing new cars (Postorino & Sarnè, 2023).

A P2P access-based service establishes a threefold relationship that encompasses three pivotal components (Wilhelms et al., 2017):

- the peer-provider, who acts as the car owner offering their assets for rent;
- the peer-user, who becomes the renter utilizing the assets owned by others; and
- the service or system that effectively connects and facilitates transactions between these parties.

In contrast to B2C car-sharing, P2P CS involves car owners who have their own reasons for participating. The primary motivation for owners to rent out their cars is the opportunity to earn money (Dill et al., 2017; Shaheen et al. (2018a)). Studies from 2013 indicate that P2P car owners can earn around $9,000 per year (Collaborative Fund, 2013), although certain types of cars, such as Tesla, may generate higher revenues due to the high demand (Puligandla, 2016). Belk (2014) introduces the concept of "pseudo-sharing," which describes a transactional relationship without a sense of community, where monetary compensation takes precedence over genuine sharing (Milanova & Maas, 2017).

Economic interests behind participating in P2P car-sharing can vary. Some participants use the service to earn money that they can spend or invest in various activities to enhance their overall quality of life. Others aim to save money, driven by the desire to reduce fixed costs associated with car ownership, such as insurance, maintenance, taxes, and parking fees, as well as minimize costs related to underutilized or infrequent car usage (Wilhelms et al., 2017). For some individuals, the opportunity to earn money through P2P CS may make vehicle ownership financially feasible when it would otherwise be unaffordable (Puligandla, 2016).

The pursuit of earning money through P2P CS brings forth additional questions regarding the impact on individuals' usage patterns and their willingness to explore alternative transportation options. In a multiyear study that began early 2012 and focused on Getaround members in Portland, Oregon, several vehicle owners exhibited minimal changes in their driving behavior based on GPS data analysis. Owners who frequently rented out their vehicles tended to proactively plan their schedules in advance (Dill et al., 2017). Moreover, approximately 30% of participants reported an increased utilization of alternative modes of transportation, such as walking, cycling, and public transit, indicating their genuine intention to implement changes they desired, such as driving less (Dill et al., 2017). This highlights how the financial incentive of P2P car-sharing can motivate individuals to actively explore and adopt alternative modes of transportation.

P2P car-sharing offers several positive aspects, including enhanced resource efficiency, the potential to reduce the overall number of cars on the road, and positive environmental impacts (Dill et al., 2017). In a study conducted by Wilhelms et al. (2017), which involved in-depth interviews with 20 car owners in collaboration with a German P2P car-sharing organization, it was found that car owners were sensitive to the possibility of enabling users to live a car-free lifestyle, reducing the prevalence of unused vehicles, and promoting environmental sustainability. However, while car-sharing often promotes an idealistic, prosocial, and environmentally conscious perspective, economic considerations tend to outweigh ethical concerns in most consumption situations (Devinney et al., 2010).

In the literature, it is noted that car owners participating in P2P car-sharing experience gratification from providing goods to others (Philip et al., 2015) and optimizing the utilization of underutilized assets (Barbour et al., 2020; Dill et al., 2019). At a local level, car owners are motivated by a desire to help the community, support the local economy, and provide mobility options to areas without B2C car-sharing systems. They also derive joy from the shared experience with others (Ballús-Armet et al., 2014; Shaheen et al., 2012). An important aspect is that car owners who have already engaged in informal car sharing outside of online platforms are significantly more inclined to offer their cars through an online platform as well (Munzel, 2019).

However, there are also some concerns that deter car owners from participating in P2P car-sharing solutions. Common concerns include the risk of vehicle damage and the fear of renters not respecting the owner's rules regarding the use of the vehicle (Dill et al., 2017). The perceived risk is associated with not knowing the renters, as the level of familiarity plays a role in sharing arrangements (Milanova & Maas, 2017), and trust becomes crucial in mitigating expectations of opportunistic behavior and other uncertainties (Kim et al., 2015). In a study conducted by Valor (2020), which involved 20 in-depth interviews with adult respondents residing in Madrid who were not users of peer-to-peer car-sharing (P2P CS), it was found that potential adopters expressed emotions of worry, fear, and anxiety related to the rental process. These emotional concerns can serve as significant barriers to the adoption of P2P CS services.

Another drawback of P2P car-sharing is the responsibility of keeping the car fueled and cleaned (Dill et al., 2017). According to utility theory, participation intentions are strongest when costs are minimized and benefits are maximized, and this principle applies to sharing schemes as well (Hennig-Thurau et al., 2007). When making participation decisions, owners weigh the monetary benefits against the perceived concerns and tasks involved.

In the case of home renting, the primary reason for not renting out is not necessarily the concern of intrusion into one's private space (Bieger et al., 2007), but rather the unavailability of the property for the owner's own use (Skak & Bloze, 2017). The same principle applies to car-sharing schemes, where owners may decline rental requests because they are too busy, need the car during the requested time, or simply prefer to have the car available for their own convenience, regardless of immediate need (Dill et al., 2017). In an online survey conducted by Shaheen et al. (2018a) in 2014, with a sample of 1,151 P2P CS members from the most popular P2P CS platforms in the United States, the researchers found that the primary concern expressed by participants was the occasional unavailability of their own cars.

In a recent study, Olaru et al. (2021) conducted an online questionnaire with 751 Australian vehicle owners to assess their collective attitudes towards P2P CS and driverless vehicles (DVs). They identified a distinct group labeled as "enthusiasts, pioneers" comprising 24% of all respondents. This group demonstrated moderate-to-high concerns about sharing but not towards DVs. Interestingly, this group had a higher proportion of male participants, were generally older compared to the "Interested, but CS concerned" subgroup, and displayed higher scores on measures of open-mindedness. The findings from this study provide valuable insights into the intersecting interest of car owners in both technology and sharing practices for the future.

From a renter's perspective, P2P CS is often seen as similar to B2C CS, and the characteristics of B2C and P2P car-sharing adopters are generally quite similar (Münzel et al., 2019). However, there are distinct characteristics that set P2P CS apart. According to a study by Münzel et al. (2019), which involved interviews with 1,835 individuals representative of the Dutch population in 2014, P2P CS renters tend to be more cost-sensitive but less inclined to use public transportation compared to B2C CS users. Additionally, P2P CS renters perceive P2P CS as offering greater flexibility and an easier means to find the specific car they desire to rent, as highlighted in research by Wilhelms et al. (2017). Shaheen et al. (2018) emphasize that car renters, driven by factors such as access to a variety of vehicles, flexibility of service, cost-effectiveness, and convenience, perceive P2P car-sharing as a means to move around without the worries and responsibilities associated with personal vehicle ownership.

Nevertheless, renters identify two discouraging factors when considering renting a car through P2P CS: the first is the responsibility of refueling the vehicle before returning it to the owner; the second concerns the need to interact with a stranger, whose reliability is unknown, which can create objections among potential renters (Rotaris, 2023). These factors present challenges that influence the decision-making process of individuals considering P2P CS.

2.6 Autonomous vehicles

2.6.1 Levels of driving automation

Vehicles began to incorporate technology with the aim of enhancing their safety systems, predominantly through assistance and warning mechanisms. The late 20th century saw the advent of the first systems that intervened in human driving tasks, with the Anti-lock Braking System (ABS) emerging in the 1970s, followed by the Electronic Stability Control (ESC) in the 1990s.

Subsequent technological advancements introduced features like Adaptive Cruise Control (ACC), Lane Departure Warning Systems (LDWS), and Advanced Emergency Braking Systems (AEBS). These innovations required sensors to constantly monitor the vehicle's surrounding environment, including the road and other vehicles.

However, the most significant proliferation of driving assistance devices has occurred since 2014, driven by technological advancements and industrial rivalry. The integration of LiDARs (Light Detection and Ranging systems), radars, and cameras into vehicles, along with the rise of machine learning and deep learning, has broadened the scope for Object and Event Detection and Response (OEDR). This fusion of hardware and software has resulted in novel technological tools such as low-speed steering assistance, Emergency Steering Function (ESF), and Risk Mitigation Functions (RMF) (UNECE, 2021).

In order to establish a unified language, SAE International has outlined six levels of driving automation in its J3016 standard (latest revision on 2021). These definitions are centered around the functional facets of the technology and are congruent with contemporary industry practices (SAE International, 2014). It ranges from no driving automation (Level 0) to full driving automation (Level 5). Figure 2.9 offers further insights into the three principal entities involved in driving: the (human) user, the driving automation system, and other vehicle systems and components along the automation levels.

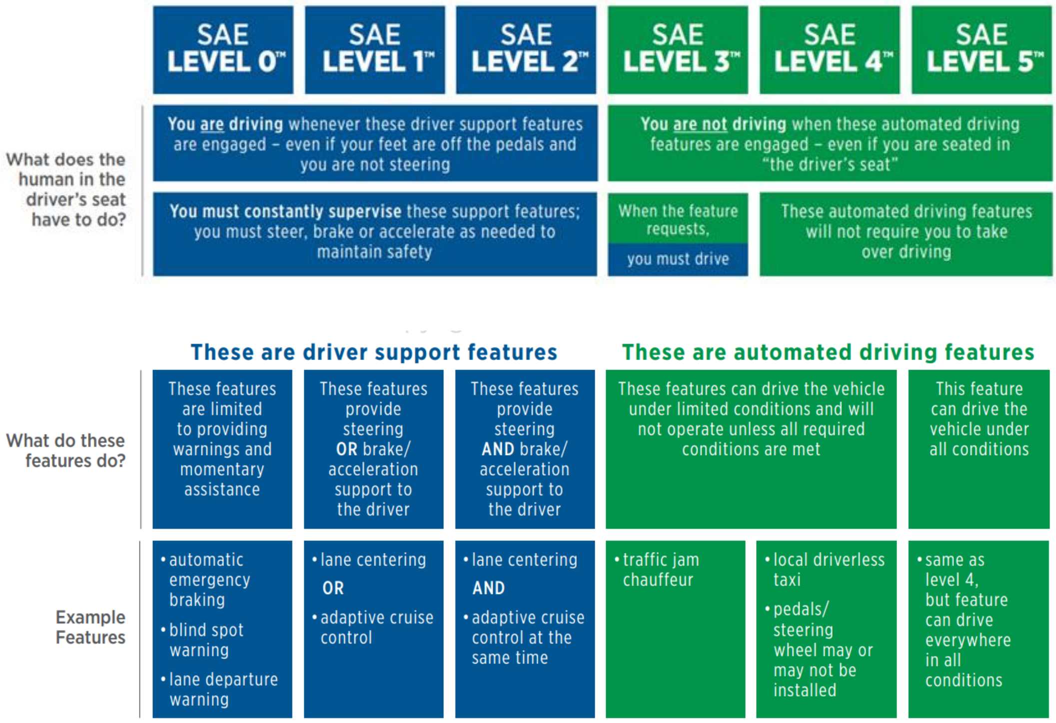


Figure 2.9 - Summary of SAE International´s levels of driving automation for on-road vehicles. *Source*: SAE (2021)

In the initial stages of autonomous driving, which include Level 0 (No Driving Automation), Level 1 (Driver Assistance), and Level 2 (Partial Driving Automation), the responsibility for driving lies primarily with the human operator, although they may be aided by various automated systems. As of 2023, many vehicles already incorporate such driver assistance features. An example of this is cruise control, which is widely available and commonly found in new vehicles across all price ranges.

Tesla is a brand that's often in the spotlight for its progress in autonomous driving. Its "Full Self-Driving" beta system, as it's branded, is capable of handling steering, braking, and acceleration under certain circumstances, although it requires periodic oversight from the driver. However, Tesla's technology is currently classified as SAE Level 2 as of 2023 (NHTSA, 2023). It has not yet reached the more advanced Level 3 (Conditional Driving Automation) that competitors such as the Hyundai Motor Group are developing.

Hyundai Motor Group has stated that by the end of 2023, it plans to introduce the Genesis G90 sedan, which is touted to be the first vehicle to employ Level 3 automation on public roads. This vehicle will be equipped with the Highway Driving Pilot (HDP) system, allowing drivers to remove their hands from the wheel on certain highways. Interestingly, South Korea, where Hyundai is based, has given approval for Level 3 vehicles to operate on public roads starting from 2022, joining Japan and Germany as the third country to allow this level of autonomous driving.

Ford is currently working on the development of Level 2+ / Level 3 autonomous technologies in-house. Similarly, Audi, BMW, and Volvo have publicly stated their ongoing efforts towards Level 3 automation. California has become a preferred location for testing these vehicles. Back in 2012, California became the third state, following Nevada in 2011 and Florida, to authorize the operation of AVs[17].

A number of AV operators have chosen not to pursue Level 3 automation due to safety concerns. At this level, drivers are still required to maintain focus on the road despite the vehicle's ability to handle certain driving tasks autonomously. Given human tendency to place undue trust in the vehicle and overlook their responsibilities, operators such as Waymo and Cruise have chosen to focus exclusively on SAE Level 4 (High Driving Automation). The expectation for a potentially distracted driver to quickly realize the need to resume control, assess their surroundings, and effectively take over driving can be unrealistic, as demonstrated by incidents such as the 2018 case where a man moved to the passenger seat while his Tesla was in autopilot mode[18], among others globally.

There have been instances of Level 4 AVs in operation for several years. For example, the CityMobil2 project trialed two fleets of six 10-passenger vehicles each from project partners Robosoft and EasyMile in seven European cities between 2014 and 2016. These vehicles operated in public, non-segregated spaces (CORDIS, 2017). In Europe, Navya and EasyMile have pioneered the use of autonomous buses on fixed routes, with over 100 tests conducted by the

[17] https://www.cga.ct.gov/2012/rpt/2012-R-0456.htm#:~:text=On%20September%2025%2C%202012%2C%20California,the%20operation%20of%20autonomous%20vehicles. , accessed in September 2023.

[18] https://www.cnbc.com/2018/04/30/man-who-put-tesla-in-autopilot-and-moved-to-passenger-seat-gets-driving-ban.html , accessed in September 2023.

end of 2022[19]. As of December 31, 2021, over 200 units of Navya's "Autonomous Shuttle", designed for passenger transport, have been sold in 25 countries since its introduction[20].

Uber started testing the idea of a driverless shared mobility service in Pittsburgh in 2016, a concept that was further developed by Aurora after it acquired Uber's Advanced Technologies Group (ATG) in 2017. Similarly, nuTomy, later acquired by Delphi Automotive and rebranded as Aptiv, initiated a pilot project for a highly automated taxi service in Singapore in 2017, although with safety drivers still onboard. Drive Me launched a pilot project in 2017 in Gothenburg where 100 self-driving Volvo cars were driven on public roads, marking leading role in the legislation and testing of vehicle automation in Europe.

Presently, Waymo One operates a ride-hailing service in San Francisco, Los Angeles, and Phoenix without a human driver in the front seat. Cruise, on the other hand, manages to run around 1,000 trips per day in San Francisco, with peaks of 2,000 trips on busy days using their fleet of 300 customized Chevy Bolt electric vehicles. Amazon subsidiary Zoox has also entered the autonomous ride-hailing market with vehicles that lack manual controls, and is developing operations in the San Francisco Bay Area and Seattle. Pittsburgh continues to be a significant hub for AV development, housing companies like Argo AI and Latitude AI that are aiming to transform the driving experience.

The term *connected autonomous vehicle* (CAV) is used to refer to autonomous vehicles that communicate with other infrastructures to collect information or negotiate their maneuvers (Shladover, 2018). This communication capability is enabled through connected vehicle (CV) technology, which complements and synergizes with the implementation of AVs to some extent (Shladover, 2018). It's important to note that connectivity is not a mandatory feature of AVs, as highlighted by Hendrickson et al. (2014).

2.6.2 Regulatory concerns

The AV policy in the U.S. was built state to state, independently. Nevada was the first state to authorize the operation of AV in 2011. Since then, more states followed the example and produced legislation related to AV. In September 2016, NHTSA (National Highway Traffic Safety Administration) and USDOT (U.S. Department of Transportation) unfolded a “Federal Automated Vehicles Policy”, a milestone to AV in the U.S. and for the world, once it was the first country´s policy in the history, related to this theme. This guidance intends to ensure the

[19] https://www.eetimes.eu/autonomous-vehicles-how-is-europe-doing/ , accessed in September 2023.
[20] https://www.navya.tech/en/regulations-are-constantly-changing-to-keep-pace-with-the-deployment-of-autonomous-vehicles/ , accessed in September 2023.

establishment of a consistent national framework rather than a patchwork of incompatible laws. It´s not mandatory neither a closed document, it´s open to interpretations and review process for stakeholders and public, in general.

In Europe, Vienna Convention on Road Traffic (ECE Regulation no. 79) is the base of legislation in terms of road transportation. It took place in 1968 and intended to facilitate international road traffic and to increase road safety by establishing standard traffic rules among the contracting parties. This legislation is still currently adopted by 74 countries, despite having been published for such a long time. Nowadays it seems outdated for new technology which doesn't fulfill the rules of driving behavior. The legislation states that "every moving vehicle or combination of vehicles shall have a driver" (article 8, parag 1) and "every driver shall at all times be able to control his vehicle or to guide his animals" (article 8, parag 5) and these rules aren´t in line with an idea of driverless cars.

In March 2016 an amendment of the Vienna Convention on Road Traffic regarding driver behavior entered into force; according to this latest amendment, systems are now deemed to be controllable if the driver can switch them off or override them (Daimler, 2016). Future functions for highly automated driving that still require a driver also meet this criterion.

Driverless cars, on the other hand, are still not permitted because even the amended treaty stipulates the need for a driver. More, the amendment doesn´t include the article 13 that highlights the questions of driverless cars. If "every driver of a vehicle shall in all circumstances have his vehicle under control" (parag 1), an automated system can´t perform all driving tasks. And we can see road legislation as the main obstacle to future technologies diffusion, but other fields of European regulation should be revised. For example, UN-R 79, a licensing regulation in the UN Economic Commission pertaining to steering equipment, did not allow automatic steering above speeds of 10 km/h (until recently).

UNECE (United Nations Economic Commission for Europe), through the World Forum for Harmonization of Vehicle Regulations (WP.29) and the UN Road Safety Instruments, developed a platform where countries around the world could gather together to adapt legal instruments and develop new ones to get automated driving functionalities (UNECE, 2021).

In 2018, UNECE established the Working Party on Automated/Autonomous and Connected Vehicles (GRVA) and developed requirements and guidelines for the automated and connected vehicles, namely the *Framework on Automated/Autonomous and Connected Vehicles* (FDAV). This Framework, drafted by China, the European Union, Japan, and the United States of America, forms a novel initiative aimed at harmonizing globally automated driving regulations and creating a more productive environment for innovation (UNECE, 2021). This guide was updated in February 2022[21].

Since 2018, GRVA achieved some results, under the 1958 Agreement. One of the first works was the adoption of amendments to UN Regulation No. 79 (Steering) to include references to Auxiliary Steering Equipment or Advanced Driver Assistance Steering System and adapt the text of the steering control operation requirements to the new technological developments.

In the same year (2018), the European Commission publishes the *EU's Strategy on Automated Mobility*, which outlines a comprehensive set of EU actions towards the deployment of connected and automated mobility systems. In the same year the European Commission also presented the revised *General Safety Regulation*, with rules addressing the need for improving vehicle and road safety.

In 2019, the European Parliament and the Council of the European Union, based on European Commission proposal, defined *New Rules to Improve Road Safety and Enable Fully Driverless Vehicles in the EU*, that entered into force in July 2022.

These rules consider automated vehicles replacing the driver on motorways (level 3 SAE) and the circulation of highly driverless vehicles like shuttle or robotaxis, in urban environment (level 4 SAE). It covers testing procedures, cybersecurity requirements, data recording rules as well as monitoring of safety performance and incident reporting requirements by manufacturers of fully driverless vehicles[22].

In the same year (2019), UNECE through the Global Forum for Road Traffic Safety (WP.1) published the Resolution on the Deployment of Highly and Fully Automated Vehicles in Road Traffic. It provides recommendations to technology developers, users, and governments to facilitate the safe and global deployment of highly and fully automated vehicles in road traffic.

GRVA also elaborated new UN regulation. In 2020 (entry in force: 2021), the UN Regulations No. 157 established uniform provisions concerning the approval of vehicles with regard to Automated Lane Keeping Systems (ALKS). It has been updated and the last amendment[23] (that entered into force in January 2023) sets that “ALKS can be activated under certain conditions on roads where pedestrians and cyclists are prohibited and which, by design, are equipped with a

[21] https://unece.org/info/publications/pub/365097 , accessed in September 2023.
[22] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_4312 , accessed in September 2023.
[23] Proposal for the 01 series of amendments to UN Regulation No. 157 (Automated Lane Keeping Systems), submitted by GRVA in June 2022.

physical separation that divides the traffic moving in opposite directions and prevent traffic from cutting across the path of the vehicle (…) for travelling speed of 130 km/h or less”. A huge step since the UN-R 79 and its limit of 10 km/h.

The amendment also stipulates the obligation for the automated driving system to comply with local traffic rules, cybersecurity and software update requirements and performance-based requirements (it includes provisions governing type approval, technical requirements, audit and reporting, and testing both on test tracks and in real-world conditions).

2.6.3 Impact of AVs

Academic scholars and industry researchers are actively exploring the potential benefits and challenges associated with the transition to AVs. This current phase of development presents a favorable time for in-depth discussions and analysis, aiming to gain a deeper understanding of the advantages that AV technology can bring.

One of the main advantages touted for AVs is their potential to improve road safety. Human errors currently account for 94% of total accidents (USDT NHTSA, 2015), and with the introduction of AVs, the goal is to significantly reduce motor-vehicle fatality rates. It is envisioned that AVs could eventually achieve fatality rates similar to those seen in aviation and rail, which are approximately 1% of the current rates (Hayes, 2011). On-road testing of AVs in California between 2014 and 2018 by various manufacturers reported 128 accidents over 3.7 million miles (Wang et al., 2020). Of these accidents, 63.3% occurred while driving in autonomous mode, with 93.7% of them being passively initiated by other parties.

However, some authors exercise caution during this transition, suggesting that when conventional and self-driving vehicles share the road, safety might worsen, especially for the conventional vehicles (Sivak & Schoettle, 2015a). Additionally, increasing safety for some users at the expense of others is not necessarily a straightforward benefit, even if the net safety risks to the entire population are lower (Lin, 2013). There are concerns that pedestrians may become less cautious and responsible around AVs, leading to unpredictable behavior that forces risk-averse AVs to slow down (Millard-Ball, 2016). Furthermore, there is evidence of offsetting behavior, where road users take additional risks when they feel safer around automated mobility (Litman, 2017). Experts argue that without the complete penetration of AVs and smart infrastructure in traffic, autonomous systems will continue to encounter the irrational and unpredictable actions of other human road users (AUDI, AG, 2021), not just pedestrians.

The adoption of AVs is expected to improve mobility for everyone, including differently abled individuals, by providing greater accessibility and enhancing their independence (Favaro et al., 2017; Lee & Mirman (2018)). Older drivers, who have extensive driving experience, may face increased risks on the road due to age-related physical and mental limitations (Sivak & Schoettle, 2015a). Similarly, impaired drivers, such as those under the influence of alcohol or experiencing fatigue, have diminished cognitive and motor function, which increases the probability of accidents.

However, there are concerns that the introduction of AVs could lead to increased congestion, counteracting the potential mobility benefits. Gruel and Stanford (2016) found that vehicle travel is likely to increase, albeit to varying degrees across different scenarios. Other researchers also argue that vehicle travel could rise due to rebound effects. These effects may result from faster or cheaper travel options, additional mileage from repositioning and empty driving of AVs, or increased demand due to perceived in-vehicle time as an opportunity for other activities (Kockelman et al., 2016; Lin, 2013; Bischoff et al., 2019; Fagnant & Kockelman, 2015; Moreno et al., 2018; Childress et al., 2015; Smith, 2012). Estimations suggest a potential increase in vehicle kilometers traveled (VKT) of around 4% to 10% (Gucwa, 2014; Fagnant & Kockelman, 2014).

The introduction of AVs can also influence travel behavior, as the possibility of multitasking and utilizing in-vehicle time for other tasks may lead to increased travel distances. This can encourage individuals to live farther away from city centers or even work in more distant locations, potentially exacerbating suburban sprawl and contributing to higher vehicle miles traveled and associated greenhouse gas emissions (Milakis et al., 2017; Millonig & Haustein, 2020; Kohler & Colbert-Taylor, 2015; Litman, 2017; Wadud et al., 2016). Carrese et al. (2019) concluded that AVs could also increase commuting travel times (by 12 %) for suburban residents who work in the city center due to relocated extra demand.

However, there are potential solutions to mitigate the challenges associated with AVs. Studies have shown that congestion reduction measures, such as congestion mitigation, speed management, and traffic smoothing, can significantly reduce congestion on freeways by up to 35% and on arterial roadways by 10% at a 50% market penetration level (Fagnant & Kockelman, 2015). Additionally, AV technologies like platooning, which involves vehicles traveling closely together in a convoy, can lead to fuel consumption reductions of up to 30% (Zabat et al., 1995) and lower CO_2 emissions by up to 20% (Barth & Boriboonsomsin, 2008). In urban environments, the benefits may be more limited without automated intersection management systems (Dresner & Stone, 2008).

However, ethical considerations pose a critical challenge. The absence of human drivers in AVs raises ethical questions regarding pre-programmed reactions to critical situations on the road. The MIT Moral Machine study highlighted the public's preference for sparing human lives, prioritizing the preservation of more lives, and showing a preference for saving younger lives (Awad et al., 2018). As AVs are deployed in the market, it is essential for leaders and manufacturers to engage with communities, provide them with necessary information, and seek their consent for the implementation of AVs on their streets (Fleetwood, 2017).

In addition to ethical concerns, other issues arise. The introduction of AVs presents new insurance and liability challenges (Fagnant & Kockelman, 2015), even at level 3 of the Society of Automotive Engineers (SAE) classification. Legislation in California, for example, requires the storage of 30 seconds of sensor data prior to a collision to assist in determining liability (Weiner & Smith, 2016). Privacy and security concerns also arise (Fagnant & Kockelman, 2015), necessitating measures to prevent cyberattacks, hostile control, and malware. AV systems utilize multiple layers of vehicle and information sources to ensure redundancy and mitigate the potential for severe consequences (Petit & Shladover, 2015).

2.6.4 Interest in AVs

Despite the challenges and concerns associated with vehicle automation, there's substantial interest in this emerging technology. Research by Schoettle and Sivak (2014) reveals about two-thirds of respondents are familiar with AVs. When asked about potential benefits, 72% mentioned fuel efficiency, while 43% pointed out time savings during travel. There's also a broad public awareness about AVs' potential impact on road safety, with many expecting fewer accidents (Bansal et al., 2016; Continental, 2015). Similarly, 60% of transportation experts believe AVs could be safer than traditional vehicles (Begg, 2014). Moreover, the ability to handle stressful situations on the road and the chance to engage in other activities during travel, such as sightseeing or chatting with friends, are among the main reasons individuals appreciate AVs (Bansal et al., 2016; Continental, 2015).

In terms of journey characteristics, AVs are found more appealing under tedious driving conditions like highway travel or traffic congestion (Becker & Axhausen, 2017). However, the public's acceptance of AVs comes with reservations. Top of the list are security and safety concerns, followed by unresolved legal issues (Kyriakidis et al., 2015; Schoettle & Sivak, 2014). In the Austin survey, 82% of respondents listed safety as a concern, followed by legislation and cost (Casley et al., 2013). Industry experts also underline liability issues, especially in AVs without a steering wheel, as significant hurdles (Underwood, 2014).

Interestingly, residents of developed countries appear most anxious about the data transmission aspect of AV technology, possibly due to widespread reports of cyber-attacks (Kyriakidis et al., 2015) or basic privacy concerns as per Maslow's hierarchy of needs (Becker et al., 2017; Maslow, 1943).

Public confidence in AVs remains a work in progress. Despite the high level of automation, 41% of respondents still feel the need to watch the road (Schoettle & Sivak, 2014). A survey by Seapine Software (2014) confirms this unease, with 88% expressing concern about AV travel. Equipment malfunction tops the list of concerns at 79%, followed by liability and system security at 59% and 52%, respectively (Bansal et al., 2016).

Researchers predict behavioral shifts due to AV adoption. In a study, conducted by Harb et al. (2018), that simulated life with a private self-driving vehicle by offering households 60 hours of free chauffeur service over three weeks, there was a notable rise in vehicle miles traveled and trip frequency. Particularly, evening and longer-distance trips increased, and there was a significant amount of "zero-occupancy" vehicle miles. The enhanced comfort and potential for multitasking offered by AVs could potentially influence longer-term habits (Becker et al., 2017). When using AVs, individuals' cost of travel reduces, and their travel time can even be transformed into a positive utility (Mokhtarian, 2018).

As for vehicle ownership, models show that the number of jobs within a 45-min driving range at the census tract level is negatively correlated with interest in owning AVs, while road network density is positively correlated with such interest (Nodjomian and Kockelman, 2019). This suggests that people living in urban areas with low work accessibility could become AV owners. Jiang et al. (2020) conducted an online survey to inquire about Americans' willingness to purchase AVs and concluded that potential owners are often located in large and dense urban regions. Another academic research found that more than half of the respondents consider giving up their second car with the introduction of AVs (Silberg et al., 2014), and 23% anticipate reducing their car ownership (Zmud et al., 2016).

The emergence of AVs has elicited varied reactions from the public. According to a survey by Kyriakidis et al. (2015), most respondents, drawn from 109 countries, expressed a preference for traditional vehicles. However, a third of these respondents were open to the possibility of using fully AVs.

A separate survey by Bansal et al. (2016) revealed that over 80% of respondents in Austin, U.S., expressed interest in owning a fully AV. However, the reality of the potential cost dampens enthusiasm for AVs. A study by J.D. Power (2012) revealed that while 37% of participants expressed interest in owning an AV, the number dropped to 20% when they were informed of a potential $3,000 price tag.

Different studies show varying levels of willingness to pay (WTP) for an AV. Casley et al. (2013) reported that 30% of participants were willing to pay more than $5,000 for an AV as their next car instead of a traditional one. Schoettle & Sivak (2014) show that 25% of respondents in the U.S., U.K., and Australia are willing to pay between $1,710 to $2,350 for an AV. Despite these figures, most respondents in these countries (around 55%) are not willing to pay more for this technology. In Portugal, highly educated drivers are willing to pay, on average, €65,671 for level 3 SAE AVs, €31,185 for level 4 SAE AVs, and about €28,622 for level 5 SAE AVs, indicating a preference for Conditional AVs over higher technology that eliminates human dynamic driving tasks (R. Rodrigues et al., 2021).

Regarding demographic factors, studies reveal that younger people are more receptive to AVs, while the perspectives of older people are less clear. Bansal et al. (2016) found a negative correlation between age and willingness to pay, but not between age and time of adoption. In contrast, Rödel et al. (2014) found that the intention to use an AV increases with age. Previous studies show that people with higher income and education levels are more willing to purchase AVs (Liu et al., 2019).

Bansal et al. (2016) identified males, individuals working in tech, city dwellers, and those with past accident experiences as more interested in AVs and more willing to pay for them. Numerous studies confirm that males are more receptive to this technology, with one outlier study by Silberg et al. (2014) suggesting that women are more interested.

In terms of driving habits, some scholars found that the intensity of driving is positively correlated with people’s interest in owning AVs (Saeed et al., 2020), their willingness to purchase AVs (Kyriakidis et al., 2015), and their willingness to pay for adding extra autonomous driving functions to their vehicles (Bansal & Kockelman, 2018). However, this is not a consistent conclusion.

These individuals, however, are less willing to pay for partial automation, presumably because it doesn't allow them to engage in other activities while in the car. Kyriakidis et al. (2015) confirmed this, adding that high-income individuals who drive more miles and travel more often are also more interested in AVs. However, there's no consensus about the influence of income on the intention to use AVs.

There is a common belief among individuals that the emergence of new technology is not only beneficial but also indispensable, and that our daily routines ought to adjust to accommodate new modes of transportation, rather than adjust to our routines (Rebalski et al., 2022). Research conducted by T. Tao & Cao (2022) indicates that the primary motivation for AV ownership is guided by the innovation-diffusion theory. This is followed by a preference for efficiency-enhancing features, and subsequently by the prospect of substituting traditional modes of transportation with autonomous ones. These studies indicate a forthcoming wave of technology adoption, with many individuals perceiving AVs simply as an advanced feature augmenting their private vehicle capabilities.

2.7 Future trends of shared mobility

2.7.1 Overview

The future of mobility technologies is shrouded in uncertainty and encompasses a wide array of potential trajectories, each teeming with its own plausible outcomes (Papa e Ferreira, 2018). Rapid advancements in these technologies present divergent paths, from the rise of automated vehicles to the adoption of shared mobility platforms. While these developments hold the promise of transforming the mobility landscape, predicting a precise direction remains a complex task.

A study led by Audi suggests that individual transport will retain its dominance in the mobility landscape, particularly in less regions and suburban areas. This is because personal vehicles, whether owned, leased or otherwise available, offer an unmatched level of flexibility and comfort (AUDI AG, 2021).

Given the substantial financial and intellectual capital presently being invested in AVs, as previously noted, there is a growing consensus within the industry that driverless automobiles are poised to become an integral element of future mobility. While some individuals perceive autonomous private cars as advantageous and flexible due to their capacity to be used concurrently by all family members (Faisal et al., 2019), others argue that the introduction of such vehicles will not elicit significant changes in behavior or daily routines (Bansal et al., 2016; Zmud et al., 2016). Furthermore, a majority of surveyed individuals (74% according to Bansal et al. (2016)´s survey) do not anticipate changing their residences in the future. Nevertheless, the enhanced comfort and potential for engaging in additional activities in the vehicle could result in long-term impacts (Becker et al., 2017).

AVs are anticipated to operate both as private and commercial units (Heinrichs, 2016; Collingwood, 2017; Wadud, 2017). While they remain largely in the testing phase, it is envisaged that fleets of shared autonomous vehicles (SAV) could become a viable alternative to private vehicle ownership and usage. P2P ACS belong to this emergent business model landscape for SAVs (Shaheen, 2019). Two notable models are:

- P2P with a Third-Party Operator: This model mirrors the current state of P2P CS, where privately owned AVs are made available for short-term, on-demand usage. As with current practices, private operators would host platforms to manage usage scheduling and financial transactions.
- P2P with Decentralized Operations: While like the third-party operator model, this scenario sees AV hosts and users orchestrating and processing usage periods via a public, open-source ledger, for example, those leveraging blockchain technology (Stocker and Shaheen 2018).

Currently, society is witnessing a paradigm shift from the unsustainable linear economic model, which is predicated on a linear "extract, produce, use, and waste" scheme, to a circular economic model emphasizing "sustainable resources, products as services, sharing platforms, life extension, and new life cycles" (Postorino & Sarnè, 2023). This transition, encapsulated in the evolution from "owning a car" to "being mobile" (Enzi et al., 2021), constitutes a virtuous cycle with vast potential for growth, innovation, environmental stewardship, and employment generation (Stahel, 2016; Velte et al., 2018).

In a near future-oriented report, McKinsey delineates four shared-mobility modes: hailed mobility (encompassing future autonomous car sharing and robot-taxis); shared micromobility (encompassing electric kickscooters, bicycles, or other innovations for shared public use); car-sharing (encompassing both company-provided cars and P2P); and a novel segment encompassing flying electric vehicles (McKinsey, 2023).

As illustrated in Figure 2.10, the global shared mobility market in 2021 was valued at an estimated $251 billion, encompassing ride-hailing, car, and bike sharing across various vehicle types (Statista, 2021). This market is expected to increase by more than threefold, by 2030.

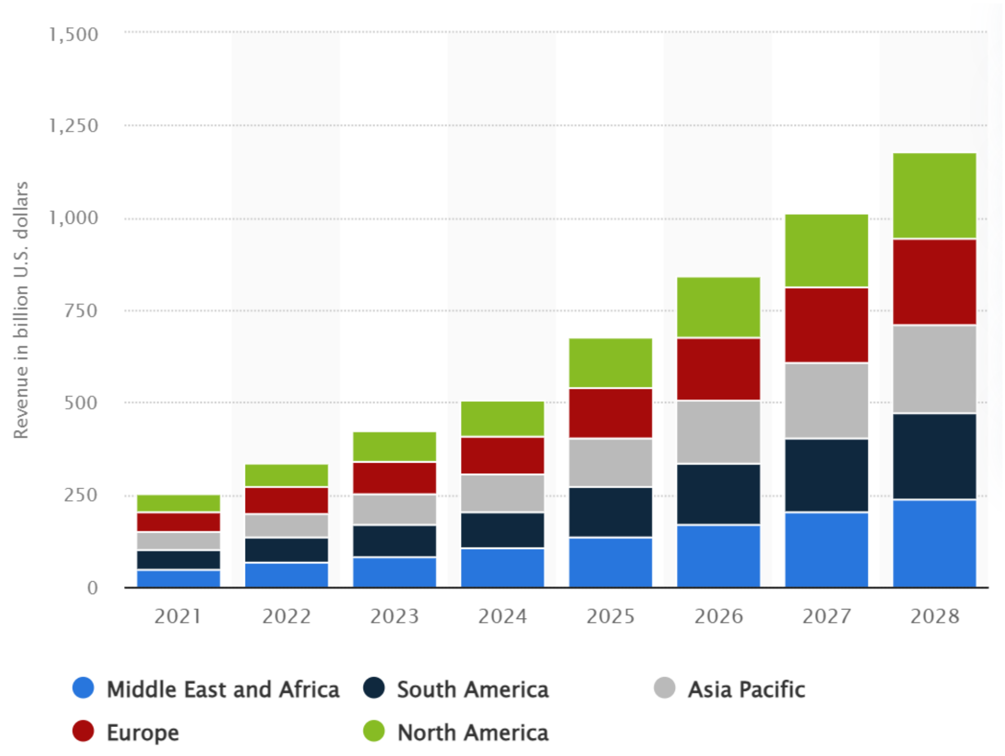


Figure 2.10 - Global shared mobility market size forecast from 2021 to 2028, by region (in billion U.S. dollars). *Source*: Statista (2021)[24]

The introduction of autonomous technology could profoundly reshape the market dynamics. With the potential to cannibalize private-vehicle use and offer a more cost-effective shared-mobility solution than current e-hailing services, revenue from robot-taxis or robot-shuttles could exceed $400 billion by 2030 (McKinsey, 2023). This forecast is contingent upon the evolution of associated regulations and technological advancements.

The general belief a decade ago was that AVs would be a regular sight on our roads between 2025 and 2030 (Langheim, 2014, Manyika et al., 2013, and Silberg and Wallace, 2012). However, this vision didn't entirely align with the sentiments of the experts in the field. A survey conducted in London showed that a mere 10% of the expert respondents believed that SAE level 5 AVs would be a common sight on London's streets by 2030; this percentage did increase to 30% when considering the possibility by the year 2040 (Begg, 2014).

While it remains unclear exactly when AVs will become a common feature on our roads, one aspect that is often overlooked is the importance of consumer adoption. Autonomous vehicles' success depends on initial adopters and widespread public trust, both developed over time. In

[24] https://www.statista.com/statistics/1229470/shared-mobility-market-size-worldwide-by-region/ , accessed in September 2023.

terms of overall market penetration, a global survey indicated that 69% of people believe that AVs will capture 50% of the market share by the year 2050 (Kyriakidis et al., 2015).

Meanwhile, the adoption of alternative work arrangements, such as remote or hybrid models, and the rise of 'satellite' workplaces - shared office spaces located closer to employees' homes - have substantially diminished commuting requirements. These changes not only shorten travel distances but also reduce frequency. A CISCO survey of 28,000 employees across 27 countries highlighted a significant preference for maintaining remote work arrangements (CISCO, 2022). Flextime users, particularly those who have core time, tend to use active modes of transport more frequently than their counterparts with rigid schedules, largely due to an increase in walking activities (Wohner, 2023). This behavioural shift carries significant potential for decarbonisation in the transportation sector (Karon & Tomanek, 2023).

Notwithstanding, the profound shifts catalysed by cybermobility carry their own economic and cultural challenges (*idem*). For instance, digital nomads relocating to the heart of foreign cities impact local demography and mobility patterns. However, counteracting factors, such as the pandemic, have suppressed (collective) transport usage, primarily due to imposed travel restrictions and modified activities (Karon & Tomanek, 2023). The change of trip types, such as increased pedestrian movement for local trips (*idem*), has presented experiential opportunities that may potentially reshape attitudes in the future. The effective encouragement of such practices can require suitable policy incentives and increased amenities (Lu et al., 2017). Yet, due to the inherent uncertainties of the near future, the precise impacts on cities and planning remain subjects of preliminary research (Guerra, 2016).

2.7.2 Shared Autonomous Vehicles

The advancement of full self-driving cars has generated interest in the shared autonomous vehicle (SAV) system. SAVs offer potential benefits such as reducing traffic (Martinez & Viegas, 2017), increasing road capacity (Olia et al., 2018), and alleviating parking pressure (Zhang & Guhathakurta, 2017), including the possibility of eliminating on-street parking altogether (OECD/ITF, 2015).

The potential traffic benefits stem from the vehicle replacement ratio, where an AV fleet could serve the trip demand with only 10% of the total number of conventional vehicles in the city (Boesch et al., 2016; Bischoff & Maciejewski, 2016). However, some studies suggest that even with this ratio, there may be an increase in vehicle kilometers traveled (VKT), up to 8% (Moreno et al., 2018) and potential congestion (OECD/ITF, 2015).

Research by Overtoom et al. (2020) examined mixed scenarios with both private AVs and SAVs, revealing the potential for high saturation levels on the road network, particularly due to passenger drop-off stops and empty kilometers. The presence of empty kilometers arises when vehicles park themselves in free spaces or roam around the city while waiting, especially if the cost of parking is higher than the operational cost (Millard-Ball, 2019). Removing parking areas, especially in city centers, can lead to more efficient utilization of urban space (Fayyaz et al., 2022).

The willingness to adopt SAV solutions varies among different groups, with young people and individuals with multimodal trip patterns being more likely to adopt them (Krueger et al., 2016). This can be attributed to the fact that individuals who regularly use different modes of transportation are more open to reassessing their mobility choices and exploring new options (Kuhnimhof et al., 2006; Krueger et al., 2016). Additionally, higher-educated and time-sensitive respondents have shown a greater preference towards automated car-sharing options (Winter et al., 2020) SAVs are expected to be relatively inexpensive and offer the opportunity for multitasking during a ride, appealing to individuals who value their time spent in transportation (Malokin, Circella, & Mokhtarian, 2015; Krueger et al., 2016; Milakis et al., 2017). SAV adopters are more likely to reside in dense urban areas, similar to car-sharing users (Bansal et al., 2016; Celsor & Millard-Ball, 2007). Car-sharing users also exhibit a higher preference towards SAV options with DRS (Krueger et al., 2016), indicating a relationship between multimodal trip patterns, car-sharing usage, and the willingness to adopt SAVs.

As expected, individuals who have held a driver's license for longer periods tend to express less interest in high-density and low-cost SAV services, as they prefer to drive and may be less familiar with the system (Bansal et al., 2016). "Car Captives", current car commuters who tend to be older and have lower levels of education, also show less interest in shared modes and are less likely to switch to SAVs (Haboucha et al., 2017; Winter et al., 2020).

Another noteworthy finding is that individuals who frequently act as passengers in cars tend to prefer SAV options with DRS, whereas public transport passengers are more inclined to adopt SAV options without DRS (Krueger et al., 2016). This suggests that individuals perceive SAVs with DRS as a distinct service and consider factors such as service configuration and price as decisive for their acceptance, particularly in a competitive market context (Krueger et al., 2016). While Fagnant and Kockelman (2016) highlighted the potential appeal of SAVs for the elderly due to the benefits of increased freedom, this aspect has not been confirmed by Krueger et al. (2016).

As the future unfolds, technology development promises new SAV business models, where P2P platforms may emerge as standalone business models or hybrid models that involve renting individually-owned vehicles on an as-needed basis to accommodate demand (Stocker & Shaheen, 2017).

2.8 Main conclusions

The decision to purchase a vehicle is influenced by many factors both rational and irrational (such as a perceived need, societal pressures, or peer pressure). This decision, much like deciding house location, has enduring consequences that shape subsequent choices. These choices can range from significant decisions, like where one's children will attend school, to daily transportation choices for work commutes.

In recent years (excluding the period of the pandemic), there's been no notable decline in car sales, indicating a persistent desire to own cars. The usage of private cars remains high, particularly in suburban regions. However, in urban centers, there are more transportation options available, and due to the close proximity of destinations, people often opt for more sustainable and active travel options.

With the increasing emphasis on sustainable development, there's been a focus on setting targets to lower harmful greenhouse gas emissions, which greatly impact the transport sector. Private vehicles are a significant contributor to these emissions. In response to this, various initiatives have been implemented in recent years to reduce carbon footprints, notably by promoting the sharing of rarely used assets like cars.

Services like ride-hailing or car-sharing have been emerging worldwide and have progressively captured a larger portion of the market. These share-based services have been enabled by technological advancements that allow users to reserve cars in real-time through their smartphones. Young urban dwellers, who typically own fewer cars, are the main users of these services. Car-sharing can be structured in two ways: B2C or P2P. In the P2P model, individuals offer their personal cars for communal use. Given that cars are typically unused 95% of the time, this approach allows for the better utilization of assets, a potential source of income, and a way to share with the community.

Additionally, technology has been advancing to support human driving, with hopes that it could eventually facilitate fully autonomous driving, corresponding to Level 5 of the SAE autonomy scale. At this level, the vehicle is fully in control, enabling passengers to use travel time for other activities. AVs are also expected to improve road safety by minimizing human error. However, achieving fully autonomous cars requires overcoming numerous technological, legal, ethical, and data security challenges. There's a portion of the population that is open to using, and potentially buying these vehicles, contingent on the selling price. The rate of adoption will be greatly influenced by early adopters and their feedback.

The introduction of vehicle automation can provide more flexibility to CS solutions, especially concerning pick-up and drop-off logistics, thereby making these solutions more appealing. The concept of SAV is widely recognized in academic literature as a potential direction for the future. However, as with traditional CS, two business models emerge for autonomous car sharing: B2C and P2P, depending on how car manufacturers will distribute these AVs.

The academia has been delving into the study of AMOD solutions, with 24/7 available shared fleets in a pure model of car sharing without ownership. However, the analysed trends and the prospects of the continued presence of private automobiles in the transportation system tend to ensure that P2P solutions may remain the most sustainable way to use cars, aligning with the decarbonization goals of transportation.

The P2P ACS solution has unique characteristics that set it apart from current solutions and the B2C ACS solution considered a pioneer in the future. The design of business and operational models will allow for the identification of essential elements for the solution to function, putting into perspective the factors that may compromise this solution´s success.

Chapter 3. P2P ACS: proposal of a mobility solution

3.1 Introduction

The previous section aimed to elucidate the transportation system, how it may evolve in the future, and how P2P ACS can emerge to fill a market niche. This section intends to analyse how the P2P ACS solution interacts with and complements the transportation system. Collectively, these chapters aim to contextualize the P2P ACS solution within the urban mobility system, providing an answer to the first research question.

The recent surge in transport sharing services, the absence of a decreasing trend in car ownership, and the uncertain future of mobility suggest the potential for a novel solution: P2P. This section introduces and explores the value of the P2P ACS solution. It includes the construction of a business model using the Canvas Business Model tool, a SWOT analysis, an examination of the solution's functionality, identification of key players, analysis of their decision impacts, and defining their interactions within the operation.

3.2 Concept, Product and Value proposition

P2P ACS is a new mobility solution that capitalizes on the idling time of AVs to satisfy urban mobility demands. For instance, a car used only for commuting would remain parked in the evening at the owner's home and during the day at their workplace. If a P2P ACS solution were implemented, the car owner could allow others to use the vehicle during these idling periods, earning financial rewards in return. Figure 3.1 illustrates a typical commute of a car within a P2P ACS solution.

Figure 3.1 – Example of a daily tour by a P2P ACS vehicle.

Assuming a work period from 9 a.m. to 6 p.m., the car would: (1) transport the owner to work, (2) carry a passenger from point A to B, (3) repeat the previous task with varying passengers and trips, and finally (4) pick up the owner and return home. The target population of this solution includes AV owners willing to rent out their cars during off-use hours, and passengers needing transport within the city.

The P2P ACS service bridges two user groups: AV owners willing to contribute their vehicles to a shared fleet, and individuals looking to use this fleet for their travel needs. The service's potential demand originates from maximizing the use of existing automated vehicles, seen as a path towards innovation, sustainability, and operational efficiency.

There has been a significant growth in local P2P car-sharing services in recent years, largely driven by a desire to share underutilized assets, particularly among younger population segments. A P2P ACS solution continues this sharing trend, further adding the appeal of high automation. Many view vehicle automation as a game-changer in mobility, positively affecting daily commutes[25].

This solution would compete with all mobility services, particularly with Autonomous Mobility on Demand (AMOD), a B2C service. Current urban mobility systems comprise various solutions: public transport like trains, buses or metros, active shared modes, flexible transport like cabs, on-demand buses, ride-sharing services like Uber, and car-sharing or car-pooling options. The coexistence of these services depends on their individual characteristics, target demographics, and geographical coverage. Each transport mode serves a different purpose, either alone or in combination with others, to ensure comprehensive passenger transport.

Differentiating factors of P2P ACS can be seen as the comfort and flexibility it offers passengers, the value provided to owners, and the system's sustainability. No single feature renders this solution unparalleled. Its value comes from comparison with other modes. For instance, it offers time and spatial flexibility compared to public transport, caters to longer distances than active modes, incorporates advanced technology and operational conditions compared to traditional cabs, and offers easy access compared to car-sharing.

The difference with AMOD is subtler. Factors such as price, access/provision, integration, operation constraints, external support or policies could influence a passenger's choice. The P2P ACS solution is primarily distinguished by the external benefits it presents: providing financial

[25] Online survey conducted by ASFA, in 2017, to around 10k individuals, in Europe (including Portugal): https://www.ipsos.com/sites/default/files/2017-05/European_Mobilities.pdf , accessed in September 2023.

incentives to the owner, utilizing existing resources, and potentially offering a more affordable option for passengers.

While the technology is still under development, current evidence supports the feasibility of such a solution: the paradigm shift in sharing and mobility behavior, continued relevance of car ownership, and promotion of sustainable development through transportation technology and policies.

In response to rising environmental concerns, society is aligning with the 3 R's policy (reduce, reuse, and recycle). Younger population segments, in particular, are prone to adjusting their use of various modes of transport to their needs (Krueger et al., 2016). When a car is necessary, they resort to car-sharing or ride-sharing solutions (Alyavina et al., 2020). This behavior has led to the rapid growth of these services across Europe. City dwellers often don't need to own a car due to the availability of public transport and other sharing mobility solutions.

The evolution of technology has also played a significant role in this behavioral shift. Applications that provide instant access to vehicles, and the increasingly integrated transport modes resulting in Mobility as a Service (MaaS) solutions, reduce the perceived need for car ownership.

Despite these changes, not everyone will give up car ownership, as demonstrated in section 2.3 'Private vehicles'. Car sales remain resilient[12] despite economic and social uncertainties, with cars being perceived as essential for daily tasks (Lucas, 2019; O'Riordan et al., 2022). Major cities continue to grapple with congestion, especially in cases where urban layouts lack density and limited urban transit options promote the use of private vehicles (Kenworthy & Laube, 1996).

3.3 Business model

Several business models frameworks have been proposed, for instance, the Business Model Canvas (BMC) by Osterwalder & Pigneur (2010), Johnson et al. (2008)'s Four Box Business Model, Bouwman et al. (2008)'s STOF model, and Weill & Vitale (2001)'s Business Model Schematics. The BMC stands out as a particularly well-recognized and established tool for articulating, deliberating, and crafting business models, as highlighted by Plenter et al. (2017). It is used for scrutinizing prevailing business strategies, steering strategic choices, and effectively conveying a business proposition to potential investors, as emphasized by Burkhart et al. (2011). At its core, a business model delineates the logic behind an organization's ability to generate, offer, and seize value (Osterwalder & Pigneur, 2010).

Diving deeper into the BMC as conceptualized by Osterwalder & Pigneur (2010), it focuses on nine pivotal elements that shape any business model: key partnerships, key activities, key resources, value propositions, customer relationships, channels, customer segments, cost structure, and revenue streams. Table 3.1 provides a detailed depiction of the BMC tailored to the mobility solution central to this thesis: P2P ACS. The following paragraphs justify the contents of each element.

Value propositions

The value proposition of a business aims to address a customer's challenge or meet their need in a manner distinct from competing offerings (Taipale-Erävala, 2021). For the consumer, the rivals of the P2P ACS solution encompass all mobility solutions facilitating transportation between destinations. This category includes public transport, active modes, ride-hailing, car-sharing, private vehicles, and AMOD solutions. The P2P ACS does not boast a solitary unique feature distinguishing it from other mobility options; rather, its strength is derived from the merger of its components. Figure 3.2 illustrates the key components of P2P ACS – autonomous, car-sharing, and peer-to-peer – each associated with specific attributes. One way to interpret this figure and understand what sets P2P ACS apart from other mobility solutions is to identify what is missing in each alternative. For instance, P2P CS lacks the “autonomous” feature, which means door-to-door travel without a driver and no parking concerns. An AV, on the other hand, is missing the "car-sharing" aspect, which suggests that the car won't be shared while parked, overlooking the sharing trend that has been evolving over recent years leading to sustainability, potentially.

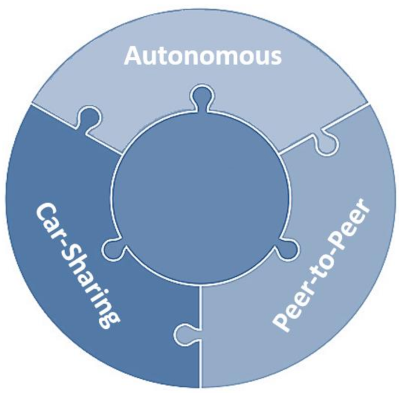


Figure 3.2 – Main features of the P2P ACS solution.

Table 3.1 - The business model canvas for a P2P ACS solution.

<table>
<tr>
<td rowspan="2">Key partnerships
City council / Local government
Investors & shareholders
Partners:
Businesses to promote P2P ACS
Car manufacturer (to encourage Clients to join as peer-providers)
Service providers:
Insurance company
Payment processors
Mapping data company
Roadside assistance
Academic researchers
Early adopters</td>
<td>Key activities
Basic services (e.g. overseeing disputes, document provision for members)
Service provision (e.g. insurance, unlocking cars remotely)
Platform management and maintenance
Contracts and payments
Balanced supply and demand (marketing and customer service)
Developing innovative projects</td>
<td rowspan="2">Value propositions
Core interaction:
Passengers satisfy their trip needs with private unused AV
For owners:
Car owners can earn money when not using cars
Convenience – easy to rent a car, flexible scheduling
For passengers:
Flexibility - Door2door service with no driver
Convenience – easy to order a car, keyless entry and cash free
For all:
Two-sided market (share, connect)
Reduced parking costs and space</td>
<td>Costumer relationships
Dedicated costumer service team
Self service
Rating and feedback system
Follow up on all costumers´ reports
Help center
Social networks</td>
<td rowspan="2">Costumer segments
Peer-provider (AV owners):
AV owners that like an extra income
Socially-minded & eco-conscious AV owners
Peer-consumer (passengers):
Passengers taking trips within the city
On-the-go young adults who can book last minute
Car enthusiastic who also like tech and autonomy
Smartphone users
Multimodal individuals that value in-vehicle time</td>
</tr>
<tr>
<td>Key resources
Different cars in the fleet (from owners)
Platform (real-time)/ network
Customers (members)
Insurance coverage
Human resources (engineers, analysts, marketeers, etc.)
Passenger feedback board</td>
<td>Channels
Website
Social networks and social media
Mobile app
Word of mouth</td>
</tr>
<tr>
<td colspan="2">Cost structure
Personnel costs (e.g. office, amenities, pay check)
Service providers costs (e.g. insurance contracts)
IT platform & Data connectivity, security, and privacy related costs
Marketing activities
Legal related-costs and Taxes
AV owners</td>
<td colspan="3">Revenue streams
Subscription fee (for all costumers)
Commission on rental transaction
Passengers pay by distance (per km) and time travelled (hourly, daily, weekly)
Passengers pay additional taxes for premium brands and high demand rates
Rule-breaking charges</td>
</tr>
</table>

Associated with these primary features are other nuanced distinctions that are crucial for differentiating the P2P ACS from other mobility solutions. Upon deeper examination, these differences and their business implications for all stakeholders become clear. The B2C solution (AMOD) is perhaps the most significant competitor in this space, but it doesn't incorporate the peer-to-peer element. The P2P CS business model, like other Sharing-Economy (SE) ventures, utilizes high-cost existing assets that owners use infrequently (Puschmann & Alt, 2016). It's more cost-effective than B2C CS because it avoids up-front expenses for new cars and their maintenance (Dill et al., 2017) and remains adaptable to market fluctuations (Wilhelms et al., 2017). Additionally, strategic decisions by B2C firms not to operate in low-profit or loss-yielding locations (Dill et al., 2017), combined with the fact that P2P CS requires fewer users per shared car than B2C CS (Wilhelms et al., 2017), means it's not restricted to major urban settings, making it more scalable (Hampshire and Gaites, 2011; Meelen et al., 2019). For vehicle owners and service providers, P2P's scalability surpasses B2C car-sharing's geographical limits, as it isn't tied to population density (Dill et al., 2019).

As for traditional taxi services and Transport Network Companies (TNC) like Uber[26] and Lyft[27], the absence of the "autonomous" element is apparent. Here, SAV can potentially outperform traditional taxis, as they can potentially provide a more system-optimal and profit-maximizing network, offering superior service quality at reduced empty travel costs (Fagnant et al., 2015). The technology that automates the vehicle removes the driver from the equation and integrates connectivity and data analytics, paving the way for more informed decisions that boost the business.

Promoting the widespread use of transit is a priority for mobility planners. Shared autonomous technologies can significantly bolster the alignment between automobiles and rapid transit (Ohnemus & Perl, 2016) and considerably enhance the appeal of SAVs by expanding the potential user base (Tart et al., 2018). Utilizing SAV fleets or even private AVs for last-mile solutions to access transit stations can eliminate secondary or tertiary time-consuming transportation transfers, which reduces the efficiency of combined public transportation modes. These synergies are extended in a Mobility as a Service (MaaS) paradigm. MaaS is seen as an enhancement for those already utilizing public transport. Integrating SAV solutions in routing and payment routines during the last mile can elevate flexibility and comfort levels during commutes (Liljamo et al., 2020). However, not everyone might perceive it as advantageous, particularly families with multiple vehicles. Those households with several cars tend to show less

[26] https://www.uber.com/pt/en/ , accessed in September 2023.
[27] https://www.lyft.com/ , accessed in September 2023.

interest in MaaS compared to those with a single vehicle or none at all. This indicates that MaaS doesn't necessarily replace a car in such families, implying a reluctance to abandon personal vehicle ownership for MaaS benefits (Millonig & Haustein, 2020).

Comparing P2P ACS with other mobility solutions is challenged by the uncertainty of the future; that is, it's impossible to anticipate every mobility solution at the time of implementing a P2P ACS. However, it can be projected that many of today's solutions might benefit from automation, such as public transport, or that new solutions like B2C ACS might emerge. From this standpoint, one can list a set of features that distinguish P2P ACS from other offerings (see Table 3.2). For instance, while buses are trending towards becoming flexible in terms of time and location, and may eventually operate without a driver, thereby offering more competitive prices, they won't still guarantee a private ride if the passenger desires such privacy.

Table 3.2 - Comparison of characteristics of different mobility solutions.

Solution / Feature	**P2P ACS**	B2C ACS	P2P Car-sharing	Ride-hailing	Sharing active modes	Bus
Alone or in group	**Both**	Both	Both	Both (plus the driver)	Just alone	Just in group
Door2door	**Yes**	Yes	Not in the origin	Yes	Not in the origin	No
Need to drive	**No**	No	Yes	No	Yes	No
Costumers	**Passengers and owners**	Passengers	Passengers and owners	Passengers	Passengers	Passengers
Use existing assets	**Yes**	No	Yes	No	No	No

(Solutions whose features differ from P2P ACS appear shaded)

The business model for P2P ACS should not only delineate how this solution stands apart from other mobility solutions but also spotlight its distinctions within similar services, as further explained in Tart et al. (2018). Within the P2P CS sector, several organizations have carved out niches for themselves. For example, Dégage[28] provides an insurance certification acknowledging accident-free driving upon an individual's exit from the organization. Conversely, Drivy, acquired in 2019 by Getaround[29], emphasizes the onboarding process by offering training to its new members, thus eliminating the requirement for an initial deposit. Furthermore, CarAmigo[30] differentiates itself by ensuring that income generated from its car rentals remains non-taxable.

[28] https://www.degage.be/degage-gefilmd/ , accessed in September 2023.
[29] https://uk.getaround.com/ , accessed in September 2023.
[30] https://location-voiture-caramigo.com/pt/ , accessed in September 2023.

Diverse car-sharing entities have also ventured into providing specialized incentives aimed at enhancing competitive distinction. To illustrate, DriveNow, a B2C entity that in 2019 merged with car2go to form Share Now[31], incentivizes its clientele with bonus minutes for the act of charging its electric vehicles, a benefit which it generously extends to non-EV drivers, rewarding them for refueling actions. In a similar vein, Partago[32], another B2C firm, proposes reduced tariffs for nighttime driving and even compensates users for early returns.

The presented Canvas business model does not highlight the nuanced differences between P2P ACS solutions. This is primarily because many of these distinguishing advantages come from negotiated concessions with stakeholders or key partners, making them unique. For instance, Io Guido[33] (B2C) offers driving privileges, such as exemptions from specific payment zones and the ability to navigate yellow lanes, all supported by significant national endorsements (Tart et al., 2018).

The value proposition underscores the definitive benefits this solution offers to customers, capturing the core interests of all involved: allowing passengers to address their mobility needs with a car that would otherwise remain idle, thus maximizing the use of precious urban space. Moreover, the model presents an array of value propositions, like convenience or flexibility, tailored for specific segments. For instance, a primary incentive for vehicle owners might be monetization, yet the simplicity of the platform plays a pivotal role – a convoluted system would undoubtedly challenge their commitment. The Canvas model further highlights broader benefits applicable to all users, such as the prevalent parking dilemma. This scenario underscores that an AV owner isn't burdened with the hassles of locating or paying for parking spaces, nor do they expend energy returning the vehicle home. Similarly, passengers avoid the burden of parking upon arrival. From a societal vantage point, this translates to a repurposing of urban space, as the demand for parking diminishes, paving the way for other public engagements.

Key partnerships

For a business to thrive, it must promote meaningful connections and collaborations with suppliers and partners. Such partnerships are pivotal for securing resources, mitigating risks, and refining both business models and operations (Taipale-Erävala, 2021). While P2P ACS is unlikely to dominate as the primary mode of transport for many, it represents a valuable addition to an expanding arsenal of transportation options, reminiscent of the current role of car-sharing

[31] https://www.share-now.com/ , accessed in September 2023.
[32] https://www.partago.be/ , accessed in September 2023.
[33] https://www.facebook.com/io.guido.car.sharing/ , accessed in September 2023.

(Munzen et al, 2019). Hence, P2P ACS enterprises should collaborate with other stakeholders to bolster its prominence as a crucial mobility solution.

The successful roll-out of SAVs requires substantial government engagement, particularly concerning regulations and infrastructure (Chen et al., 2021). Local administrations play a pivotal role in mobility planning. Partnering with local governments can be mutually beneficial - sidestepping potential legal obstacles and jointly analyzing urban mobility needs. With the advent of Mobility as a Service (MaaS) platforms, municipal authorities can fund regional platforms to promote and reserve not only public transit but also P2P ACS services. This boosts the visibility of such shared mobility solutions, echoing the suggestions by Shaheen et al. (2020) for car-sharing. The fusion of digital payment systems allows P2P ACS users to seamlessly utilize metro and bus cards, ensuring these solutions complement or even merge with public transport. Collaborations with public transport providers within a MaaS framework will undeniably influence the business model canvas, necessitating the inclusion of 'public transport authority' and 'mobility service providers' as key partners, and emphasizing 'adapt API' as a pivotal company activity.

A burgeoning trend within the industry leans towards granting access to assets instead of traditional ownership transfers. This evolution poses challenges for entrenched firms. Yet, intriguingly, research has spotlighted intricate dynamics where Original Equipment Manufacturers (OEM) and B2C companies may stand to gain by facilitating P2P rentals across various situations. Ford's encouragement for new car owners to enlist with CarAmigo, a P2P car sharing firm, exemplifies this strategy (Tart et al., 2018).

A study by Tang (2022), utilizing data from GoFun[34] (a B2C car rental platform that integrated P2P sharing), compared profitability impacts on both the platform and the OEM. The results suggested that while the P2P introduction often augments the B2C platform's success, it could occasionally be detrimental for the OEM. Factors like high consumer usage and distinct product quality variances can reduce OEM profitability. Conversely, when the market is characterized by low usage and heightened product competition, P2P sharing can bolster consumer rental experiences, driving up OEM product demand and profitability.

Further research by Abhishek et al. (2021) analyzed the interplay between P2P rental markets and OEMs. Their findings spotlighted the pivotal role of consumer usage rate heterogeneity in

[34] https://www.gofungroup.com.my/mobile/home , accessed in September 2023.

influencing market outcomes. If these rates and heterogeneity are significantly pronounced, OEMs stand to benefit from both facilitating sales and endorsing a P2P rental ecosystem.

Other indispensable partners for this business sphere include service providers overseeing various operational aspects. Features like real-time mapping for wait-time visualization greatly influence mobility choices. Seamless mobile payments are now fundamental for user experience. Most B2C and P2P CS companies offer insurance, as indicated by Tart et al. (2018). And with vehicles evolving into 'computers on wheels', road-side assistance must be equipped to address novel challenges with innovative solutions.

In conclusion, academic researchers hold immense significance. For P2P ACS solutions to retain relevance within the mobility ecosystem, continuous innovation is essential. Engaging early adopters could very well determine the trajectory of such businesses, be it their meteoric rise or untimely decline.

Revenue streams

The 'Revenue Streams' block represents the money a company earns from each of its customer segments. Here, we have two customer segments: the peer-providers (or AV owners) and the peer-consumers (or passengers). This structure, with its two customer groups, is known as a two-sided market business. A positive correlation arises when an increase in one user group boosts the other group's numbers, leading to a better match. Conversely, a negative effect emerges if demand and supply are mismatched, or if user heterogeneity complicates matching, which may lead people to reduce or discontinue platform use (Parker et al., 2016).

Central to a two-sided market business is the platform. Hafermalz et al. (2016) outline three ways a platform can support sharing:

- A meeting space, facilitating communication between members who decide on transactions (like couchsurfing).
- A marketplace, where the platform intermediates transactions between peer-providers and peer-users (like Airbnb).
- A matchmaker, actively pairing supply and demand based on specific criteria (like Uber).

Platforms, typically web-oriented, reach broad audiences and offer enhanced features. They act as trusted intermediaries, providing comprehensive insurance that protects both vehicle owners and renters during mishaps (Rotaris, 2022). This insurance is automatically activated when a user begins driving and remains effective until the car's return (Karla Münzel et al., 2020).

Potential business models for a P2P ACS service include the C2C (consumer-to-consumer) and C2B2C (between peer-consumer and peer-provider via the platform or a linked service provider).

In the C2B2C model, consumers access a platform to request services; the request gets processed, and the service/product is dispatched. If the platform operates for profit, the payment process typically facilitates the deduction of transaction fees (Plenter et al., 2017). In most cases, a third-party P2P company oversees vehicle sharing and retains a portion of the earnings (Shaheen, 2019). For instance, Drivy car owners retain 80% of the rental fee, while Drivy takes 13% and Allianz receives 7% for insurance (Tart et al., 2018). Similarly, approximately 35% of car-sharing fees go to CarAmigo (*idem*).

In the C2C model, peer-consumers access the platform to purchase services, while peer-providers access it to sell services. Service and money exchanges occur directly between these parties. Here, the vehicle owner can set the service price. BlaBlaCar exemplifies this model, where drivers determine trip costs, split among agreeing passengers (Tart et al., 2018).

Figure 3.3 details these business models and inter-agent relations. Both models employ direct channels, excluding intermediaries from the overarching system.

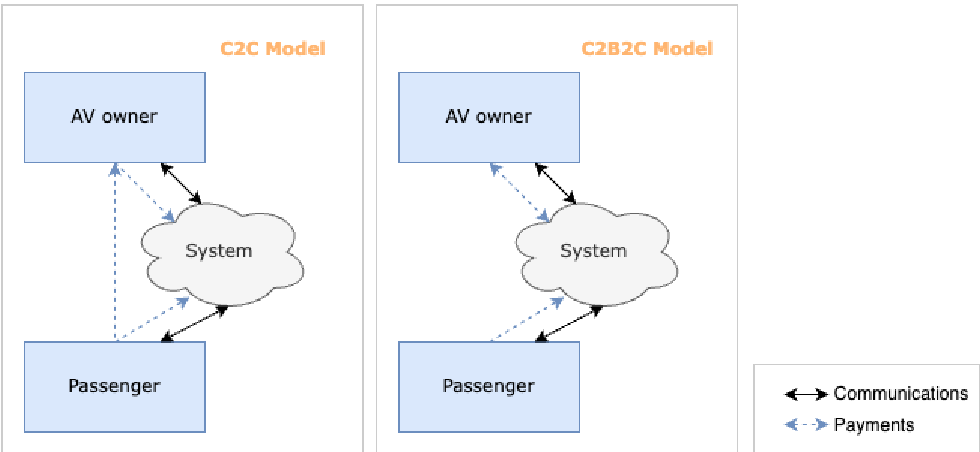


Figure 3.3 – Plausible business models for P2P ACS solution (C2C and C2B2C).

A primary model distinction is risk transfer to the system. Upfront payments to vehicle owners are system expenses. This approach (in the C2B2C model) might appeal to vehicle owners as it omits usage from the equation. However, they might receive lower hourly rates, which will be fixed between the owner's minimum accepted rate and the system's maximum affordable rate while maintaining acceptable risk. The second significant difference is that the system must anticipate the service level to set hourly rates for the owner. If a model for dynamic hourly rate calculation exists, this issue is debatable; otherwise, it's crucial.

Monetary transactions can follow two paths: (a) payment for usage, or (b) payment for service. Various methods can be adopted within each category. Most car-sharing organizations charge per kilometer or a set distance; some charge after surpassing a limit, while others charge based on distance and time (Tart et al., 2018).

Car-sharing solutions often require memberships with subscription and deposit fees. For instance, Dégage charges members a subscription fee of €35 with a refundable €75 deposit, whereas CarAmigo requires a €500 deposit (Tart et al., 2018).

Companies may impose additional fees on passengers. Uber employs dynamic pricing, adjusting prices with demand. Car2go and Zipcar[35] levy extra fees for airport rides and rule-breaking, respectively (Tart et al., 2018). Taxi drivers in Portugal have added charges for luggage or inter-municipality trips. Platforms can also earn indirectly through advertisements, customer data, or both (Plenter et al., 2017).

Business profitability and efficiency depend on technology, location, vehicle types, and ownership schemes (Chen et al., 2021). Pricing and fee structures will be critical in the market, although forecasting with emerging technology can be challenging. Bösch et al. (2018) showed that AV technology reduces operational costs, even if it increases AV purchase prices. Yet, CS's increased vehicle usage can heighten maintenance costs while somewhat alleviating financial burdens (Chen et al., 2021).

The literature provides a range of pricing for AMOD solutions. For instance, rates as low as €0.25-€0.27/km are suggested by Dandl et al. (2019) and \$0.19-\$0.32/mile according to Stephens (2016). On the higher end, prices can reach \$1.42-\$2.24/mile as indicated by Nunes et al. (2021), factoring in externalities costs and group effects. Additionally, Wadud (2017) posits that AMOD solutions are approximately 30% less expensive than conventional taxis.

Key activities

The activities within BMC are pervasive across most shared mobility companies. Unsurprisingly, activities such as the development and maintenance of the platform, contract management, and payment processing are present. More specific tasks related to shared solutions concern the need for document verification of new members during registration. This is already a standard

[35] https://www.zipcar.com/ , accessed in September 2023.

procedure in many shared mobility solutions. For instance, Uber screens its users against certain quality criteria; meaning, peer-providers' cars must meet specified standards to be eligible to participate in the Uber platform (Plenter et al., 2017).

There are also questions about how to grant access to vehicles or ensure that insurance adequately covers trips during operations. Furthermore, there's the essential aspect of business expansion, whether concerning passengers or vehicle owners, to ensure a balanced supply-demand relationship and the sustainable development of the solution.

Certain activities are unique to each business. For instance, Drivy, a P2P car-sharing company, requires the installation of a box in fleet cars to ensure a GPS connection (Tart et al., 2018). However, it's challenging to pinpoint such specific needs in advance for a future solution. These needs fall under the activity titled "Developing innovative projects", aiming to address technological advancements and even changes in company factors.

In the context of management decisions, such as MaaS (Mobility as a Service) integration, additional activities may arise, such as the need to provide data to authorities or update centralized information platforms (API) (Polydoropoulou et al., 2020). When it comes to technological developments, the widespread adoption of IoT (Internet of Things) can help in broadcasting hazardous situations identified by a vehicle in transit, thereby preventing potential accidents. This contributes to the safety of everyone on public roads, including pedestrians (Chen et al., 2021).

Key resources

The primary resources crucial for the success of this business model are the vehicles, the platform, and the passengers. P2P models offer some advantages over B2C models, particularly due to the diversity of available cars. For instances, it is crucial that a fleet encompasses wheelchair-accessible, premium, and electric vehicles for achieving success.

The platform stands out as the central resource since it bridges the other two key resources. If a company owns a platform, it can monetize it; however, this comes with associated costs and requires significant manpower (Tart et al., 2018). This manpower is vital for ensuring the company's smooth operation, establishing its presence in the market, and building relationships with both new and existing customers. A feedback system is critically important to instill trust, given that this business fundamentally relies on trust between the parties - a trust that's challenging to establish and maintain.

There are additional resources that, while not essential, can substantially assist a company's growth. For example, Autolib, a B2C car-sharing company, boasts a fully electric fleet and has strategically positioned charging stations near metro stops and major commercial and residential areas (Tart et al., 2018). While this setup may entail costs for the company, it enhances brand visibility and offers drivers the convenience of easily accessing vehicles throughout the city.

Cost structure

The fundamental distinction between P2P (Peer-to-Peer) and B2C (Business-to-Consumer) resides in their implementation structure. B2C companies bear the burden of initial investments, such as purchasing new vehicles, and are also responsible for ongoing maintenance costs (Dill et al., 2017). The rest is similar. Although a core team is necessary to ensure the delivery of essential services within the company, a lean staff can manage primary operations, while external providers can take on ancillary tasks under an outsourcing arrangement. Refueling or recharging is typically a requirement for clients renting a car (Dill et al., 2017; Tart et al., 2018), and taxes are applied to those who do not adhere to the rules.

Beyond human resources and outsourcing, certain departments incur expenditures in areas like marketing campaigns, platform development (encompassing cloud services, data management, APIs, *etc.*), and legal fees. These legal expenses might arise from litigation or regulatory requirements, as well as from taxes associated with licensing or revenue processing.

Costumer segments

Customer segments delineate the distinct groups a business seeks to engage and serve (Taipale-Erävala, 2021). In a dual-market structure, there exist two primary customer segments. On one end, we find peer-providers - those offering their private AV for rental - and on the other, individuals using these vehicles to travel.

This segmentation stems from an in-depth literature analysis detailing the characteristics of current P2P Car-sharing owners and users (as elaborated in section 2.5.2 ‘Peer-to-peer car-sharing’).

For car owners, participation primarily requires ownership of a vehicle. An additional motivating factor is the monetary gain, which can potentially offset their vehicle's maintenance costs (as shown in the section 5.3 ‘Results’). Many appreciate the opportunity to serve their community by providing mobility through an asset that otherwise remains idle.

Given the anticipated higher costs of AVs compared to traditional ones, concerns arise. At a cursory glance, one might assume that only the affluent can afford such vehicles, contradicting the primary motivation for many—earning supplemental income. However, a nuanced view suggests otherwise. For instance, despite their existence for several years, electric vehicles only recently began to solidify their market position. While electric cars are pricier than their traditional counterparts, a significant 8% of new car sales in Portugal are fully electric (as detailed in section 2.3 ‘Private vehicles’). As sustainability becomes increasingly pivotal and rapid technological advancements democratize access, more individuals can now afford these vehicles.

Another aspect to consider is the potential blur between private owners and businesses in the P2P sector. While certain providers, like Uber drivers, increasingly adopt business-like operations, traditional businesses, having witnessed Airbnb's success, are also exploring P2P platforms to attract clientele. This blurring of lines, seen as businesses present themselves as peer-providers, stirs legal and societal debates surrounding P2P services.

On the peer-consumer end, the demographic encompasses anyone needing transportation. AVs are touted for their inclusivity, potentially serving the disabled, elderly, or those temporarily incapacitated (like inebriated individuals). However, technological adaptability can be a hindrance for some. Access to the platform necessitates a smartphone, leading to potential disparities, especially for those without mobile phones or digital access (Shaheen et al., 2017). Moreover, many have doubts about AV safety (Seapine Software, 2014; Bansal et al., 2016).

A notable advantage of P2P systems over B2C models is their scalability beyond urban areas, as P2P Car-sharing requires fewer users per car to be profitable than B2C variants (Wilhelms et al., 2017). Yet, most car-sharing services predominantly focus on urban areas with a high user density. These regions typically comprise younger, multi-modal individuals who value their in-transit time (refer to section 2.7.2 ‘Shared Autonomous Vehicles’).

Although many P2P Car-sharing solutions primarily target local commuters, some mobility services, like Uber or BlaBlaCar -and even global franchises like McDonald's - also view tourists as a key segment due to their widespread presence and brand familiarity. As businesses aim for broader expansion horizons, this consideration becomes crucial.

Costumer relationships

Customer relationships pertain to the types of interactions businesses recognize as necessary with specific customer segments to bolster sales and retain clientele. Within the realm of P2P CS business models, and by extension, other Sharing-Economy businesses that facilitate the renting of assets, achieving a critical mass is essential. Puschmann & Alt (2016) posit that to be self-sustainable, these models require an ample convergence of resources and users. This notion of sustainability is echoed by Wilhelms et al. (2017), who underscore that insufficient participation from asset owners can hamper the growth potential of such platforms.

Keeping customers satisfied involves having a dedicated team ready to address all queries throughout the process and resolve daily challenges. Maintaining a content customer base can be leveraged on social media as a promotional strategy to attract new clients and expand the business.

Yet, it is not just about sheer numbers. The P2P ACS team should place a premium on cultivating public trust. Emphasized by both Puschmann & Alt (2016) and Gao et al. (2017), the cornerstone of such models is fostering a pervasive trust atmosphere. For instance, Plenter et al. (2017) shed light on the importance of trust majority tools that provide transparent insights, allowing individuals to gauge the consensus of the majority. This engenders an environment where a Reputation System (RSy) can flourish, serving as a tool that both bolsters trust and provides insights into an individual's standing in the eyes of their peers (Wu et al., 2016). Corroborating this, Postorino & Sarnè (2023) conducted an experiment within a P2P CS framework, unveiling that a well-executed RS can incentivize honesty and deter malicious intent, thus championing this mobility model.

Other proposed models highlight user engagement, often realized through ratings (Keymolen, 2013), endorsements (Lauterbach et al., 2009), or referrals (Jøsang et al., 2007). Plenter et al. (2017) assert that owners often lean towards transacting with familiar or similarly aligned individuals, creating trust through relatability, or finding an 'alter ego'. In scenarios like rural or less densely populated regions, Rotaris (2022) suggests that P2P services might naturally mitigate the unease associated with engaging strangers, given the heightened likelihood of community familiarity.

The Canvas illustrates that the business model for P2P ACS should incorporate feedback and rating systems. It's imperative to offer personalized responses to any comments or concerns that arise during operations to bolster trust. To foster more enduring connections among participants in this solution, additional promotional strategies can be employed, such as building communities, loyalty programs, or co-creation initiatives like 'living labs' (Polydoropoulou et al., 2020).

Channels

Companies utilize various channels to communicate their value propositions to customers. These channels are essential, as they allow customers to familiarize themselves with the company's offerings and gauge the value they provide (Taipale-Erävala, 2021). In today's digital age, platforms like websites and social media are primary avenues for promotion, especially for tech-savvy businesses. Collaborations with other enterprises, such as hotels, airlines, local community groups, or third-party retailers, can further amplify this online footprint (Polydoropoulou et al., 2020).

Peer influence plays a pivotal role in modern marketing strategies. Positive testimonials from satisfied customers can be an incredibly potent tool for brand endorsement. With the rise of 'influencer' as a legitimate profession, it underscores the profound market impact such individuals wield. Beyond leveraging external influencers, the company itself should actively shape market perceptions through conferences, workshops, and information sessions.

Mobile applications serve as a primary conduit between businesses and their clientele in the digital age. Given that it's the primary touchpoint for customers seeking services, it's crucial to ensure regular updates, timely communication, and user-friendly interfaces.

While call centers remain relevant in many industries, their necessity is debatable in the realm of on-demand, online-exclusive shared mobility solutions. As technology continues to evolve and big tech companies shift towards automated and digital-first customer service solutions, the traditional call center's relevance might diminish.

New Canvas

The business model illustrated in Table 3.1 adheres to the framework proposed by Osterwalder and Pigneur (2010). One of the primary reasons for the popularity and success of the Business Model Canvas (BMC) is its simplicity and its near-universal applicability to a diverse range of business models (Plenter et al., 2017). However, it falls short when it comes to innovating business models for digital platforms operating within a two-sided market, as crucial factors remain inadequately addressed (Scholten, 2016; Plenter et al., 2017; Taipale-Erävala et al., 2021).

To counter this limitation, Scholten (2016) introduced a revised canvas. Notable amendments include the bifurcation of segments into customer and producer categories and the tailoring of attributes such as journey, channels, price, and value proposition for each segment. Central to this model is the core interaction, which should be streamlined, appealing, and value-driven for users. Surrounding this core are the partners, filters, rules, and tools and services that bolster a productive core interaction.

Plenter et al. (2017) unveiled an alternative canvas, adjusting both its structure (with the addition, editing, or removal of elements) and content (enhancing instructions, information, or integrating tools and methods), yet preserving much of the original canvas's architecture. Echoing Scholten (2016), they advocate for a distinct segmentation for users and providers while replicating adjacent features such as value proposition, relationships, and channels. Moreover, Plenter et al. (2017) introduce an additional layer for providers by weaving in the peer-provider's value proposition, supplemented by new elements like complementary activities, complementary resources, provider-user relationships, and provider-user channels.

However, both the original canvas by Osterwalder and Pigneur and Scholten's adaptation neglect the broader business environment, a vital determinant for platform businesses (Taipale-Erävala et al., 2021). Coes (2014) also critiques the original BMC for omitting competition and its inability to assess how businesses cater to customer needs. Addressing these gaps, Taipale-Erävala et al. (2021) recommended the incorporation of elements like network effect tactics, value units, and outsourced resources adjacent to the core.

While the model showcased draws primarily from Osterwalder and Pigneur's (2010) proposal, many of the suggested attributes and modifications have been integrated into the business model's construction. Features such as segmentation by peer-provider and peer-consumer, or the value proposition centered around core interaction, adhere to this unconventional approach not evident in Tart et al. (2018). Many added characteristics, including filters, tools, network effect tactics, or outsourced resources, are discussed throughout the text.

3.4 SWOT analysis

The SWOT framework, which looks at Strengths, Weaknesses, Opportunities, and Threats, is a key strategy tool used worldwide (Puyt et al., 2023). This method started with a group from the Stanford Research Institute in California, led by Robert Franklin Stewart. They first called it the

SOFT method because it focused on good results (satisfactory), chances to grow (opportunities), problems (faults), and possible risks (threats) (*idem*).

The SWOT framework provides insights into an entity's internal capabilities (strengths and weaknesses) and external scenarios (opportunities and threats), guiding robust decision-making processes (Kotler et al., 2018). Emphasizing both assets and challenges, the SWOT analysis delivers a holistic view instrumental in shaping strategies (Helms & Nixon, 2010). A detailed SWOT evaluation of the P2P ACS solution is presented in Table 3.3. The "+" (or a more emphasized "+++") rating was used to gauge the impact of a given strength, weakness, opportunity, or threat. For instance, if a strength lets the sector leverage or mitigate issues from environmental shifts, or if a vulnerability is balanced out by such changes, then the strength is assigned a higher weight, as suggested by Ramos et al. (2000).

Over the years, the SWOT framework has faced numerous criticisms, including the intricate interactions of its factors (Weihrich, 1982), the overwhelming list length, the absence of priority or weight assignments, and the lack of data verification for claims (Hill and Westbrook, 1997). Furthermore, there's criticism about the description of effects rather than the underlying causes when assessing weaknesses (Hussey, 2002), among others. Despite various attempts to modify, improve or integrate it with other methods, original SWOT analysis remains a pivotal strategy due to its simplicity. It seeks to strike a balance between the external challenges and opportunities a company confronts and its inherent strengths and weaknesses (Andrews, 1971), leading the company to success.

The SWOT analysis presented here aims to provide a clear picture of the key elements to consider, serving as a foundation from which a strategic plan for business development can be crafted. The analysis attempts to focus on the P2P ACS solution, while sidestepping challenges associated with AVs, even if some aspects might overlap. For instance, an AV might encounter data processing issues. While this could be seen as a weakness during the AV deployment, it is not truly pivotal to the success of the P2P ACS solution, as it is assumed that such a challenge was overcome earlier in time. Or even the motion sickness that was recently overcome with the latest version of Google's glasses. However, the acceptance and widespread adoption are common points between the implementation of AVs and the P2P ACS solution, even if their primary focus differs.

Table 3.3 – SWOT analysis for P2P ACS solution.

Strengths	**Weaknesses**
Flexible and convenient for customers. + AV owners can earn revenue. ++ Relatively low set-up costs and low investment growth strategy. +++ Can build a presence incrementally with a small fleet and area. + Can serve closed markets (local brands). + Operation area can be sparse. + Suitable for first/last mile in dense urban areas. ++ Potential for a great variety of vehicles on offer. +++ Suited for EV. + Visibility (from tech and share) in marketing sense. ++ Platform (central) can easily manage the fleet. +	Parking requirements for AVs (if many cars are available). ++ Co-branding with local government authority as part of integrated transport solution. + Replication of the model on a city-by-city basis. + Own brand schemes from manufactures may restrict consumer choices. ++ EVs require strategic public charging points. + The concept may stand or fall on the quality of the app used. + Not suited for longer trips (on a commuter basis). + Care needed after passenger´s use. +++ The need for fuel, energy or for maintenance interventions can affect fleet supply. +++
Opportunities	**Threats**
Fits with the “on-demand” and “sharing” attitude. ++ Low costs for vehicles owners. + Potential lower fares for passengers (based on low set-up costs and driverless). +++ Market expansion is possible (pushing out the boundaries of the area served). + Suitable for cross AV marketing. + Can reduce demand for parking spaces in central urban areas and hence offer benefits for locals. +++ Demand data can help to justify public measures. + Integration with MaaS. ++ Feedback of early adopters. ++	Market penetration depends highly on the number of available AV owners. + Taxes on robots. ++ Regulatory concerns may impact operation set-up. ++ Limited fleet may make this model vulnerable to competition from business fleets (due to expensive vehicles, to autonomous unbelief and small number of AV in the market, restriction in peak hours) +++ Automation´s concerns may affect the demand. + Autonomous will change in-vehicle Value of Time (hence, potentially generating new travel behaviors) +++ Manufactures will become a strong ride-railing player and can restrict AV private selling. +++ Owners can purchase more and more vehicles to rent and overrun the sector. +

Impact: + small; ++ medium; +++ high

Internal environment

The ‘strengths’ component in the SWOT framework pertains to the positive attributes inherent within an organization. The business model of P2P ACS revolves around leveraging underutilized AVs from some parties to fulfill the mobility needs of others. This entire concept is anchored in the idea of sharing and striving for a sustainable transportation system grounded in product reuse. Its success hinges on everyone who wishes to become customers, be they passengers or AV owners or both. This section underscores how to capitalize on the benefits this service can offer to its clientele and how to make the venture thrive in a competitive landscape, setting itself apart from other mobility solutions. These insights are merely a summary of the extensive discussion in the section 3.3 'Business model', which delves deeply into the competitive advantages of this business.

This solution might be mistaken for the AMOD option from the passenger's perspective, but its unique features could carve out a successful niche. One of its strengths is the potential for gradual, sustainable growth since the P2P company does not need to pay the up-front cost for new cars or cover ongoing maintenance (Dill et al., 2017). It can also be an alternative solution in confined areas where commercial potential profit is lower due to higher operation costs and niche segments that intent to remain local (closed markets). Current options like Cruise[36] or Waymo[37] operating in U.S. cities have uniform conditions. However, offering a variety of vehicles – from economical to SUVs or sports cars, electric to hydrogen-powered – could attract a wider customer base. This solution leverages cutting-edge automotive automation, catering to individual travel needs while also addressing environmental concerns. Such benefits can elevate the solution's value and serve as strong marketing points to both consumers and stakeholders.

The company's internal dynamics also have certain limitations that might hinder its success. These limitations are captured under the 'weaknesses' in the SWOT framework. For the P2P ACS model, potential operational issues that could tarnish the company's reputation or constraints that might deter passenger interest are concerns. The system's reliance on vehicle owners for fleet availability and their role in the venture's success is pivotal, necessitating continual trust-building efforts.

Expanding the business can pose challenges. As it thrives on local connections, it's local stakeholders - from city councils to users, both vehicle owners and passengers - that drive its success. Local government authorities play a crucial role in supporting the solution, especially if it requires public spaces for parking or facilities for vehicle maintenance and charging. Taking this model elsewhere would mean rebuilding this trust network from scratch. Then there's the parking conundrum. The P2P ACS model aims to keep vehicles operational for most of the day. Yet, there's a need for designated stop zones near high-demand areas to ensure minimal

[36] https://getcruise.com/ , accessed in September 2023.
[37] https://waymo.com/ , accessed in September 2023.

passenger wait times. Collaborating with local authorities to earmark these zones is vital, aiming to reduce wait times and optimize urban space for public enjoyment.

External environment

Investment in introducing technology to the automotive market has been significantly high. Major automotive brands have partnered with tech companies to remain competitive in the race to achieve Level 5 SAE autonomy. There are high stakes involved. This industry represents almost $2 trillion in revenues, accounting for more than 10% of the U.S. GDP[38]. In 2015 alone, nearly 7 million people were employed in the U.S. auto industry[39], with an additional 3.8 million working as motor vehicle operators[40] (Corwin and Pankratz, 2017).

Ride-hailing companies are equally determined to stay in this race, anticipating a future molded by SAV. A case in point is Uber, which has been testing self-driving car technology in San Francisco for several years. Global population and urbanization growth tendency are leading to the rise of megacities, that along with the continuous interest in vehicle ownership (as shown in Figure 2.2), the introducing of AV in the market and, if no other measures are applied, can lead to scenarios of congestion (OECD/ITF, 2015). These factors greatly influence the operation of a P2P ACS solution. The P2P ACS solution, when paired with urban measures tailored for the success of AMOD solutions, can free up urban space for diverse purposes and yield benefits for residents, such as enhancing the quality of life.

From an economic standpoint, the benefits of automation, relative to the initial total cost of ownership (TCO), are considerably higher for commercial applications compared to personal cars. Hence, it's logical for commercial entities, like taxis and other mobility service providers, to lead the way in adopting full automation for smaller vehicles (Wadud, 2017). However, barring any drastic measures that restrict vehicle purchases - like the reports suggesting a ban on new diesel vehicle sales by 2040 in certain European countries (Chrisafis & Vaughan, 2017; Milliken & Shirbon, 2017; Schmitt, 2016) - the P2P ACS solution remains a promising prospect.

Any business aiming for success must adapt to changes in its external environment. It's crucial to understand the emerging opportunities and threats and to strategize accordingly. It's worth noting that what might seem as threats to some can be seen as opportunities by others, depending on the perspective (Morris, 2005).

[38] https://www.bea.gov/data/gdp/gross-domestic-product (based on a first-quarter 2017 GDP of $19 trillion, as reported by the Bureau of Economic Analysis), accessed in September 2018.
[39] https://www.bls.gov/iag/tgs/iagauto.htm (based on information available for 2015), accessed in September 2018.
[40] https://www.bls.gov/oes/current/oes_nat.htm (based on information available for 2015), accessed in September 2018.

One external factor that might impact the solution is the level of technological and scientific understanding the general public has regarding the AVs that make up the solution's fleet. Pilot projects across Europe have brought attention to this issue, educating the public (Rebalski et al., 2022), and have been pivotal in enhancing the solution's appeal (Chee et al., 2020). In a survey conducted by Chee et al. (2020), participants who experienced the AV during a trial in Sweden found it to be safe and comfortable. They were also willing to pay a premium for personalized AMOD services in the future. The P2P ACS solution can also serve the purpose of promoting the adoption of AVs, allowing passengers to try out and build confidence in autonomous vehicles, similar to previous examples.

Given that the hallmark of a two-sided market like P2P CS is the presence of cross-group network externalities, its success hinges on achieving a critical mass on both sides of the market (Rotaris, 2022). The success of this new CS model mandates the implementation of effective marketing strategies and awareness campaigns, as indicated by Awasthi et al. (2009).

The P2P ACS solution, as an innovation, will undoubtedly have an adoption curve marked by distinct phases. Rogers (1982) proposed a model of willingness to adopt innovations, breaking it down into five adopter categories: innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%), and laggards (16%), each representing a specific percentage of the total population. Rogers believed that the early adopters acted as change agents - individuals capable of influencing the decisions of others, potentially accelerating, or decelerating, the diffusion of an innovation. The role of early adopters in product satisfaction and its communication is crucial for subsequent mass adoption (Wadud, 2017).

While innovation holds a certain allure, the influence of peers and viral messaging about new products or services are powerful marketing instruments (Aral & Walker, 2011; Godinho De Matos et al., 2014) that can sway people's decisions. Godinho De Matos et al. (2014) demonstrated that peer influence might have contributed to roughly 14% of iPhone 3G sales at EuroMobile over an 11-month period. Aral & Walker (2011) presented evidence of contagious adoption of a Facebook application; after introducing the application to about 10,000 users, they witnessed viral messaging surrounding the movie industry.

The economy is one of the major external factors that can influence a solution of this kind. Economic instability has been a defining characteristic of recent years, particularly due to significant events like the housing bubble burst in 2009, a global pandemic (COVID-19) that lasted nearly three years (2019-2022) reducing consumption of goods and services, and the war in Ukraine that began in 2022. This conflict further hampered economic recovery, which has been compounded by rising interest rates and consumer goods prices, thereby reducing the purchasing power of individuals amid stagnant wages. However, focusing on the future and the challenge of navigating the market, a notable variable stands out that could significantly impact the pricing of technological solutions: the taxation of robots and artificial intelligence (AI).

There are numerous questions surrounding this topic, such as defining the subject of taxation, weighing its pros and cons, and deciding on the type of tax. Its implementation could profoundly affect final pricing. The definitions from Anand (2022) and Popovič & Sábo (2021) suggest that a robot or AI can operate autonomously, without human intervention, and can learn new tasks, making it a prime candidate to replace human labor. Notably, a fully automated vehicle (level 5 SAE) distinctly fits within the robot/AI category.

The concept of taxation arises from the issue of job displacement. Anand (2022), drawing from the historical precedents of significant global changes, mentions that the introduction of robots/AI, unlike previous technological advancements, impacts most employment sectors. It doesn't allow for easy transition of workers to other areas, which strengthens the argument for taxation. Sá & Martins (2021) delve into the tax disparity between robots and humans, highlighting the subsequent consequences for all stakeholders. If there's a cost difference, there'll be a preference to deploy robots/AI in roles traditionally occupied by humans. This shift leads to decreased state income tax revenues (one of the primary annual tax sources) and increased unemployment-related costs (Sá & Martins, 2021). Guerreiro et al. (2022) view taxation as an incentive to adjust work schedules, suggesting that individuals might work part-time, and a tax on robots/AI might offset reduced wages, leading to an improved quality of life. However, taxation might also inhibit the potential benefits of robots/AI, such as enhanced safety (like reduced road accidents, as covered in this thesis) or risk shifting manufacturing to countries with cheaper labor (Sá & Martins, 2021).

These arguments aim to lay the groundwork for discussing the need for robot/AI taxes, their application ranging from the "ownership, use or supply" (Anand, 2022) of a robot/AI, and the extent of their imposition. Popovič & Sábo (2021) suggest a tax based on two attributes: use and concern. Abbott & Bogenschneider (2018) discusses the concept of tax "neutrality" between human and automated workers, which can either reduce the differential between robots and human workers or disincentivize robot use entirely. South Korea has already implemented a robot tax, which essentially amounts to a reduction in the tax incentives robots previously enjoyed. Such contributions can offset the tax revenue lost from automation and fund guaranteed minimum incomes (Sá & Martins, 2021) or finance and boost professional education programs to reskill workers, helping them transition to new roles (Chand et al., 2021).

From the standpoint of the legal environment, there are significant regulatory concerns surrounding AVs. Europe is at the forefront of AV legislation on a global scale and seeks to accelerate its pace to keep up with technological advancements in the automotive industry. The most recent developments in AV regulation are outlined in section 2.6.2 'Regulatory concerns'. Although the P2P ACS solution utilizes AVs, it must also consider legislation specific to the sharing economy, which often lags behind technological advancements. The rapid emergence of key players in the sharing economy, such as Uber, Airbnb, and the like, has frequently outpaced regulatory measures, as mentioned in Tart et al. (2018). Uber, a globally recognized company, has expanded to multiple countries and has challenged the scope of national legislation in the ride-hailing market, resulting in numerous lawsuits and fines against them. While current legislation is a clear concern, it's essential to recognize that laws, policies, and measures should act as incentives to promote the benefits that could arise from the diverse mobility solutions of the future, making initiatives like the P2P ACS viable.

3.5 P2P ACS design

3.5.1 Constraints of a P2P solution

Academic research extensively studies the AMOD model, forecasting that AVs will serve as a collective fleet. Contrarily, the P2P ACS approach seeks to utilize vehicles individually owned, with availability hinged on the times owners don't use them, typically when they would be parked. Such nuances significantly impact daily operations.

We opted for a simulation approach to grasp the effects of this restricted availability on the operational landscape. The research model was based on the SimMobility MT software design (Lu et al., 2015) - a tool with a track record in various studies, known for its reliability in gauging and forecasting demand across scenarios (Balac et al., 2017). SimMobilitity MT integrates the AMOD solution as a transport option and models the behavior between the agents in this solution. During the stay at MIT, working with this model gave me the opportunity to understand the core of the modeling and make analogies in the solutions.

In the AMOD framework, three main players emerge: the requesting passenger, the driverless vehicle, and the orchestrating controller. Meanwhile, the P2P ACS model necessitates an additional player: the vehicle's owner, who decides on the AV's availability (refer to Figure 3.4). This decision-making aspect is inherent to this model, which is the structural and conceptual difference compared to AMOD.

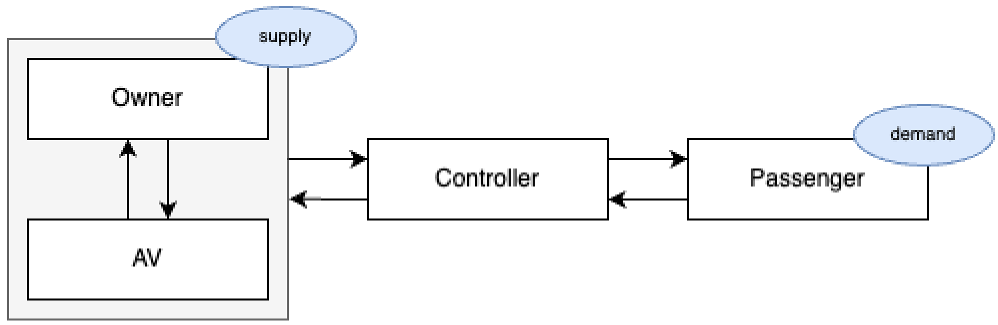


Figure 3.4 – Players in P2P ACS solution.

The operation of a P2P ACS solution resembles to the AMOD in terms of demand and control. However, two premises regarding the AV fleet must be acknowledged:

1. The fleet size is contingent upon the number of households willing to purchase an AV and subscribe the P2P ACS service;
2. Unlike the AMOD scenario, private AV owners do not make their vehicle available for the entire day (24 hours). The willingness to provide the service is constrained by household schedules and the perceived benefits of participation.

There's a timeline spanning from long-term decisions (like purchasing) to short-term ones (such as lending) that influences the operation of this solution. The number of vehicles available in the fleet stands as a pivotal component in a mobility solution. The balance between supply and demand must be maintained to ensure mutual benefits.

If there's an oversupply of vehicles with limited demand, vehicle owners might lose interest. The mandate for maintaining a clean vehicle and the lending duration, which restricts personal use in times of need, could be perceived by vehicle owners as an investment without adequate revenues. Conversely, if there's a high demand with few available vehicles, final customers' waiting times become unacceptable. Passengers may initially lose confidence in the service, and if this imbalance exacerbates, failing to meet passenger needs renders the operation unsustainable.

Various factors determine the operation's success, ranging from interest and usage to the overall experience both from AV owners and final passengers. The model designed here aims to address most of the challenges that might influence the intricate operation of a P2P ACS solution, although not all possible situations can be covered and analysed at this conceptual stage.

3.5.2 Demand

Demand for a P2P ACS solution should be examined in several stages: intention to use, subscription, and usage behavior.

Given that technology is a central component of this solution, it's crucial to consider the profile of individuals willing to use ride-hailing apps and/or AVs. While ride-hailing apps, although not universal, are widely used, full vehicle automation might deter certain segments of the population. Literature reviewed in section 2.6 ‘Autonomous vehicles’ reveals that a portion of the population remains skeptical or reluctant toward this technology. This limited intent indicates that the P2P ACS solution will not appeal to everyone.

The subscription to the P2P ACS solution will undoubtedly be influenced by its operational features, its integration with other mobility options, and its public portrayal. The passenger experience hinges on service characteristics. Metrics like wait time are crucial for passenger satisfaction. If waiting times exceed expectations, this could deter passengers from repeatedly using the service.

The P2P ACS solution operates within a broader mobility system, with several transport modes potentially in direct competition. The choice to use P2P ACS is determined by the passenger's valuation of this service: whether by comparison, such as preferring not to share space with others or prioritizing travel comfort (compared to public transport); or through individual appreciation of the state-of-the-art technology and sustainable sharing inherent to P2P ACS.

Passenger behavior should also be considered. The platform must be adaptive to the passenger's decisions throughout the process; for every action, multiple reactions should be anticipated. For instance, a passenger might abandon the app after being taken aback by the ride's cost, or if no vehicle is immediately available, they might choose to wait a few minutes before requesting again. There should also be alternative routes at every step to accommodate behavior changes. For example, after requesting a ride, passengers might change their pickup location because they have walked in the meantime, finding an alternative transportation, or deciding to make an unplanned stop mid-journey. This could alter the trip's duration and vehicle occupancy.

All these considerations shape the desired model. Intention to use and subscription influence the *a priori* choices passengers make, while behavior affects the solution's real-time modeling, introducing additional variables or actions. The model presented, as mentioned earlier, aims to highlight the differences in an existing solution (SimMobility MT) that mirrors an AMOD solution. These changes arise from incorporating earlier theoretical considerations and unique features of the P2P solution.

Individuals, based on their daily schedules and their household's economic and social attributes, as well as the transport system and P2P ACS features, decide when to employ this solution. After this choice, they become passengers. Figure 3.5 illustrates the passenger's decision-making process concerning the P2P ACS service.

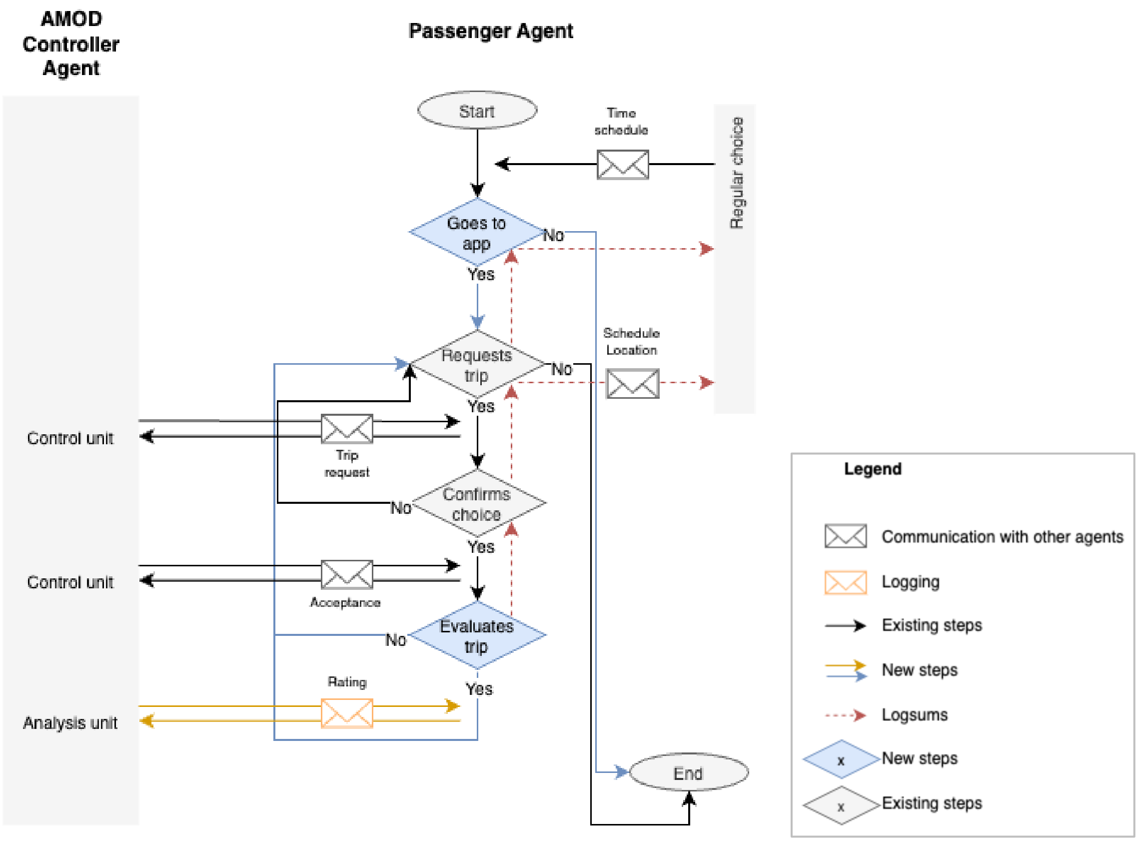


Figure 3.5 – Passenger decision process.

When deciding, an individual accesses the app with the intent to request a ride ("goes to app"). After specifying their requirements, they receive information like price or wait time. They can accept or decline these terms ("confirms choice"). If accepted, they can travel in the vehicle assigned by the central system. Afterward, they can provide feedback on their trip ("evaluates trip"). If they have no further travel needs, they exit the system ("end").

This decision-making process involves various messages exchanged between the passenger and the central system, accompanied by feedback loops at each step (logsums). These feedback loops evaluate individual behavior at each stage and adjust the modeling process to minimize errors. For instance, if an individual consistently chooses the P2P ACS solution (*a priori*) but tends to abandon it upon seeing the ride's price, it indicates room for model refinement. Models, or tweaks to models, are vital in assessing improvement measures. For example, models can predict the demand impact of reducing waiting times during specific hours, guiding the investment in this measure.

3.5.3 Supply

The AMOD solution operates with a corporate fleet wherein the availability of vehicles is fixed. In contrast, the alternative P2P ACS solution relies on a fleet of private AVs. Here, a new element enters the operational process: the vehicle owner, who makes decisions regarding the AV's availability.

However, unlike the passenger, the vehicle owner needs to make long-term decisions to participate in the P2P ACS solution. The purchase of a vehicle is typically a decision that impacts a household's finances and tends to influence the family's mobility for an extended period. Yet, purchasing is merely the first step to accessing this service. After acquiring the vehicle, the owner must subscribe to the solution and decide whether to make the vehicle available, as illustrated in Figure 3.6. Nonetheless, the decision-making isn't a straightforward path. For instance, the potential profitability from renting out the AV can significantly influence the decision to purchase the vehicle. These feedback processes should not be overlooked.

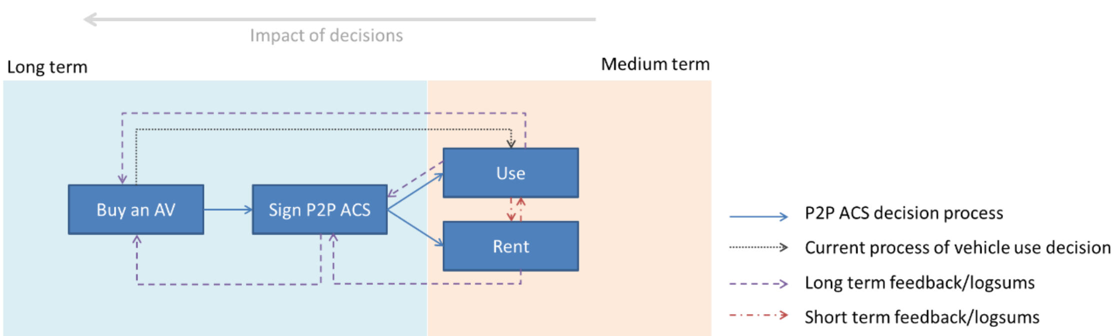


Figure 3.6 – Supply creation model in a P2P ACS solution.

Figure 3.6 illustrates the decision-making model from the supply side, emphasizing actions that impact longer time frames (like purchasing a vehicle for several years versus lending an AV for just a few hours). This model includes four decision-making functions from the supply side:

1. *Purchase*: To build a service of this kind, a pool of private AVs is required. Considering private ownership of these types of vehicles is not common today, it is essential to

analyse who would be willing to buy an AV based on potential features. A utility function should be established that determines the likelihood of AV purchase by households, based on economic, social, and mobility characteristics of households, as well as the AV´s features, the overall transport system´s performance, and the described P2P ACS service. Initially, a simplified model that uses current adoption forecasts from the literature for different AV scenarios can be proposed, excluding agent characteristics (random allocation).

2. *Subscription*: Next, the owner decides about subscribing to the studied P2P ACS service for potential lending of their AV: allowing their vehicle to be used by another person and earning money for it. This function includes economic and social characteristics of households, mobility patterns, and features of the transport system and the P2P ACS service. For a start, a simplified model drawing from current P2P car-sharing service adoption experiences can be proposed, adapted to possible AV scenarios, disregarding agent characteristics (random allocation).
3. *Usage*: The AV's usage relates to the activities and travel plans of the owner. The hierarchical system of SimMobility MT defines, using discrete choice models, the household's transport mode choice and each agent's routine. Introducing the P2P ACS service might influence AV usage. If the profit from lending surpasses the threshold that an owner is willing to accept to switch transport modes, the regular choice is impacted (opportunity cost). The utility function should also incorporate the expected gain from lending the vehicle. Initially, the lending gain's influence on the utility function for AV usage shouldn't be considered, though it's anticipated this component will be implemented later.
4. *Lending*: Finally, it is essential to determine which owners use the vehicle for personal use versus lending it out for the P2P ACS service. For this stage, it is assumed that all owners use the AV for their personal benefit over the P2P ACS service. The availability for the AV to join the pool is dependent on when the AV is idling (provided they've subscribed to the service).

Furthermore, combining the issues of supply and service, decisions (3) and (4) might need to be revisited during operations to allow adjustments based on the system´s performance.

Lending the vehicle to the P2P ACS fleet largely depends on the profit. This gain doesn't have to be purely monetary; the reward from contributing to society and helping others has been identified as one of the reasons people participate in P2P solutions, as pointed out in Chapter 2.

However, this benefit should outweigh, for everyone, the responsibilities of participating in this solution (*e.g.*, cleaning the vehicle), the feeling of loss (*e.g.*, the hypothetical need to use the vehicle), or sharing concerns (*e.g.*, risks to the car).

The operation of the P2P ACS solution involves a medium-term decision-making process by the AV owner, as shown in Figure 3.7.

Daily, the vehicle owner connects to the app (“goes to app”), informs the central system of the terms they're willing to accept to lend the car under (“yields AV”), and is informed about the vehicle rental forecast. Based on this information, the owner can choose to accept (“confirms choice”), allowing the vehicle to join the car pool of available AVs (“accepts activation”). After an initial waiting period, the owner receives a message to rent out their AV and can confirm/accept trips (“accepts trip”) and rate the passenger (“classify”), based on cleanliness, delays, or changes, until the vehicle's availability period ends. If there's an auto-accept feature, based on the owner's prior decisions or another business model, the owner is freed from the need for constant responses; in this scenario, a set of predetermined criteria eliminates certain actions from the workflow diagram on the right side (green area) of Figure 3.7.

Underpinning vehicle availability, whether in manual or automatic mode, is the individual owner's reaction to delays. For lending, the owner stipulates that the AV should be available for personal (or family) use at a specific time and location. During the lending period, the vehicle may respond to multiple requests until reaching the limit of available time. If delays occur, it is crucial to factor in the owner's tolerance for such delays and incorporate this parameter into the proposed central allocation algorithm.

Note that this conceptual model does not account for future changes, specifically regarding: (a) population; (b) planning; and (c) usage perception. The way individuals view or use AVs differs from how they perceive traditional vehicles. This difference is due to the full automation of AVs, enabling them to cater to more family travel needs. While it is suggested that these variations are not considered to ensure the feasibility of the model, they can be examined in later phases by developing various scenarios based on the outlined topics.

Building on this perspective, the vehicle circulation behavior model posits that human driver factors and individual stochastic behaviors are replaced with diminished fixed values. Moreover, the pricing of AVs should be in line with the reference values found in the literature (Nahmias-Biran et al., 2019).

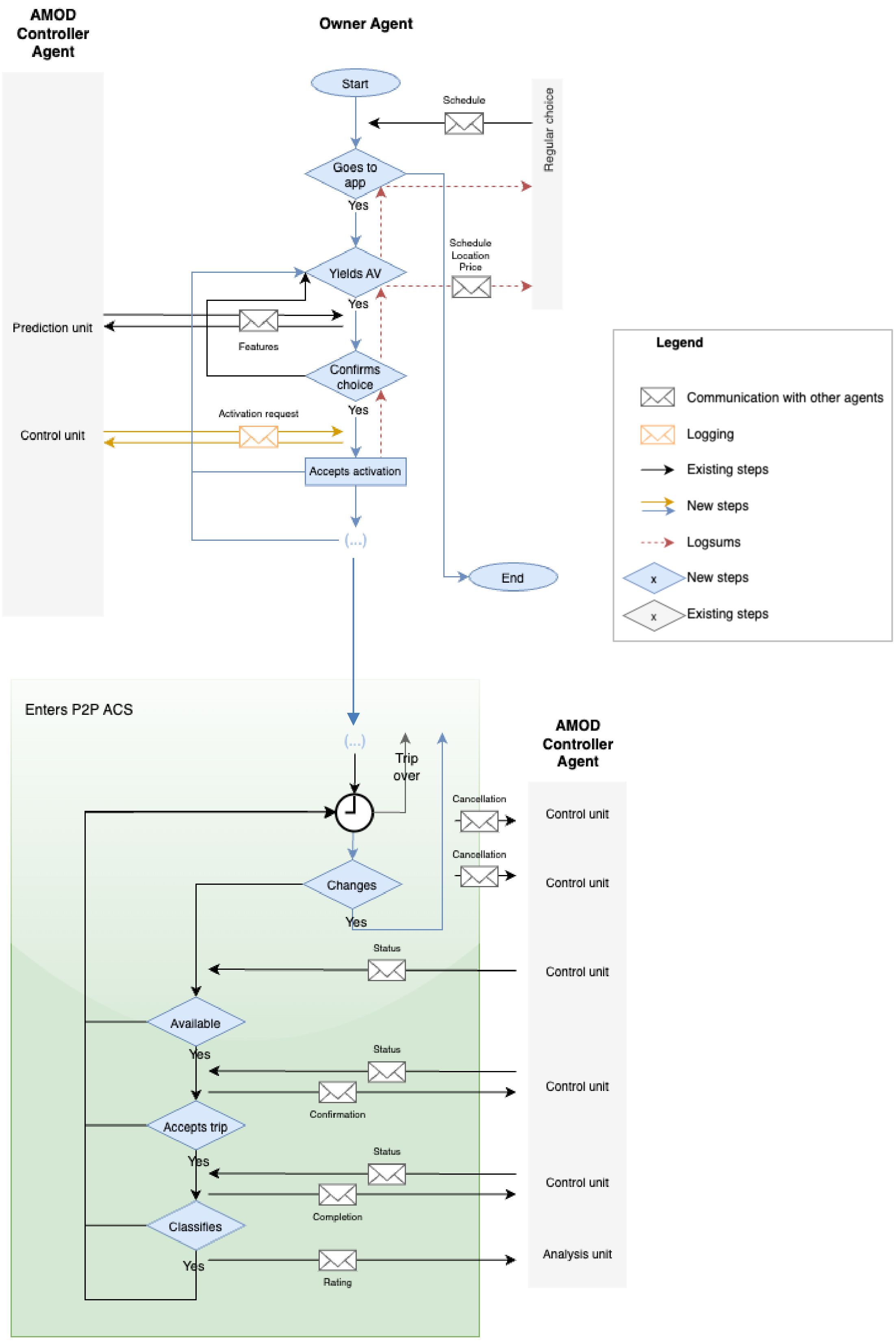


Figure 3.7 – Owner decision process.

3.5.4 Platform

The central system governs the entire operation of the P2P ACS solution. The decision-making process of the AMOD controller, integrated with private AVs, can be referenced in Figure 3.8.

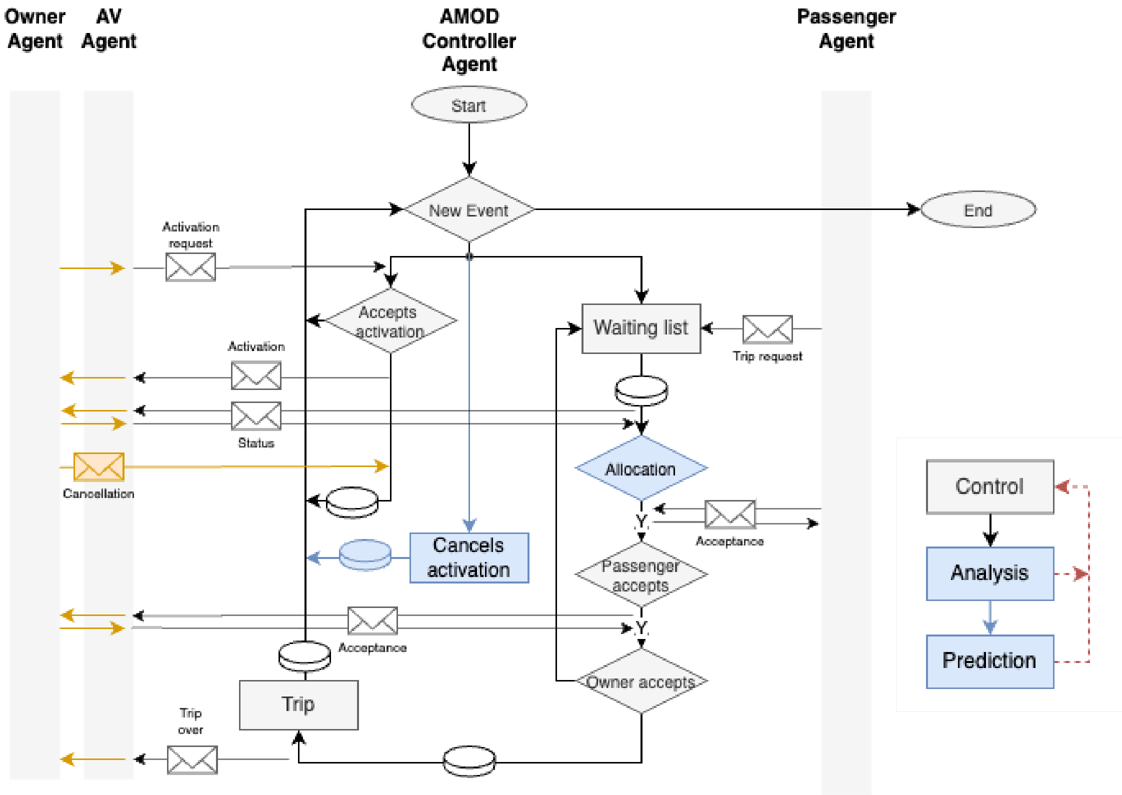


Figure 3.8 – Platform decision process.

This model incorporates dynamic management, where actions are updated upon a new event ("new event"), whether it's a service activation request, cancellation by the AV owner, or a travel request from a passenger. If the passenger initiates contact, the central system searches for an available vehicle ("waiting list"), assigns that vehicle to the passenger ("allocation"), and, upon mutual agreement between both the passenger ("passenger accepts") and the vehicle owner ("owner accepts"), the central system oversees the passenger's journey ("trip"). At the journey's end, the vehicle is returned to the waitlist.

The waitlist is populated by vehicle owners who can, at any time of the day, request the central system to activate their vehicle as part of the fleet, a request which the central system may accept, or decline based on the current number of available vehicles ("accepts activation"). Proper vehicle number management can set earning expectations for vehicle owners but might also deter participation. Following the simplification principle, the model may opt for no entry barriers, allowing automatic central acceptance upon activation requests from owners.

The third event showcased in Figure 3.8 is the removal of the vehicle from the waitlist ("cancels activation"). Depending on the chosen model for owner´s decision making process (as seen in Figure 3.7), this event can be triggered either by the vehicle owner communicating with the central system or automatically at the end of the vehicle's availability period.

To simulate the P2P ACS operation, a robust and instantly accessible database is vital. Integrating waitlisted vehicles with space-time constraints (imposed by the owner) and state changes (allocated vs. available) means this list undergoes constant access and modification. This database is larger and more frequently accessed than the one used for simulating the AMOD solution.

To cater to travel requests, vehicles are allocated per request. At this stage, various validation states come into play, including:

1. Energy check; and
2. Time availability check.

The algorithm must determine if the AV has enough energy to complete various routes – to the journey's start point, the allocated journey itself, and then back to the drop-off point or nearest charging station. If there's insufficient energy for the tasks, the vehicle should head to the nearest charging point. Optimal points should be set based on the remaining availability period, ensuring a minimum energy is left for the owner's final trip. To avoid overloading the simulation, one can use the algorithm from (Hanna et al., 2016), where an energy-deficient AV becomes unavailable for a specific period, then returns fully charged.

Also, the vehicle's availability to travel and return within the owner's specified timeframe should be ensured. When time-constrained, the vehicle might wait for a shorter travel assignment or proceed to its final destination immediately.

In a more extensive version, the central system might undertake additional functions, making this solution more appealing. Traditional AMOD systems solely focus on operations, where the central system handles "control": managing communication and vehicle allocation. However, this model suggests introducing new roles to the central system, like analytics and forecasting, which could analyze historical data or predict hourly gains from lending vehicles.

The P2P ACS service pricing should be grounded on the projected costs for autonomous mobility services (Bösch et al., 2018), considering occupancy assumptions or the overall fleet size, as outlined by (Hörl, 2017) in their study on modeling autonomous taxi services in Switzerland.

3.6 Main Conclusions

Investments in the automotive industry’s technological advancements signal a prominent role for AVs in the future. While shared mobility solutions have gained traction, the allure of private vehicle ownership persists. In this landscape, the P2P ACS solution emerges with notable business potential.

Envision a future where AV sharing isn't just a concept but a living reality. Here, the P2P ACS solution shines, harnessing privately-owned AVs - often idly parked - to fulfill urban transportation demands. At its core, this model banks on two distinct groups: vehicle owners, open to the idea of renting their cars, and urban passengers in search of convenient transit. What makes P2P ACS stand out in the crowded mobility market is its unique triad of features: the autonomy of vehicles, the ethos of shared mobility, and a peer-to-peer approach. This blend not only provides passengers with unprecedented flexibility and comfort but also ensures monetary benefits for vehicle owners and potential improvement of cities’ quality of life by freeing parking places allocated to idling private cars.

The essence of the P2P ACS solution lies in its distinct business model. It deftly weaves together nine pivotal elements: key partnerships, core activities, vital resources, value propositions, customer relations, distribution channels, target customer segments, cost strategies, and revenue streams. While it resonates with facets of existing shared mobility blueprints, it boasts unique attributes that set it apart, underscoring its differentiated positioning.

Delving deeper with a SWOT analysis reveals both the potential and challenges of the P2P ACS. While its strengths and inherent weaknesses are crucial, it's the external factors - opportunities and threats - that pose intriguing considerations. As with any non-existing and potentially future solution, data gaps exist, making current projections based on today's knowledge possibly restrictive. Undoubtedly, tomorrow's socio-economic shifts may usher in challenges not currently foreseen.

This solution falls under a two-sided market. It's a dynamic platform that bridges vehicle owners with passengers, facilitating seamless transactions. Operationalizing this vision means the platform handles ride requests and journey allocations efficiently. While reminiscent of the B2C ACS model, P2P ACS faces unique operational nuances. The "fleet" size is inherently variable, depending on the willingness of households to participate. Moreover, the availability of vehicles oscillates with household schedules and perceived benefits. Thus, besides navigating the complexities of AVs and passengers, P2P ACS must also account for the decisions of vehicle owners.

Chapter 4. An ABM to explore the P2P ACS solution

4.1 Introduction

In the previous chapter, we outlined the theoretical operational model of the P2P ACS solution from scratch. This chapter bridges the gap between theory and the practical application of the thesis. It aims to demonstrate how this new model was implemented from a computational perspective. Efficiently implementing the P2P ACS operation will yield valuable insights to support decision-making processes.

The model was integrated into a broader one, leveraging some of its components essential for trip generation and creating the operational environment. The pre-existing model simulates mobility in Greater Lisbon. This chapter discusses the challenges faced during integration, how they were overcome, provides context to the study area, and delves into the modeling choices for each of the agents involved in this mobility solution.

4.2 Multi-agent simulation models

Modeling is a multifaceted process that begins by translating a real-world problem into a representative structure within the simulation realm, a step known as abstraction. This abstraction undergoes analysis and optimization before any derived solution is mapped back onto the original issue. Broadly, models can be categorized as analytical or simulation-based. The latter encompasses sets of guidelines, like equations, flowcharts, and cellular automata, which forecast how a system will evolve based on its current status.

Three prominent paradigms in simulation modeling are System Dynamics (SD), Discrete Event (DE), and Agent Based (AB) modeling. Of these, the Agent Based approach stands out due to its versatility and robustness, it not only captures intricate structures and dynamics but also aids in model construction when global interdependencies are ambiguous (Borshchev & Filippov, 2004). Further, AB models are more modular, meaning modifications generally result in localized rather than overarching changes (*idem*).

Agent Based models predominantly operate in discrete time, transitioning from one event to the next. Agents within this framework can represent entities across various scales and natures, from physical entities like pedestrians or cars, to abstract entities like customers or competing corporations. A defining characteristic of agent-based models (ABM) is their decentralization. Unlike SD or DE models where global behaviors are explicitly stated, ABMs derive global behaviors as emergent properties from the interactions of countless individual agents, each governed by its own set of rules. These agents coexist, interact, and communicate within a shared environment. Such an approach, where behavior is built from the ground up, is aptly termed 'bottom-up modeling'. Within this paradigm, agents' behaviors are often delineated using statecharts.

In the realm of autonomous car-sharing, a considerable body of research focuses on modeling the operation of corporate-driven AV fleets (*e.g.,* Bischoff & Maciejewski (2016), Boesch et al. (2016), Carrese et al. (2019), Moreno et al. (2018), OECD/ITF (2015), Overtoom et al. (2020), among others). ABMs are frequently employed to understand the implications of AV, offering insights for management decisions and broader system understanding (Jing et al., 2020).

Within the evolving domain of future mobility simulations, a few institutions have carved a niche for themselves. Notably, SimMobility and MATSim have emerged as go-to simulation tools, referenced in works by Azevedo et al. (2016), Basu et al. (2018), Oh et al. (2020), Paschke et al. (2017), Wang et al. (2018), among others. SimMobility (Adnan et al., 2016) is a product of the Future Urban Mobility research group, developed under the collaborative efforts of the Singapore-MIT Alliance for Research and Technology (SMART). Conversely, MATSim (Axhausen et al., 2016) is an innovative open-source simulation tool, originating from collaborative efforts at ETH Zurich and TU Berlin. Their prominence arises from a robust demand module that captures individual preferences, which plays a pivotal role in determining the success of mobility solutions like autonomous car-sharing (ACS) services. Over the past decade, these tools, coupled with other simulation and optimization techniques, have been instrumental in studying various facets of ACS, such as service attributes, fleet sizes, and urban impacts like congestion and parking demands. Three key service attributes shaping the efficacy of ACS are travel cost, travel time, and waiting time (Krueger et al., 2016).

SimMobility MT (Lu et al., 2015) is a distinctive simulation tool rooted in agent and activity-based models, considering interactions between multimodal transport demand and supply. It is a hybrid simulator that blends micro-simulation for demand and meso-simulation for supply, utilizing event-driven components for the former and temporal elements for the latter. The software comprises three primary components: pre-day (planning), in-day (action), and supply (network and operation). Agents' behavior adapts based on their evolving understanding of urban conditions. This learning is mirrored through a feedback mechanism wherein the pre-day and in-day components access information from the supply output, such as travel time and costs. The software even accounts for agents altering their choices in response to unforeseen events. Available transportation modes encompass buses, trains, cars, car-sharing, motorcycles, taxis, autonomous mobility on demand (AMOD), bicycles, and walking. Each agent's movements are simulated concurrently, with mode-specific controllers orchestrating the journeys for all active vehicles.

The SimMobility MT software laid the foundation for the design of the P2P ACS model discussed here. This tool has been employed in numerous studies, consistently demonstrating its reliability for observing and predicting demand across varied scenarios (Azevedo et al., 2016; Basu et al., 2018). However, the P2P ACS model is versatile enough to be adapted to other simulation frameworks that model individual decisions at both the demand and supply levels, such as the AnyLogic software.

AnyLogic is a sophisticated simulation modeling tool known for its versatility in supporting multiple simulation methodologies, including SD, DE, and AB modeling. AnyLogic was developed by The AnyLogic Company (formerly XJ Technologies), a global organization founded in 1998. The company's roots trace back to Russia, and over the years, it has expanded its presence worldwide.

The main motivation behind the development of AnyLogic was to provide a single platform capable of integrating various modeling techniques. Traditionally, different tools addressed different modeling methods, which often isolated them in their respective domains. AnyLogic was groundbreaking in its ability to blend these methods seamlessly, allowing modelers to use the best approach (or a combination of approaches) to tackle complex and multifaceted problems.

4.3 Study area of Lisbon

The Lisbon Metropolitan Area (LMA) is a dynamic and expansive region in Portugal, comprising 18 municipalities that stretch from Mafra in the north to Setúbal in the south. Dominated by urban settings, the LMA has evolved over the years, with populous hubs sprouting around the central municipality of Lisbon.

The suburban areas within the LMA are not mere extensions of Lisbon but have seen significant independent growth. They have developed their own unique identities, hosting a myriad of activities, from cultural events to business hubs. However, the gravitational pull of Lisbon remains undeniable. As the heart of the LMA, Lisbon is a bustling epicenter that attracts daily commuters and visitors in droves (as shown in Figure 4.1). The reasons are manifold: a dense concentration of landmarks and points of interest, a plethora of employment opportunities, and a rich array of educational institutions.

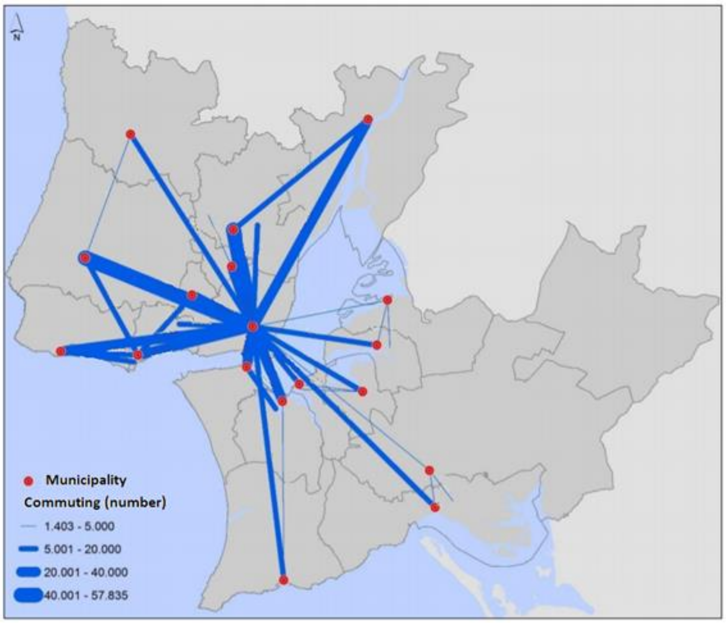


Figure 4.1 - Primary and secondary destinations for inter-municipal travel by municipality, as of 2011. *Source*: AML (2019)

The LMA boasts a robust road network, seamlessly integrating key national routes, high-capacity internal roads, and peripheral ring roads that radiate beyond Lisbon's core metropolitan zone. Augmenting this infrastructure are supplementary roads that amplify the network's accessibility, ensuring comprehensive coverage across the region (Marques da Costa, 2016).

Complementing the roadways, the LMA is enriched by four pivotal rail corridors: Azambuja, Sintra, Cascais, and Setúbal. These railways not only bolster regional ties, seamlessly connecting Lisbon to neighboring hubs, but also extend their reach to distant parts of Portugal, with the Cascais Line being the sole exception.

Further enhancing mobility, the LMA is enveloped by a vast bus network, a linchpin in delivering efficient public transport coverage across the expanse. Zooming into Lisbon itself, the transport entity Carris orchestrates 97 routes, deploying a diverse fleet of 765 vehicles, encompassing buses, trams, and funiculars. This intricate web spans roughly 726 kilometers, factoring in the stretch of single-track regions (Carris, 2020).

Beyond Carris, several other bus operators play a pivotal role in ensuring seamless mobility throughout the LMA. In 2022, Carris Metropolitana commenced operations in the LMA, servicing an impressive 600 bus routes (AML, 2021).

Lisbon's urban landscape is further complemented by an expansive metro network that stretches over 40km. This network not only ensures swift and dependable transit within the city but also extends its reach to adjacent municipalities like Amadora and Odivelas. Ambitious plans are underway to further augment the metro infrastructure within Lisbon and extend it to the municipality of Loures. Complementing Lisbon's metro system, the southern riverbank is served by three subway lines catering to the municipalities of Almada and Seixal.

In addition to traditional public transportation, Lisbon presents a diverse array of alternative transportation choices, encompassing taxis and ride-hailing platforms like Uber. As of 2016, the LMA boasted 4,654 licensed taxis, with a substantial 3,497 of them plying the streets of Lisbon (AML, 2017). However, the distribution of these licenses across the municipalities of LMA is uneven, leading to disparities in taxi availability. For instance, while Seixal has a mere 0.2 taxis per thousand inhabitants, Lisbon stands at a robust 6.9. When juxtaposed with major European metropolises such as Madrid, Paris, or London, LMA 's taxi density is somewhat modest (*idem*).

While the national taxi fleet has largely remained consistent, Lisbon has witnessed a modest uptick in its taxi licenses, adding 56 new ones, which equates to a 1.6% increase in the city's taxi contingent (AML, 2017). This growth, however, hasn't matched the meteoric rise in tourism Portugal has enjoyed in recent years, subsequently amplifying the demand for taxis. To illustrate, 2019 saw a 6.4% surge in overnight stays in the LMA compared to its predecessor (INE, 2020).

Lisbon's transportation ecosystem is diversifying with the inclusion of shared road mobility solutions. CarAmigo has been at the forefront of this transformation, introducing a peer-to-peer car-sharing platform since 2017, which empowers residents to share their personal vehicles. In a slightly different vein, Emov unveiled an electric car-sharing service in 2018, and its operations are now expanding to encompass the municipality of Amadora. DriveNow also marked its presence in Lisbon, offering car-sharing services between 2017 and 2020.

Moreover, Lisbon is witnessing a surge in active transportation modes. An increasing number of its denizens are gravitating towards walking and cycling. The city has responded by introducing GIRA, a bike-sharing initiative with docking stations strategically placed along Lisbon's primary routes. Complementing this are several operators like Lime and Bolt, offering flexible bike and scooter services, allowing users to park in designated zones, thereby promoting convenient and eco-friendly transit options.

The LMA serves as a gateway for tourists, with two major entry points: the Lisbon Airport, nestled within the municipality and equipped with a metro station for swift access to the city's heart, and the Port of Lisbon, a mere stone's throw from Lisbon's historic quarters.

Statistical data from INE (2017) paints a detailed picture of the LMA. Spanning an area of 3,015.24 km^2, it shelters a population of 2,821,349 individuals. This demographic represents a significant 27.4% of Portugal's population, translating to a population density of 935.7 inhabitants per square kilometer. Delving deeper, the mobile segment of this population, comprising individuals aged between 6 and 84, constitutes 80.4% of the LMA 's total demographic (INE, 2017).

Vehicle registration data reveals that the LMA is home to 1,416,439 registered light motor vehicles (ASF, 2020). This statistic underscores a pronounced motorization trend among its residents, with a rate of 50.2%. Table 4.1 offers a granular view, detailing the distribution of registered light vehicles across each municipality within the LMA. Notably, the car occupancy rate in the LMA stands at 1.60.

Table 4.1 - Insured Vehicle Fleet, 'light vehicles' category. *Source*: ASF (2020).

District	Municipality	Number of Cars	
		2010	2019
Lisboa	Alenquer	19,944	28,379
	Amadora	64,317	87,102
	Arruda dos Vinhos	6,117	9,553
	Azambuja	9,240	12,987
	Cadaval	6,957	9,702
	Cascais	100,674	130,602
	Lisboa	313,277	331,956
	Loures	83,241	131,850
	Lourinhã	12,885	18,479
	Mafra	36,699	55,878
	Odivelas	59,791	73,893
	Oeiras	113,134	178,432
	Sintra	168,052	207,827
	Sobral de Monte Agraço	4,686	10,693
	Torres Vedras	39,565	55,587
	Vila Franca de Xira	58,404	73,519
Total		1,096,983	1,416,439

The automobile stands as the predominant mode of transportation in both the LMA and within the municipality of Lisbon itself. Specifically, cars are responsible for a significant 58.9% of all journeys in the LMA and 45.1% within the Lisbon municipality, as depicted in Figure 4.2. This vehicular dominance has been consistent over the past two decades, and its influence shows no signs of waning. Yet, insights from the IMOB survey (INE, 2017) highlight an emerging trend: a marked increase in the embrace of active transportation methods. In recent times, the shift towards these active modes has been remarkable, now accounting for 23.5% of all commutes in the LMA and an impressive 30.4% within the municipality of Lisbon.

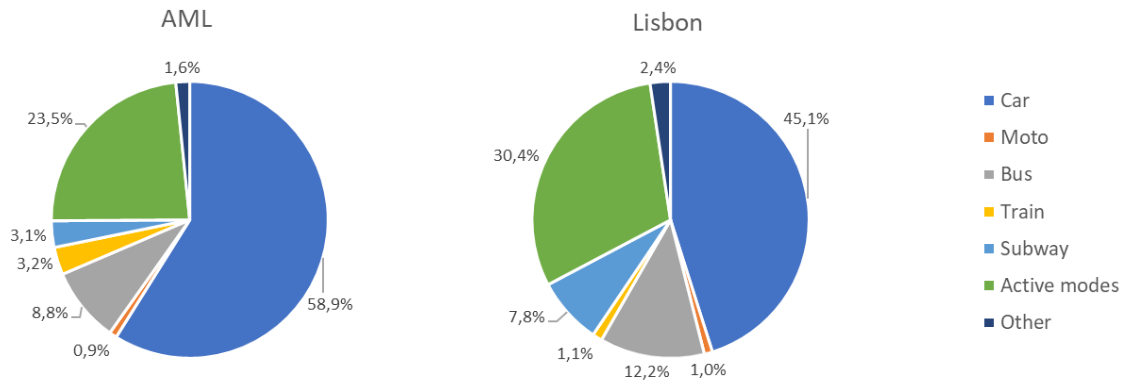
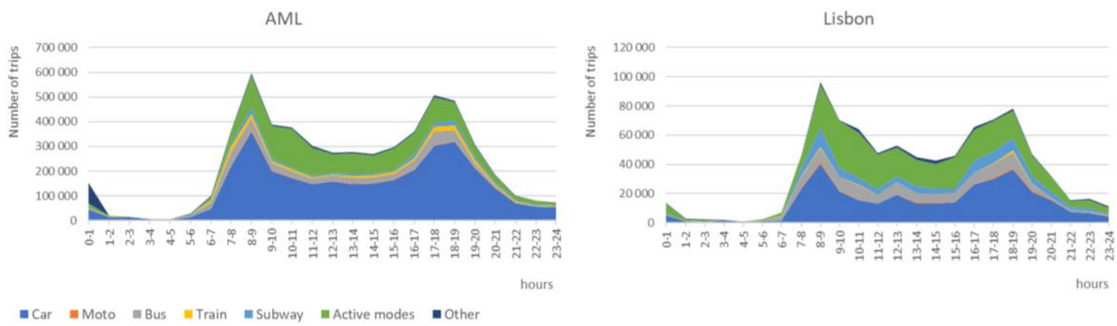


Figure 4.2 - Comparison of transportation modes: LMA (left) vs. Lisbon (right). *Source*: INE (2017).

The LMA sees an estimated 5.4 million daily trips, averaging 2.6 trips per person. Individuals spend about 72.5 minutes daily commuting, with the average journey spanning 11km.

Figure 4.3 showcases daily travel trends, emphasizing the busiest times of day. In LMA, the morning rush is between 8-9 a.m., while the evening sees a prolonged rush from 5-7 p.m. Notably, the LMA 's peak evening travel (5-6 p.m.) precedes Lisbon's peak hour (6-7 p.m.). Additionally, Lisbon experiences a minor surge in trips from 12-1 p.m.



*Hourly distribution calculated based on a weighted sample made available by INE.

Figure 4.3 - Daily trip count comparison: LMA (left) vs. Lisbon (right). *Source*: INE (2017).

Accessibility within the LMA is diverse, reflecting the multifaceted nature of its terrain. Around 43% of the metropolitan expanse is accessible from the county center within just 10 minutes, serving nearly 90% of its inhabitants. This is attributed to the urban population density and the closeness to major roadways (Marques da Costa, 2016). Such accessibility underscores the range of travel choices and interconnectedness available to LMA residents.

Portugal's transportation dynamics have recently been reshaped by a surge in tourism. In 2019, the nation greeted 29.5 million visitors, leading to 77.8 million overnight stays (INE, 2020). Of these stays, domestic guests accounted for 29%, with international visitors making up the remaining 71% (*idem*). This pattern is mirrored in local accommodations. On average, visitors spend 2.69 nights in hotels and 2.2 nights in local lodgings (*idem*).

The LMA stands out as a top tourist magnet, claiming 25.9% of the total overnight stays (INE, 2020). The region saw a 6.4% growth in overnight stays year-on-year. Interestingly, Lisbon's tourism has a seasonality rate of 32.3%, suggesting that while summer months (June to August) see a spike, the demand remains fairly steady year-round (*idem*).

The main gateway for tourists in Lisbon is Lisbon Airport, which has seen a dramatic rise in passenger traffic over the past decade. From 2010 to 2019, passenger numbers skyrocketed from 14 million to a staggering 31 million (PORDATA, 2020). Another pivotal gateway for tourists is the Port of Lisbon. In 2019 alone, it welcomed 313 cruise ships, translating to 502 thousand transit passengers and an additional 36.3 thousand who disembarked to explore the city (INE, 2020). This burgeoning tourism sector has undeniably reshaped Lisbon's transportation landscape and travel behavior.

For many, especially those unfamiliar with a city's transit system, taxis become the go-to mode of transportation. This is especially pronounced in tourist-heavy contexts like Lisbon, where taxis not only offer convenience but also bridge the gap in navigating unfamiliar terrains. Figure 4.4, showcasing the spatial distribution of taxi services in 2016, underscores this trend. Two dominant taxi trip hotspots emerge: the bustling tourist and commercial zones in the city and key transit junctions like the Lisbon Airport or the Expo Bus/Railway Station. These hubs epitomize the dual role of taxis, serving both the city's visitors and daily commuters.

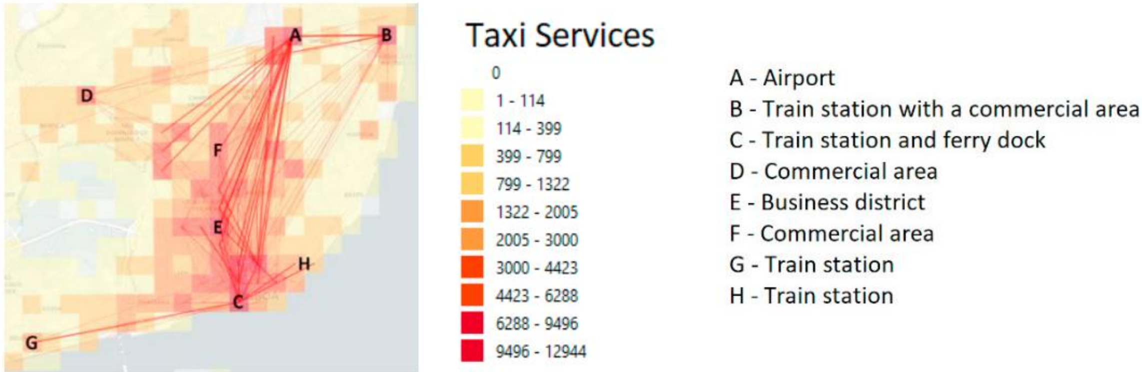


Figure 4.4 - 2016's heatmap of taxi demand hotspots in Lisbon, showcasing their interconnections based on taxi services data. *Source*: P. Rodrigues et al. (2020).

Per the study, taxis in Lisbon predominantly cater to brief intra-city commutes, as illustrated in Figure 4.5. A significant 77% of taxi rides last between 5 to 20 minutes, underscoring their popularity for swift transits. Distance-wise, the majority of these trips span 2 to 5 kilometers, mirroring Lisbon's condensed layout. To put it in perspective, Lisbon can be visualized as a 10 km x 10 km square, emphasizing the concise distances taxis typically traverse within its confines (P. Rodrigues et al., 2020).

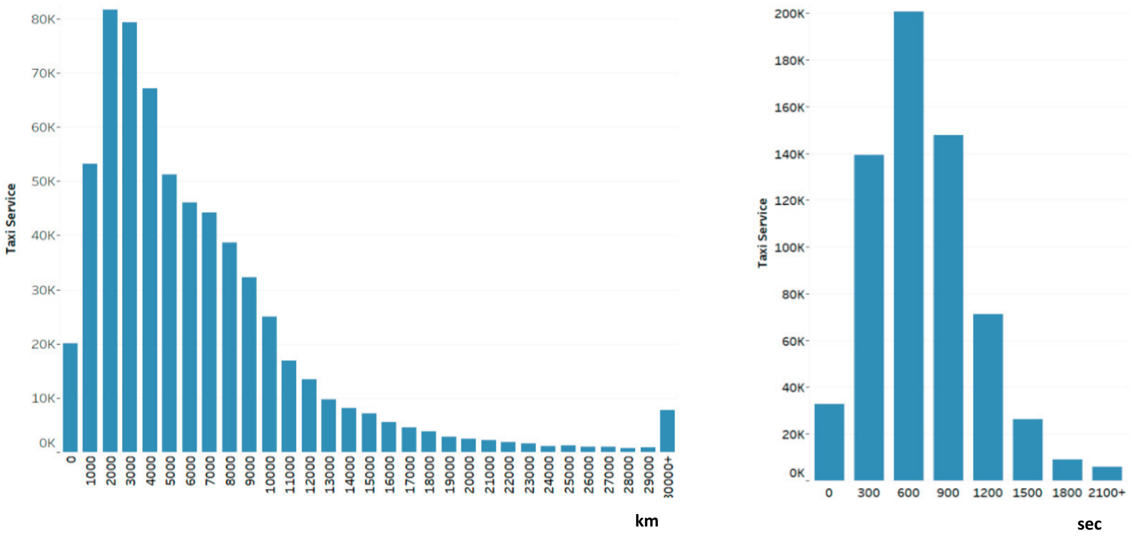


Figure 4.5 - 2016 Lisbon trips: Distance distribution per 1km intervals (left) and duration in 5-minute intervals (right). *Source*: P. Rodrigues et al. (2020).

From a comprehensive spatial-temporal evaluation of taxi services, we discern that taxis play a pivotal role in addressing first and last mile transportation challenges, largely attributed to their adaptability (P. Rodrigues et al., 2020).

Additionally, an insightful snapshot of the hourly distribution of taxi services within Lisbon municipality (as illustrated in Figure 4.6) unveils specific patterns: On weekdays, there's a pronounced surge in demand around 9 am, which then sees a consistent decline until 8 p.m. In contrast, weekends record a diminished frequency of taxi services, contributing to just 23% of the total weekly demand. A notable spike in demand is observed from midnight to 1 a.m. - often tied to recreational outings - along with a morning peak at approximately 11 a.m., marking a slightly later rush compared to weekdays (P. Rodrigues et al., 2019).

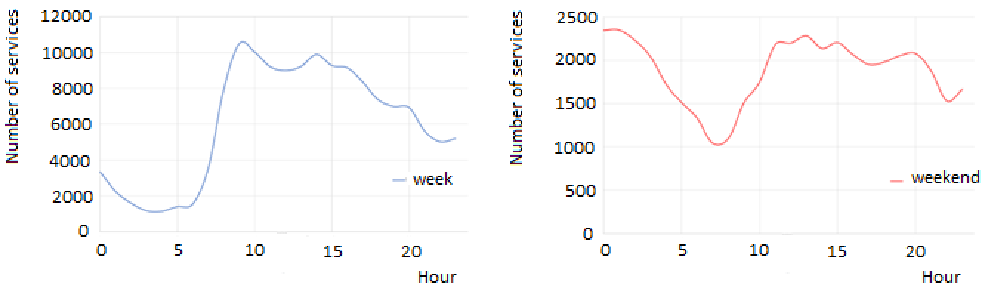


Figure 4.6 - 2016's hourly taxi demand distribution: Weekdays (left) vs. Weekends (right).
Source: P. Rodrigues et al. (2019).

4.4 Overview of the agent-based model for Lisbon

4.4.1 Generation steps

The Agent-Based Model (ABM) employed in this research has a rich history, having been iteratively refined over a span of a decade by an interdisciplinary team of scholars from the Instituto Superior Técnico (IST). This model serves as the foundation for a myriad of research projects and has been cited in multiple academic publications, including works by Lopes et al. (2014), Martinez & Viegas (2017), OECD/ITF (2015), among others.

The simulation framework of choice for this study was AnyLogic, a robust software suite developed by a Russian research consortium. AnyLogic is not merely an agent-based simulation tool; it is a versatile platform that also supports system dynamics modeling and discrete event simulations. The software offers Java-based classes that facilitate the creation, execution, visualization, and data collection from Agent-Based Simulations (ABSi), making it an indispensable tool for intricate modeling tasks.

The ABSi build-up process has three steps[41] (Santos, 2016):

[41] Santos considers a 4th step related with the generation of the demand of a new mode of transportation based on the mobility individual choices, that he used in his PhD dissertation.

1. Generation of the synthetic population;

2. Generation of the daily activity log for each individual;

3. Generation of the probability for each individual to use a specific mode of transportation, achieved through the calibration of the Discrete Choice Model (DCM).

Synthetic population

In this study, the constructed synthetic population is imbued with a diverse array of individual attributes, painting a vivid picture of its characteristics. These include factors such as age, gender, marital status, educational attainment, and employment status. Further adding depth, each individual is tethered to both a household and a specific dwelling. The foundation for these intricate attributes is rooted in a tapestry of sources, comprising the 2001 Census, the SOTUR survey[42], ACAP (Associação Automóvel de Portugal) statistics, and the SCUSSE survey[43]. A detailed compendium of these data sources can be accessed in (Eiró, 2015).

To bring this synthetic population to life, the Iterative Proportional Fitting (IPF) methodology, a technique previously spotlighted in works by Birkin & Clarke (1988), was employed. The meticulous process behind this generation is elucidated further in writings by Martinez & Viegas (2009). The precision of the IPF technique yielded a synthesized population of 2,700,474 individuals, nested within 1,013,102 unique households. This translates to an average household composition of approximately 2.67 individuals.

When juxtaposed with the most contemporary Census data from 2011, the attribute values of the synthetic population showcased remarkable alignment. As noted by (Eiró, 2015), discrepancies were negligible. While a minor overestimation in population size was observed, tallying 2,682,687 inhabitants as per (Santos, 2016), the congruence between the two census surveys (2001 and 2011) remains commendable. This harmonious alignment stands as a testament to the model's relevance, even when drawing from earlier data epochs.

[42] Research project under the MIT-Portugal Program, which aimed to define innovative solutions attractive to private investment and urban development measures that could leverage these solutions (Santos, 2016). More information in (Silva & Martínez, 2011).

[43] Research project under the MIT-Portugal Program, which aimed to study new intelligent modes of transport and services with a strong focus on ITS and its integration with the car and public transport in order to efficiently meet the increasing daily activities and lifestyle of urban travelers. Gonçalo Santos, in the scope of his PhD thesis and framed by the InnoVshare and SCUSSE projects, conducted a survey to study the demand for CS in Lisbon. This survey was composed of: sociodemographic characterization, revealed preferences and stated preferences regarding the use of innovative modes of transportation. It was disseminated by internet and complemented with CAPI interviews, in the period Apr 2011 - Feb 2012. Detailed information about the survey can be found in (Santos, 2016). Tomás Eiró, PhD student in the same period and member of the same project, used the survey data to estimate the demand for SC as input in the AnyLogic model (Eiró, 2015).

Throughout the course of this thesis, the 2011 Census stood as the pinnacle of contemporary national population studies. Yet, it's imperative to recognize that demographic and societal shifts could have transpired in the interim since its data collection. A side-by-side juxtaposition of the model outcomes with the latest data sourced from IMOB in 2017 can be gleaned from Table 4.2. This comparative analysis shines a light on a discernible uptrend in educational attainment in Portugal. Concurrently, there's a contraction in the active workforce, a phenomenon potentially tied to escalating unemployment figures or the broader narrative of an aging populace.

Table 4.2 - Comparative analysis of generated attributes for LMA: Model estimation and Census 2011 data vs. IMOB 2017. Sources: Eiró (2015), INE (2017)

<table>
<tr><th></th><th></th><th>Model</th><th>Census 2011</th><th>Absolute difference</th><th>IMOB 2017</th><th>Absolute difference</th></tr>
<tr><td rowspan="3">Population</td><td>Persons</td><td>2,700,474</td><td>2,843,513</td><td>-143,039</td><td>2,821,349</td><td>-120,875</td></tr>
<tr><td>Households</td><td>1,013,102</td><td>1,155,972</td><td>-142,870</td><td>-</td><td>-</td></tr>
<tr><td>Persons per house-hold</td><td>2.67</td><td>2.45</td><td>0.22</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">Gender</td><td>Male</td><td>47.73%</td><td>47.82%</td><td>-0.09%</td><td>46.92%</td><td>0.81%</td></tr>
<tr><td>Female</td><td>52.27%</td><td>52.18%</td><td>0.09%</td><td>53.08%</td><td>-0.81%</td></tr>
<tr><td rowspan="5">Martial status</td><td>Married</td><td>68.77%</td><td>68.28%</td><td>0.49%</td><td>-</td><td>-</td></tr>
<tr><td>Divorced</td><td>5.73%</td><td>6.26%</td><td>-0.53%</td><td>-</td><td>-</td></tr>
<tr><td>Separated</td><td>1.85%</td><td>1.81%</td><td>0.04%</td><td>-</td><td>-</td></tr>
<tr><td>Single</td><td>11.69%</td><td>11.91%</td><td>-0.22%</td><td>-</td><td>-</td></tr>
<tr><td>Widower</td><td>11.96%</td><td>11.74%</td><td>0.22%</td><td>-</td><td>-</td></tr>
<tr><td rowspan="6">Education level</td><td>No education or kindergarten</td><td>19.38%</td><td>19.09%</td><td>0.29%</td><td>13.40%</td><td>5.98%</td></tr>
<tr><td>Basic school: 6-9 years</td><td>37.11%</td><td>36.39%</td><td>0.72%</td><td rowspan="2">44.74%</td><td rowspan="2">2.49%</td></tr>
<tr><td>Basic school: 10-13 years</td><td>10.12%</td><td>10.55%</td><td>-0.43%</td></tr>
<tr><td>Secondary school: 14-18 years</td><td>18.82%</td><td>19.14%</td><td>-0.32%</td><td>19.68%</td><td>-0.86%</td></tr>
<tr><td>Graduate school: 18-23 years (=>)</td><td>14.56%</td><td>13.94%</td><td>0.62%</td><td>21.44%</td><td>-6.88%</td></tr>
<tr><td>Other</td><td>-</td><td>-</td><td>-</td><td>0.74%</td><td>-</td></tr>
<tr><td rowspan="6">Employment status</td><td>Less than 15 years old</td><td>15.06%</td><td>14.86%</td><td>0.20%</td><td>14.73%</td><td>0.33%</td></tr>
<tr><td>Active</td><td>51.77%</td><td>52.17%</td><td>-0.40%</td><td>43.63%</td><td>8.14%</td></tr>
<tr><td>Student</td><td>6.28%</td><td>6.61%</td><td>-0.33%</td><td rowspan="3">35.20%</td><td rowspan="4">-8.47%</td></tr>
<tr><td>Retired</td><td>18.64%</td><td>18.07%</td><td>-0.57%</td></tr>
<tr><td>Other</td><td rowspan="2">8.25%</td><td rowspan="2">8.29%</td><td rowspan="2">-0.04%</td></tr>
<tr><td>Unemployed</td><td>6.44%</td></tr>
</table>

For an in-depth exploration of the synthetic population's validation and trip generation methodologies, we recommend delving into Eiró (2015) and Martinez & Viegas (2009). These references offer a thorough and nuanced understanding of the validation procedures.

Activities log

An intricate stochastic activity diary was crafted for the synthetic population, seamlessly weaving in both mandatory commitments (like work or academic pursuits) and discretionary engagements (such as personal endeavors, social gatherings, or meal periods). This suite of activities was coherently sequenced in a daily timetable, ensuring temporal compatibility. The locales for these activities were pinpointed based on a blend of the prevailing land-use distribution and spatial considerations.

Trips linked to mandatory activities took precedence in the diary. For instance, if an individual's work hours span from 9 a.m. to 5 p.m., a subsequent gym visit would only be slated post 5:30 p.m. Viegas & Martínez (2010)´s rule-based model played a pivotal role in decomposing the vast landscape of trips across the study domain. This model drew its vitality from a 1994 mobility survey of the study area, a sweeping endeavor capturing around 60,000 journeys and insights from 23,000 participants (Tis.pt 1994). Moreover, an activity database from 2009 was roped in to modernize the travel patterns captured in the inaugural survey.

Activity distributions, segmented by type and time-slot within the study perimeter, were harnessed from the SCUSSE project's comprehensive survey. This data was compartmentalized into five distinct activity brackets and organized over five temporal windows. An intrinsic assumption of the model was that those committed to mandatory trips would recalibrate their routines based on both the commute length to their workplace and their age demographics. The Lisbon mobility plan's data from 2005 (CML, 2005) was tactically integrated to refine the probability values extracted from the SCUSSE survey, thereby attenuating errors. The data's recalibration was realized through an auto-adjusting regression mechanism, leveraging fresher datasets (Eiró, 2015). Furthermore, the SCUSSE survey bequeathed insights on average trip lengths and their variability based on intent and timing. Essential specifics like the commencement of daily activities and their respective spans were sourced from URBITRAF (Tis.pt, 2002).

Activity location determination utilized land-use data meticulously gathered by Martínez (2010). The decision grid for destinations was critically shaped by the travel distances individuals encountered, with tailored distance decay functions incorporated for distinct activity categories, in accordance with the insights of Martínez et al. (2013).

When defining the trip blueprint for the "work" category, the Viegas & Martínez (2010) model ingeniously leveraged fuzzy theory, casting the mobility patterns gleaned from sample data over the vast synthetic populace. The departure and arrival points, transport modalities, and journey inception were discerned through a synthesis of statistical indices relating to land use and the transport network's dynamics.

The "study" category brought into play a gravity model, which methodically allocated educational institutions based on proximity to either a household head's domicile or place of work. For tertiary learners, institutions were earmarked with a discerning approach, giving precedence to establishments boasting higher *numerus clausus* (limited admission) ratings.

Every individual's daily itinerary was meticulously curated, ensuring that their travel time doesn't breach a stipulated threshold. This travel time budget drew inspiration from empirical studies conducted in economies mirroring Portugal's income profile, as detailed by Schafer & Victor (2000). A meticulous assessment of transit durations between zone pairs (encompassing 281 zones) was undertaken, pooling in comprehensive transit and roadway datasets. The resultant average time metrics catered to the diverse transport modes available for each journey's start and endpoint. A special note on those below 18: their mobility trajectories and subsequent activity hubs are sketched based on a set of assumptions delineated in Eiró (2015).

The synthesis of non-mandatory activities, factoring in both type and chronological footprint, was realized by marrying data from the SCUSSE project survey with ancillary sources. This exercise adopted a bifurcated model. In the preliminary phase, pivotal parameters such as the count of non-mandatory activities, their kick-off time, span, and maximal travel stretch were crystallized. These were then adeptly woven into a feasible 24-hour framework. The subsequent phase bore the responsibility of fleshing out the destinations for these activities, ensuring the proposed travel durations seamlessly dovetailed with the pre-defined time allocations, as underscored by Santos (2016).

To encapsulate the diverse nuances in individuals' daily routines, the model ingeniously spawns ten distinct mobility patterns. These patterns predominantly spotlight mandatory travel activities, acting as keystones that shape the overarching mobility narrative and influence the interspersing of ancillary activities. Consequently, there exists a marked consistency within these mobility sets, as evidenced by the minimal coefficient of variation.

The intricacies of the model that crafts the activity diary for our synthetic populace are meticulously laid out in Eiró (2015)'s treatise. This document also vouches for the efficacy of the trip generator – an advanced activity-based simulator – in mirroring real-world datasets.

As the narrative unfolds, several pivotal elements crystallize, including:

- The synthetic populace, adorned with rich socio-economic markers.
- A meticulously curated activity log for each individual.
- The intertwined journey narratives – vividly capturing departure points, destinations, initiation times, and activity durations at each juncture (as detailed in Santos [2016]).

Statistically, the model spins out an average of 1.98 trips for every individual and a heightened 2.58 trips for those demonstrating mobility. This numerical landscape nestles comfortably between the 1.6 trips benchmark observed in Lisbon in 2001 and the 2.3 trip forecast projected by Eiró (2015), which was derived from a regression model juxtaposing daily per capita trips against GDP per capita.

Table 4.3 offers a panoramic view of trip distribution, segmented by purpose and the temporal bracket. Given the hybrid nature of the generator's outputs, which amalgamates datasets from both the Mobility survey (1994) and SCUSSE (2011), these figures are juxtaposed within a singular table row. For the sake of contextual relevance in evolving scenarios, comparisons have also been drawn with the more contemporary IMOB dataset from 2017.

Table 4.3 - Comparison of Trip Distributions by Purpose and Time of Day: Activity Generator Outputs juxtaposed with Data from Mobility Survey (1994), SCUSSE (2011), and IMOB (2017).

Purpose	Day periods				
	7h - 10h	10h - 16h30	16h30-19h	19h - 24h	0h - 7h
Work / Study	53.33 % 48.42 % / 69.16 % 63.90 %	16.10 % 28.69 % / 17.88 % 20.29 %	2.01 % 3.79 % / 3.38 % 4.43 %	1.98 % 2.88 % / 1.53 % 1.84 %	26.58 % 16.21 % / 8.05 % 9.53 %
Personal	24.86 % 19.38 % / 28.89 % 29.07 %	51.49 % 57.02 % / 56.78 % 45.03 %	15.64 % 12.53 % / 9.44 % 18.88 %	6.86 % 7.74 % / 1.96 % 5.85 %	1.15 % 3.34 % / 2.92 % 1.17 %
Well-being	9.41 % 12.58 % / 9.41 % 19.96 %	40.95 % 53.36 % / 62.27 % 49.92 %	19.74 % 13.62 % / 14.77 % 14.96 %	26.96 % 18.03 % / 12.43 % 13.14 %	2.95 % 2.41 % / 1.13 % 2.01 %
Social	32.92 % 30.74 % / 25.35 % 12.95 %	37.43 % 24.28 % / 57.47 % 59.33 %	25.35 % 31.26 % / 9.20 % 15.33 %	4.31 % 8.71 % / 7.98 % 10.67 %	0.00 % 5.01 % / 0.00 % 1.72 %
Meal	0.13 % 1.78 % / 0.00 % 11.02 %	56.49 % 89.32 % / 80.46 % 64.62 %	4.73 % 2.49 % / 0.00 % 6.53 %	38.23 % 6.04 % / 19.54 % 16.64 %	0.42 % 0.37 % / 0.00 % 1.19 %
Return home	2.29 % 1.83 % / 1.87 % 4.56 %	31.54 % 31.48 % / 31.18 % 35.43 %	42.14 % 40.39 % / 39.02 % 32.53 %	19.34 % 22.98 % / 27.06 % 23.32 %	4.70 % 3.32 % / 0.87 % 4.15 %

Color coding:
blue, high positive variation; orange, high negative variation

Activity generator	
Mobility survey, 1994	SCUSSE, 2011
IMOB, 2017	

The analysis reveals that the generator somewhat overestimates the number of work/study trips during the 0h-7h timeframe. The authors attribute this overestimation to potential extended commuting distances, a byproduct of urban sprawl, as outlined by Eiró (2015). However, more contemporary data underscores that the proportion of trips for this purpose within this period remains on the lower end, suggesting a minor misalignment in the model's predictions. Conversely, between 10h and 16h30, the model's estimated trip count falls short of both the original survey data and the recent IMOB dataset.

Discrete choice model

For determining passengers' mode of transport selection, a discrete choice model from the InnoVshare project was utilized. While this model predominantly centered on the adoption of car-sharing (CS) and minibuses, it also encompassed conventional transportation means. The model's calibration encompassed various factors, ranging from socio-demographic attributes to land use, vehicular and public transport usage, and operational transport-related aspects. Eiró (2015) provides an exhaustive list of these specific attributes and their affiliated coefficients. Calibration was achieved using both stated and revealed preference data sourced from the SCUSSE project survey. This exercise deployed a multinomial logit model, achieving an adjusted-R^2 value of 0.358.

The assignment of transportation modes is determined based on the utility derived from the discrete choice model for each mode. This is then adjusted according to the individual's trip chain and daily schedule (time window). A comparison with the most recent data from IMOB (INE, 2017) reveals that there are certain trends the model does not capture. The model underestimates the modal share of car usage and active modes compared to the IMOB data, and evenly distributes the difference across public transportation shares.

4.4.2 Model simulation

The Agent-Based Model (ABM) for Lisbon is grounded in the theoretical framework of the market. It is constructed based on the interactions of three key players: the user, the operator, and the regulator. The transportation offerings are characterized by various attributes, as defined by the operator. When faced with the need for a journey, an individual evaluates all the spatial-temporal attributes and costs set by the operator. Ultimately, the individual makes the most optimal choice for their trip and thus becomes a user. The overall mobility landscape is shaped by the regulator, who sets certain rules. These rules influence both the operator and the user, affecting their subsequent decisions and, ultimately, the entire mobility system.

The model, developed using the AnyLogic software, was originally designed to simulate the car-sharing operation in Lisbon. Throughout its development, care was taken to retain the elements that facilitated the car-sharing operation. However, these elements were deactivated to reduce computation times. Furthermore, tables related to car-sharing (for instance, the locations of car-sharing stations in the new network) were updated, taking into account the newly introduced variables. The older variables were replaced in the foundational model. All elements pertaining to the car-sharing operation will not be detailed or explained in the subsequent text.

AnyLogic software employs agent-based modeling to replicate the dynamics of a system. Agents can represent a variety of entities, such as physical objects, vehicles, products, ideas, people, organizations, and more. These agents either interact with one another or are placed within an environment that possesses its own unique dynamics. Table 4.4 displays the agents that were considered for the ABM for Lisbon, hereafter referred to as the "*base model*".

Table 4.4 - Agents present in the original ABM (for Lisbon) model.

Agent (active object class)	Description
Centroid	Centroids of the Grid200
Clients	People who move within the AML
Grid200	The city of Lisbon is divided into squares of 200m x 200m. In total, there are 1,968 squares.
Grid500	The AML is divided into squares of 500m x 500m. In total, there are 3,997 squares.
Macro_centroid	Centroids of the Grid500
Main	Agent that recreates the simulation environment
Nodes	Nodes of the road network
Presentation_view	Presentation environment, while the simulation runs
Road	Edges of the road network
Zone	Areas that divide the AML (Z66) (division into municipalities + parishes of Lisbon)

The foundational model integrates various spatial resolutions, stemming from the utilization of diverse data sources. These include the municipal-level aggregation, the zoning system from the Lisbon Mobility Plan (Z66), the zones delineated by the SCUSSE project (Z281), a grid-based system for the LMA with squares measuring 500m x 500m (referred to as Grid500), and another grid-based system specifically for Lisbon with squares of 200m x 200m (known as Grid200). For the purposes of the simulation, which focuses on P2P ACS operations, this study predominantly employs the Grid200 system.

The AnyLogic software is built upon the Java programming language. Java is an object-oriented programming language where classes serve as the blueprints for objects. Essentially, a class is a collection of common properties or attributes that can later be filled with specific data. For instance, a "vehicle" object might have a class with attributes like "brand," "owner," and "age." Different vehicles would then have varying brands, owners, or ages. Table 4.5 provides an overview of the classes that were incorporated into the base model.

Table 4.5 - Classes present in the original ABM (for Lisbon) model.

Class (java class)	Description
DijkstraAlgorithm1	Shortest path calculation algorithm (graphs)
Clusters_dist	Distance between points (return condition)
EntryRates	Incidence rates by age and mode of transport (calculation assistant)
Graph	Support for distance calculation in graphs
Groups	Aggregates lists from other classes
Household_cl	Characteristics of a household (assignment)
LG_Group	Probabilities of transport alternative groups and ordering (calculation assistant)
LG_order	Cumulative probabilities of transport alternatives and ordering (calculation assistant)
Order_modes	Probabilities of using alternatives (assignment)
Route	Characteristics of routes (assignment)
Survey_summary	Aggregates lists from other classes
Trip	Characteristics of trips (assignment and calculation assistant)
Trip_set	Characteristics of the set of trips (assignment)

The class 'DijkstraAlgorithm1' was replaced in the most recent version.

To simulate the model using the AnyLogic software, a set of instructions must be provided to the system. The simulation begins with the 'Main' agent. After importing essential libraries required for the simulation, the 'Main' agent sequentially invokes various functions. These functions aim to replicate the mobility scenario in the LMA. Figure 4.7 illustrates the initiation process of the simulation.

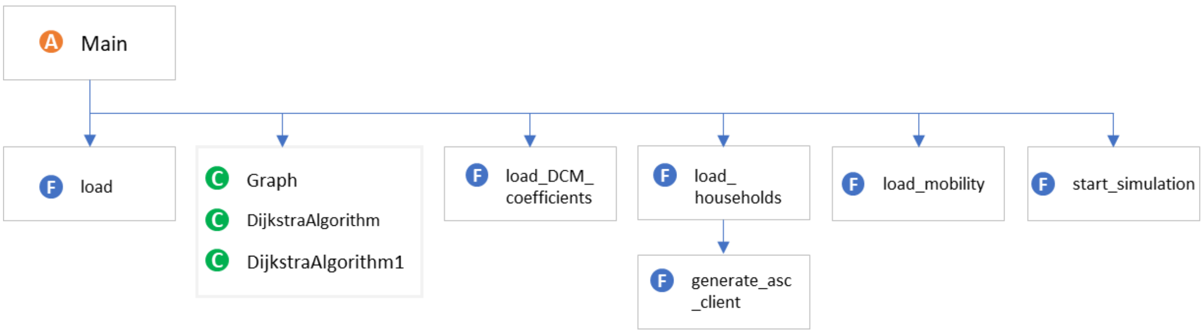


Figure 4.7 - Scheme of functions called within the 'Main' agent for trip generation purpose.

In the AnyLogic software, the 'Main' agent initiates the process by calling the 'load' function. This function loads information into the agents 'Grid200', 'Grid500', 'Centroid', 'Node', and 'Road'. The tables containing the necessary data to populate these agents are located in the [Basic_inputs] database. Subsequently, the road network graphs are created using the Dijkstra algorithm. However, in the most recent version, this step has been replaced by a function, as detailed in the following section. The 'load_DCM_coefficients' function imports coefficients from the database, which contains information from the work of Eiró (2015). These coefficients are then used in the MNL function that describes the utility of different transport types (see Table 4.6).

Table 4.6 - Transportation alternatives and explanatory variables of the MNL used in the base model.

Explanatory Variables			
Alternative Specific Attribute	Socio-Economic Characteristics		Alternatives
0 – ASC	9 – Parking	18 – A35_65	0. PC -private car
1 – TT_Private	10 – ND_CP	19 – A65	1. MT - motorcycle
2 – TT_Public	11 – Pass	20 – DIST	2. TX – taxi
3 – Access_time	12 – Income	21 – ENTROP	3. BS - BUS (light transp mode)
4 – Waiting_time	13 – EHOME_P	22 – HIGH	4. WK - walking or biking
5 – Fuel_cost	14 – EWK_OUT		5. HV - heavy public transport: subway and rail
6 – Tariff	15 – OWN_CAR		6. PHV - private transport + heavy public transport
7 – Toll	16 – A25_35		7. CB - BUS (light)+ heavy public transport

The subsequent function loads and organizes data in the 'Households_cl' class. The 'generate_asc_client' function, invoked by the previous one, adjusts the Alternative Specific Constant (ASC) for each 'Client' agent. The 'load_mobility' function brings in all the trip information, sets rules for trips (including those outside the LMA), and calculates distances for all transport modes. Some examples of these rules include: those without cars cannot choose cars as a transport alternative, those with garages don't pay for parking, and if a journey takes more than an hour on foot, it's not considered a viable option. Lastly, the 'start_simulation' function determines the trips for the 'Clients' agent. Due to computational constraints and the expansive nature of the LMA study area, a scale parameter was introduced, correlating the 'Clients' agent with a real-world number of users.

From the analysis of the previous steps, it's evident that there are no population or trip generation models included within the model. Instead, data is imported from pre-existing tables. For more details on the creation of these tables, refer to section 4.4.1 'Generation steps'. The generation process yielded one table detailing population characteristics and ten different tables describing trip features, as illustrated in Figure 4.8.

Results | Messages

	Zone_residence	Household	Member	ID	Sex	Age	Marrital_Status	Work	Education_level	Rendimento	Modo	Carta	N_carros	EstabTrab	BGRI_house	EstacResid	code	hh_income	Own_car	acti
1	13	851	3	1931	0	11	4	2	2	0	0	1	1	0	1818	0	1	1531,783	0	1
2	1	852	1	1932	0	57	1	5	2	781,8569	0	1	2	0	1813	0	1	1550,831	1	1

Results | Messages

	ID	Trip	Purpose	Home_based	SCOM	Z281_From	Z281_To	BGRI_Origin	BGRI_Destination	Start_time	Duration	End_time	Flexibility_Origin	Flexibility_Destin	Activity_time	Utility
1	1153966	1	3	1	0	168	172	1	566	0	0,7231408	14,85323	3	3	0,9172387	-2.094_-1.331_-8.285_-5.013_-
2	1155610	1	1	1	0	168	278	1	619	7,782583	1,039753	8,282582	3	1	13,63611	-2.257_-1.466_-8.395_-4.757_-
3	1285126	4	6	0	0	168	177	1	812	20,87904	0,9574181	24	3	3	0	-2.503_-1.572_-9.074_-5.605_-
4	2539773	2	6	0	1	168	172	1	3493	15,85966	0,680507	24	2	3	0	-2.038_-1.303_-8.182_-3.902_-

Figure 4.8 - Example of tables related to the population (below) and trips (above).

The 'start_simulation' function aims to assign transportation modes to each trip undertaken by the 'Client'. To view the entire process, please refer to Figure 4.9.

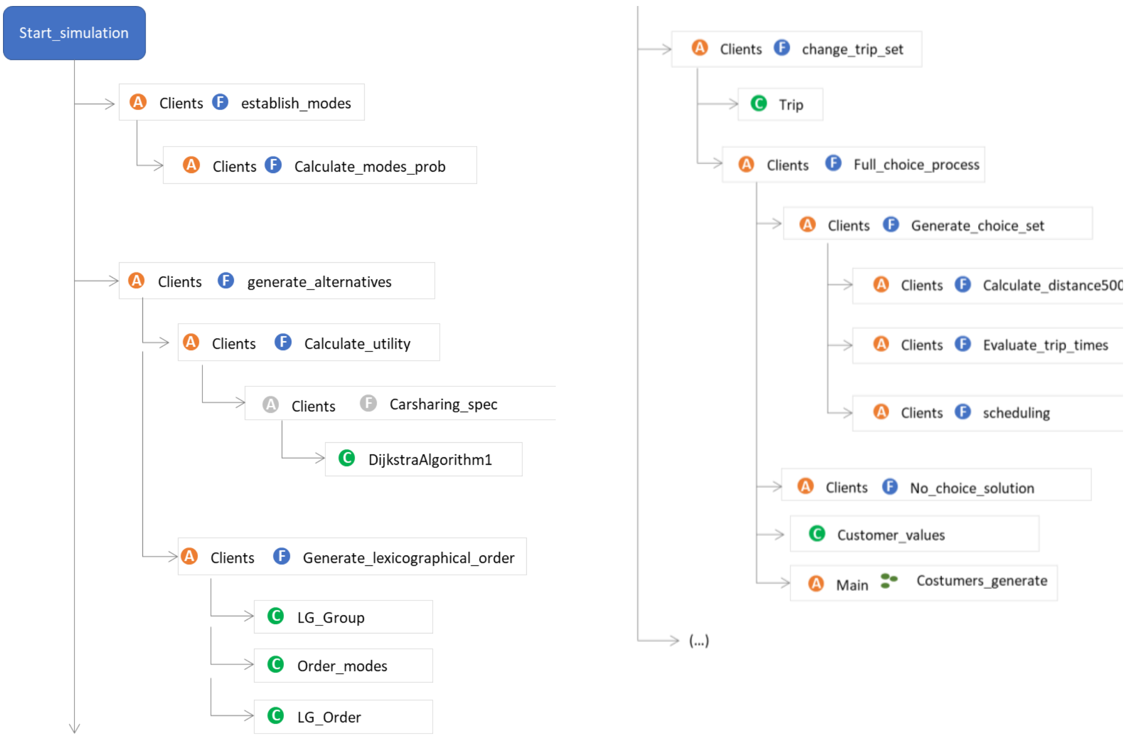


Figure 4.9 - Scheme of functions called within the 'Clients' agent for assigning transportation modes to each person's trips.

The process begins by calculating the utility of all transportation modes, taking into account all valid trip sets and every trip within the set for each individual. This is done through the ‘establish_modes’ and ‘calculate_modes_prob’ functions. For each individual, it defines groups of transportation modes and ranks them based on maximum utility (accounting for all trips). In this context, the NLM is used, a model that clusters alternatives into broader categories. The different colors in Table 4.6 indicate the three nests utilized. The utility of the various alternatives is then recalculated using the 'generate_alternatives' and 'calculate_utility' functions. The subsequent function, 'generate_lexicographical_order', arranges the modes based on their probability of use. It then populates the trip variables with information corresponding to the feasible modes for that trip, as seen in the 'change_trip_set' function.

The final phase involves the 'full_choice_set' mode assignment process. It starts by calculating the time and distance between the trip's origin and destination points using the 'calculate_distance500' function. It then assesses if the travel times fit within the non-active periods. If there's room to adjust the activity's flexibility, it checks if the trip now fits. This returns a true/false outcome through the 'evaluate_trip_times' function. Ultimately, it reconciles trips where the travel time exceeds the available time, making adjustments based on flexibility at both the origin and destination through the 'scheduling' function. The 'generate_choice_set' function ensures that the trip chain using TI or TI+TC is logical. For instance, if an individual travels by car, they should also return home by car at the day's end. If no feasible trip chain exists, the 'no_choice_solution' function is invoked, and the mode choice is narrowed down to either car or walking. The 'Full_choice_process' function groups the trips and creates new agents. In the case of the P2P ACS solution, these will be 'passengers' and 'owners'.

One distinctive feature of the base model is that the day starts at 5 am. This facilitates the transition between different days since mobility reaches its lowest peak at this time. Each day consists of 1,600 hours, slightly more than the actual 1,440 hours in a day, ensuring all ongoing trips can conclude. The simulation is designed to run for multiple days. At the end of each day, data pertaining to that day is saved in SQL tables, and at the start of each new day, a fresh schedule for individuals is generated.

4.5 Updates on ABM for Lisbon

The version of the AnyLogic software used to run the model is 6.9.0, which is considerably outdated (the most recent version being 8.8.4). Transitioning to a newer version was ruled out for two primary reasons: the additional work and costs involved. When the model was opened in a more recent version of the software, it encountered severe compatibility issues. The effort required for revision, coupled with the initial unfamiliarity with the model, would have been too time-consuming, leading to the decision to forgo compatibility efforts. Additionally, there was the financial aspect of procuring a new license for this version, especially since the model wasn't compatible with the student license due to its size restrictions (for instance, the number of agents).

Throughout the learning process of the base model, certain code segments were identified that could benefit from optimization. For instance, SQL queries within loops should be avoided. An SQL query inside a loop can often lead to performance and scalability issues, especially when the number of iterations is high. A simple analogy would be: in a phone survey, one can either call a person ten times, asking one question each time, or call once and ask all ten questions consecutively - the latter being more efficient. In the model's case, since the query aimed to access non-local database information and the number of iterations was substantial, it was essential to move several queries outside the loop to prevent script overload.

During the modification and creation of the new module, general Java programming conventions were also considered. For instance, class names should typically be nouns, written in title case with the first letter of each separate word capitalized, and should use full words—avoiding acronyms and abbreviations. This wasn't the case in the base model, as seen in classes like ‘Trip_set’ or ‘Order_modes’. Furthermore, both the modified code in the base model and the new code developed for the P2P ACS module were thoroughly commented.

Road Network

Modifying the road network was the most time-consuming aspect of the entire alteration process, but it was an indispensable step to get the simulation up and running. The modeled P2P ACS solution aims to simulate the service operation within the city of Lisbon. To achieve this, a denser road network is required, one that can differentiate between various routes on a more granular scale. However, since the base model was designed for the LMA, it's also essential to have a road network covering this entire area. Yet, if the road network is as dense as the one existing for the city of Lisbon, then the model would take a considerable amount of time whenever it performs any action related to the network (like loading node data, edges, constructing the graph, running the Dijkstra algorithm, etc.). The graph used to create the road network in the base model had a total of 37,716 nodes, which was quite heavy. The decision was made to design a new network that would ensure coverage of the LMA but would be denser within the Lisbon municipality. The outcome was a graph with 25,360 nodes, significantly reducing the computation time (see Figure 4.10). The computation time of the Dijkstra algorithm is quadratic in relation to the number of nodes, although some variations of the algorithm can optimize this computation time.

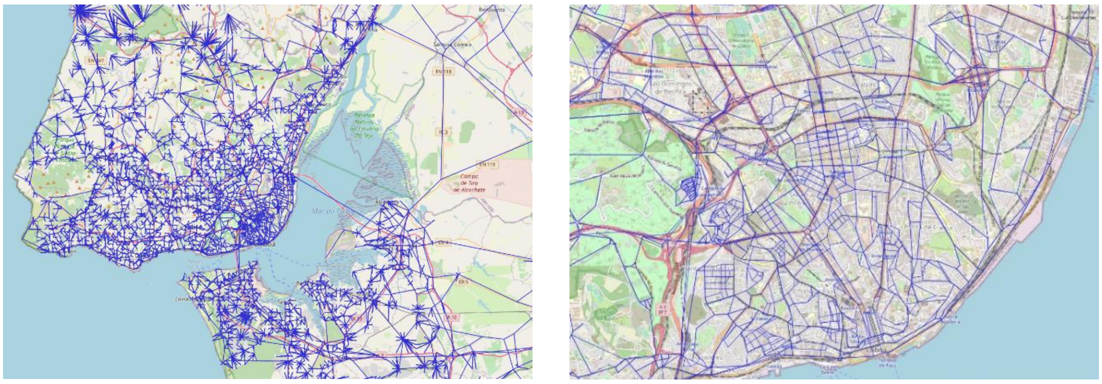


Figure 4.10 - Final road network, overlaid on the aerial photograph from Google (on the left is the LMA, and on the right is the municipality of Lisbon).

To construct this network, it was necessary to have two distinct road networks for the LMA: one that was more comprehensive (referred to as 'rrLX') and another that represented only the primary and secondary axes (excluding more localized access roads) (named 'rrAML'). Both networks were trimmed based on the boundaries of the Lisbon municipality. To achieve this, a Python script was employed to identify all nodes either inside or outside the designated area for the city. The Python script was executed using the Jupyter Notebook software. The city's boundaries were available on the CMLisboa website, represented as a structured set of georeferenced points. The algorithm used for this purpose is called the 'Even-Odd Method'. This algorithm operates as follows:

> 1. *Construct a line segment between the point* (P) *and a known point outside the polygon*

> 2. *Count the number of times the line segment inersects the polygon boundary*

> 3. *If the number is odd,* P *is an internal point; otherwise it is external*

Subsequently, it was essential to identify all the edges connecting the different nodes. Basic table manipulation work facilitated the filtering of selected nodes from both tables ('rrLX' and 'rrAML'), and the edges that only connected the chosen nodes. This task was accomplished using the Microsoft SQL Server software.

Edges connecting nodes within the city of Lisbon to nodes outside the city were also pinpointed in the 'rrAML' table. For nodes outside Lisbon, the original nodes were easily identified. For those within Lisbon, if the node wasn't present in the 'rrLX' table, the closest node to the georeferenced node in the original table was used. In the end, connections were visually verified by comparing different databases to ensure the accuracy of the results. This visualization was done using the QGIS3 software.

The tables in the [Basic_inputss] database related to nodes and edges underwent modifications. All altered tables were prefixed with 'x_P2P_ACS' (where 'x' is the original table name) for easy identification. The new tables are located in the same databases as the original ones (see Figure 4.11). Other tables, which referenced the original tables, were also modified. New columns were created, and the same naming method was applied. There was also a need to adjust the code in the base model to reflect the name changes of the tables and columns and to adapt certain variables. For instance, since capacity or parking information is only available for roads within the Lisbon municipality, it was essential to ensure these variables could take a null value. Another example is the new numbering (ID) for nodes and edges, which now starts at 0 instead of 1.

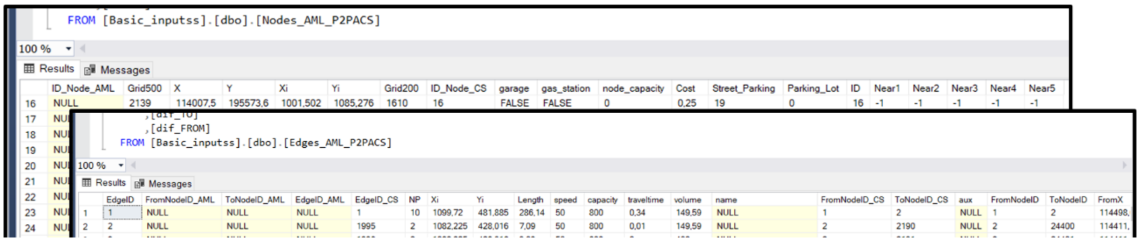


Figure 4.11 - Example of table renaming following the modifications to the road network.

To ensure that the new road network met its intended purpose, especially since the density of the road network had been reduced, a compatibility test was conducted. The primary routes between the different municipalities and the municipality of Lisbon were compared in terms of travel time and distance with the routes provided by the Google Maps application. The results indicate that the routes are similar in distance, with maximum differences of up to 8%. The travel times show more significant variations, with the times from the model's network being more conservative than those presented by Google (for 4 a.m.). The paths chosen by the Dijkstra algorithm, considering the proposed network, tend to align with Google's second or third choices. This suggests that the travel times associated with the edges represent average travel times throughout the day.

Dijkstra algorithm

One of the modifications made to the base model was the introduction of a new function named 'load_network' (refer to Figure 4.12). This function leverages an external library, JGraphT, to invoke the Dijkstra algorithm. JGraphT is an open-source Java library that employs various algorithms to address graph-related problems (see org.jgrapht). This change was driven by the computational time the base model's custom-built algorithm was consuming during graph construction. Hence, there was a need to utilize a more efficient version of the algorithm that was also compatible with an older Java version.

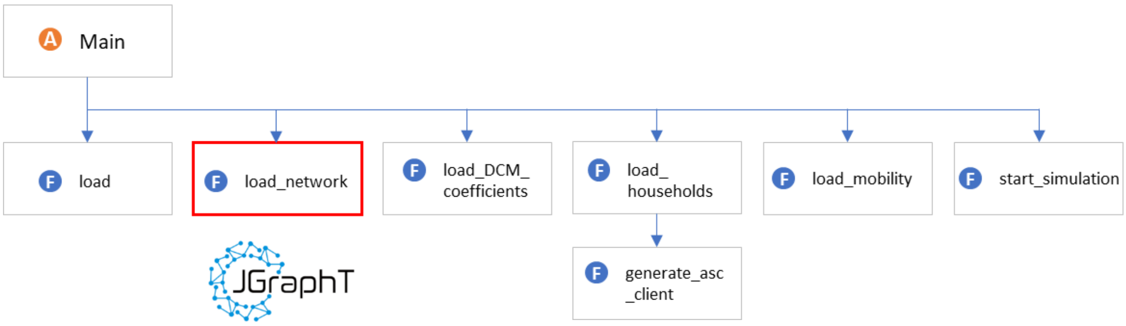


Figure 4.12 - Modification of the 'load_network' function.

The primary modifications to the base model included:

a. Introducing a new library in the 'import section' at the beginning of the process (within the 'Main' agent);

b. Establishing a constructor (class) named 'AnyLogicWeightedEdge' to populate the weights of the edges;

c. Creating a 'biblioDijkstra' function associated with the 'Main' agent, which invokes the 'SimpleDirectedWeightedGraph' function provided by the library to generate routes;

d. Lastly, the 'load_network' function was developed. This function uses the constructor, adds vertices and edges to construct the graph, and sets functions to calculate travel time and distance (for subsequent use).

Grids

From the outset of integrating the P2P ACS module into the base model, it became evident that there was a need to integrate both grids used, with each other, and with the road network. To recall, the Grid500 covers the LMA with juxtaposed squares of 500x500m, while the Grid200 divides only the municipality of Lisbon into squares of 200x200m. This need for compatibility arises because an individual resides in a Grid500 and travels between Grid500s, but the simulation of the P2P ACS operation isn't suitable for such a small scale (which affects the results of the operation and subsequent analysis).

In summary, the compatibility processes were aided by Python algorithms that measured distances (on the XX and YY axes), sorted, and assigned the nearest point. Tables were created in the databases, and new elements were added to the base model.

To link the Grid500 to nodes, a new table named 'Grid500_Nodes' was created in the [Car-sharing_ABM] database. This table assigns the nearest network node to the centroid of the Grid500. Additionally, a new collection named 'nodeCollection' was added to the 'Grid500' agent, which is constructed in the 'load' function. To link the nodes to the Grid500, a column was added to the 'Nodes_AML_P2PACS' table in the [Basic_inputss] database, assigning the Grid500 to which the node belonged. A new variable, 'grid500', was also created in the 'Nodes' agent. A similar process was carried out for Grid200.

Congestion

The function that calculates the time a vehicle takes to travel between an origin/destination pair takes into account the impedance caused by vehicle accumulation, commonly referred to as congestion. A brief analysis of the impact of the impedance function on the overall system shows that the percentage of time in circulation doesn't seem to be affected, potentially having a variation of ±5% compared to the average circulation time if congestion is not considered. This variation aligns with the fluctuation of the simulation itself (due to its random usage component), so it wasn't deemed significantly important. However, this function was activated, and all simulations are conducted considering the adverse effect of congestion on travel time.

Demand

While the preceding section highlighted certain discrepancies in the mobility data, addressing these inconsistencies was beyond the purview of this study. Correcting such disparities would necessitate a comprehensive additional effort, which doesn't fit within the established timeline of the PhD project. Nevertheless, to ensure a dependable trip database for evaluating the P2P ACS operation in Lisbon, a pivotal adjustment was made: we moderated the trip demand during the afternoon peak hours relative to the morning peak. This trend, corroborated by the IMOB data (as seen in Figure 4.15), is evident in numerous cities globally, given the staggered departure times of individuals in the afternoon.

The trip reallocation primarily centered on the "return home" activity, which predominantly characterizes the afternoon peak, constituting roughly 80% of all journeys between 4:30 p.m. and 7 p.m., as detailed in Table 4.3. The reallocation algorithm evaluates the average trip percentage per hour from the initial five databases during the 4 p.m. to 9 p.m. window and juxtaposes it with the IMOB survey data from 2017. Table 4.7 offers a side-by-side comparison of these figures.

Table 4.7 - Weighted values employed for the reallocation of journeys during the afternoon peak period.

Hours	Anylogic Database			IMOB Database		Weighted Redistribution	
	Average Trips	StdDev	Percent	Trips	Percent	Values	Percent
16-17	560,624	153.4	41.8%	212,440	16.8%	-150,000	-100.0%
17-18	305,507	178.1	22.8%	345,928	27.4%	27,548	18.4%
18-19	228,163	317.1	17.0%	342,606	27.1%	60,582	40.4%
19-20	148,167	127.4	11.1%	230,836	18.3%	43,307	28.9%
20-21	97,349	252.7	7.3%	130,835	10.4%	18,563	12.4%
Σ	1,339,811	Σ	100,0%	1,262,645	100,0%	Σ	0,0%

Another aspect scrutinized was the typical work schedule in Portugal. As depicted in Figure 4.13, the data from the AnyLogic databases suggests longer working durations when contrasted with the findings from the IMOB (2017) survey specific to the LMA.

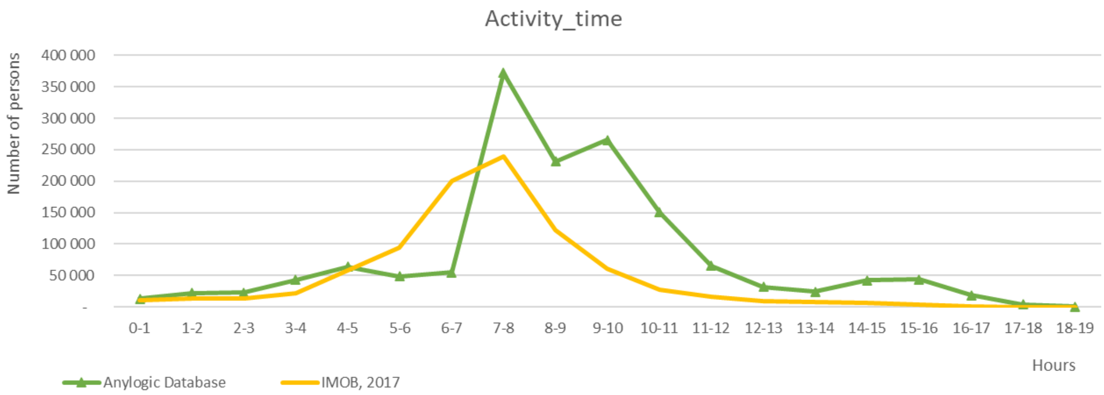


Figure 4.13 - Comparative Analysis of the Work Duration from the IMOB (2017) Survey[44] and the AnyLogic Database.

To align this data more closely, the duration of the activity was randomly reallocated, drawing from the percentage values showcased in Table 4.8.

Throughout the refinement process, two critical filters were implemented to mitigate potential unintended consequences. Initially, the algorithm opted for a random selection of trips to reschedule, ensuring the spatial distribution remained intact. Subsequently, the focus was on individuals who didn't have subsequent trips after their "return home" activity, preserving the logical sequence of activities. Post-filter application, the algorithm pinpointed 150,000 trips,

[44] The work period extracted from the IMOB, 2017 database was calculated based on the difference of the ending of the trip with work/study purpose and the beginning of the next trip (if the person has more trips for work/study, the activity time of these periods is added to the first one).

mirroring the discrepancy between the peak figures from the initial databases and the IMOB data, from INE (2017).

Table 4.8 - Percentage values utilized for reallocating work/study activity durations based on IMOB (2017)'s peak hours.

Activity_time (hours)	# Persons	Percentage
5-6	93 840	14,3%
6-7	200 777	30,6%
7-8	238 861	36,4%
8-9	122 708	18,7%
Σ	656,186	100%

The approach bifurcated based on the primary intent of the original trip (or the individual's initial trip, given that the subsequent one typically involves "returning home"):

- For trips centered around work or academic pursuits, the activity duration underwent adjustments in line with Table 3.6 values, specifically targeting individuals with activity spans exceeding 8 hours. Activities initially concluding between 4 p.m. and 5 p.m. were rescheduled to fall between 5 p.m. and 9 p.m., drawing from Table 3.5 values. The activity's commencement was deduced by subtracting its duration from the end-time.
- For trips rooted in personal, wellness, social, or dining reasons, the activity's onset was advanced by a random duration, up to 2 hours. While the activity duration remained consistent, its conclusion was recalibrated. This adjustment ensured that these activities didn't commence outside the 10 a.m. to 4:30 p.m. window, given the database's recorded dip in such trip purposes during this period compared to survey data. This modification aimed to rectify potential data disparities.

This meticulous process was superimposed on the foundational database, which is segmented into five tables. The outcomes are visually represented in Figure 4.14, Figure 4.15, and Figure 4.16. The revised data, averaged across the five modified tables, will serve as the foundation for the P2P ACS model simulations.

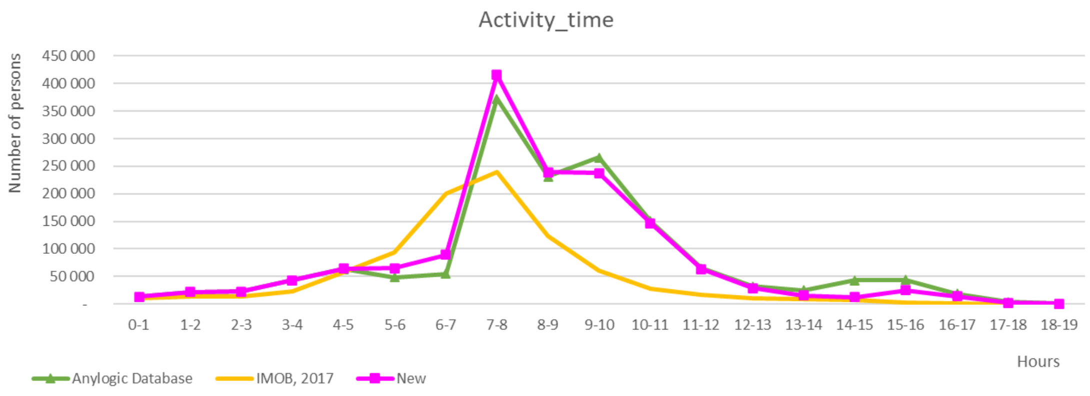


Figure 4.14 - Outcome of the data refinement process pertaining to work duration.

Figure 4.14 depicts a nuanced modification to the work time schedule, with a mere 3% of trips categorized under "work/study" undergoing changes. The zenith of working hours continues to be clustered around 7-8 hours daily. Additional refinements resonate with the insights from IMOB (INE, 2017), bolstering the credibility of the revised data.

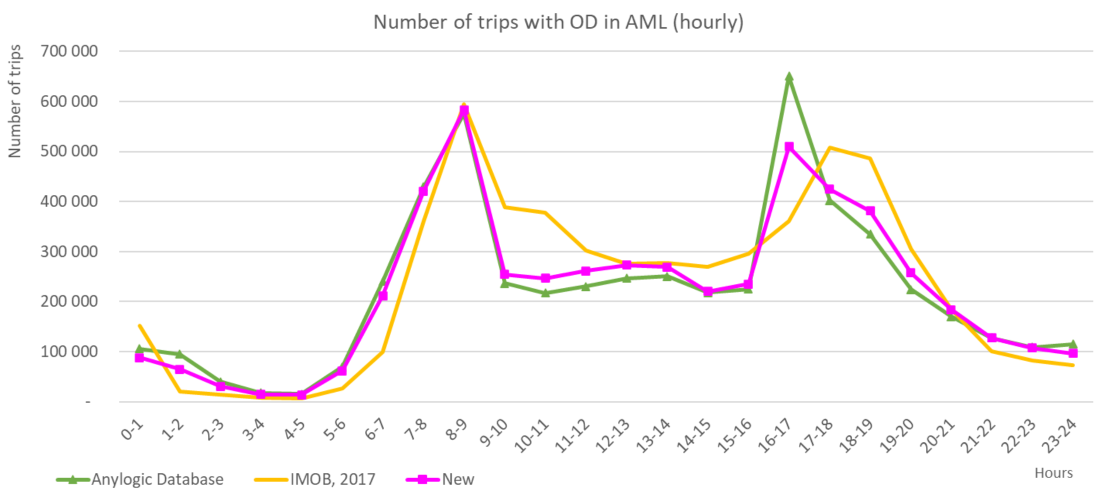


Figure 4.15 - Outcome of the data review process for LMA 's trips.

The aim to disperse the afternoon peak hour was effectively realized, all while upholding specific constraints. These constraints included maintaining demand levels at the day's onset and closure, and abiding by the proportionate allocation of trips based on purpose within designated time frames, as outlined in Table 4.8. These strategies collectively contribute to a more equitable and authentic depiction of daily mobility trends.

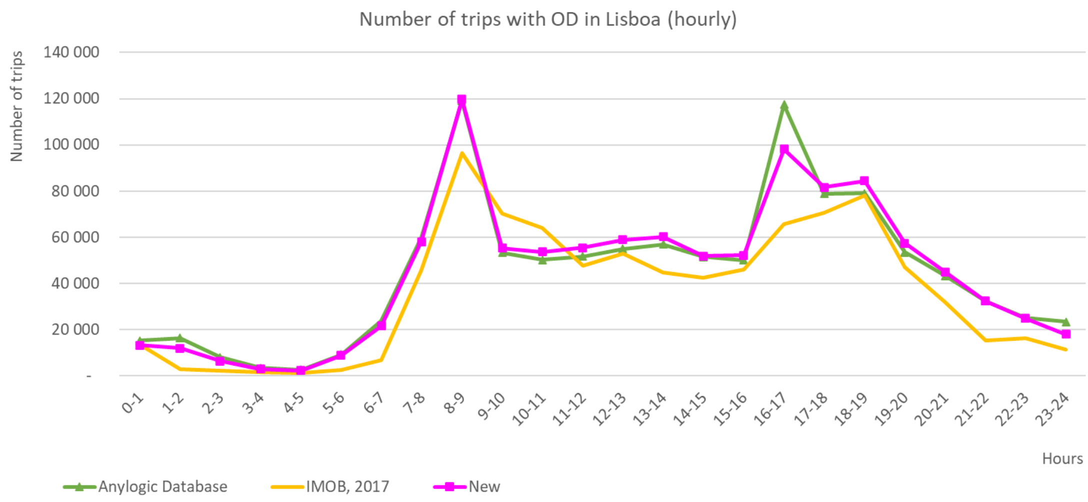


Figure 4.16 - Outcome of the data review process for Lisbon's trips.

The modification was executed on the LMA database, with conspicuous alterations notably concentrated within the Lisbon region, which stands as the central point of interest in this investigation. A discernible reduction in the afternoon peak hour and an amelioration in the distribution of trips across the day are evident outcomes.

While the P2P ACS model will evaluate a fraction of the city's comprehensive demand, these adjustments are anticipated to exert minimal influence on the eventual outcomes. Nevertheless, these meticulous refinements endeavor to faithfully mirror the authentic mobility dynamics in Lisbon and to offer an optimal comprehension of the prevailing scenario.

4.6 Implementing the new P2P ACS module

4.6.1 Overview

The P2P ACS solution is simulated using a multi-agent model, which is structured in two main phases as illustrated in Figure 4.17:

- Phase I: Allocation of Supply and Demand to the P2P ACS Service - This phase consists of two components. These components replicate the decision-making process of either the vehicle owner or the passenger when choosing between renting an AV or opting for the P2P ACS solution, respectively.
- Phase II: Simulation of the P2P ACS Module - This phase introduces a segment that models the interaction between the demand (from passengers) and the supply (from vehicle owners) within the P2P ACS system.

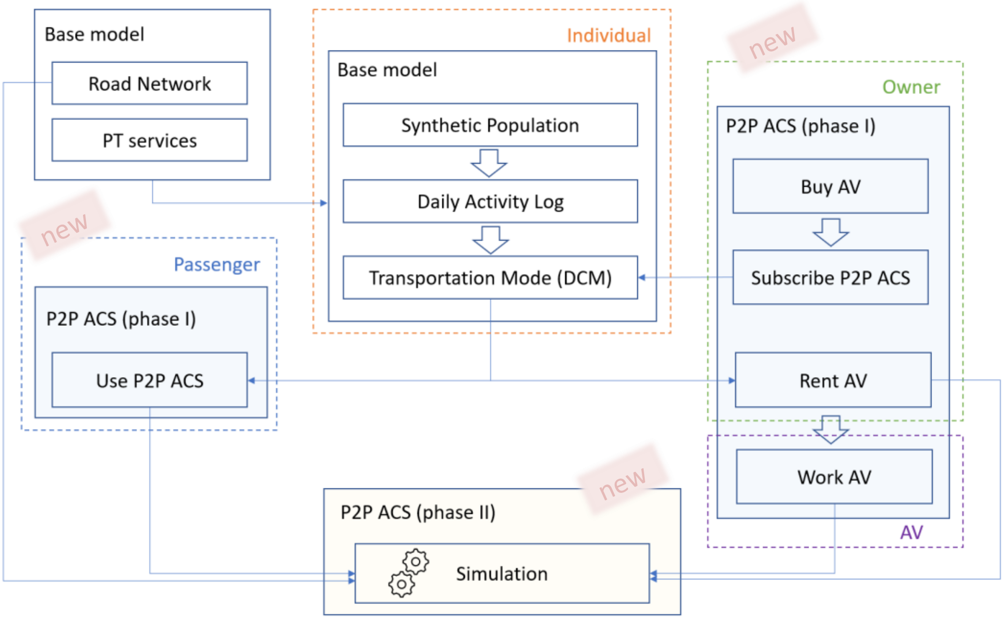


Figure 4.17 - Overview of the P2P ACS multi-agent model.

AnyLogic is a software that supports agent-based and discrete-event simulation (as well as system dynamics, which was not used in the developed work). In the case of event-based modeling, process flowcharts are constructed. In Phase II, several flowcharts are presented that mimic the behavior of the agents to simulate and evaluate the P2P ACS operation.

For this module, four agents were considered: the passenger, the AV, the central system, and the vehicle owner. The first three agents are consistent with previously published work on fleet-based AMOD (Azevedo et al., 2016; Basu et al., 2018; Oh et al., 2020). However, the fourth agent, representing the vehicle owner, captures the intricate daily decision-making process.

Table 4.9 displays the agents introduced by the P2P ACS module. This table includes the four agents identified earlier, along with two additional agents that support the simulation's operation. The 'Municipality' agent was designed to store information related to movements between municipalities for quick access. The 'Message_Queue' agent was developed to address the challenge of message reception, given the high volume of messages at any given time and the parallel processes running. This agent is more complex than the previous one and will be explained in the following section.

The P2P ACS service operates on the foundation of communication between its various agents. Most actions, which are state changes, occur due to the sending or receipt of messages. All these communications are centralized within a single agent named 'Message_Queue'.

Table 4.9 - Agents within the P2P ACS Module.

Agent	Description
Ataxi	Shared autonomous vehicle
Central_P2PACS	Platform
Message_Queue	Agent that controls the sending and receiving of messages between other agents
Owner	AV owner
Municipality	AML municipalities
Passenger	P2P ACS solution's passenger

Given that the model is built on an older version of AnyLogic, which doesn't support the "queue" function, an alternative approach was needed. To guarantee the successful delivery of every message, a primary or 'root' agent was designed to substitute for this function, effectively managing the list of messages.

Furthermore, every message sent has an associated requirement for a delivery confirmation by the message recipient. This ensures that messages are not just sent, but also successfully received. Figure 4.18 provides a detailed illustration of the entire process for a single message being transmitted from Agent A to Agent B.

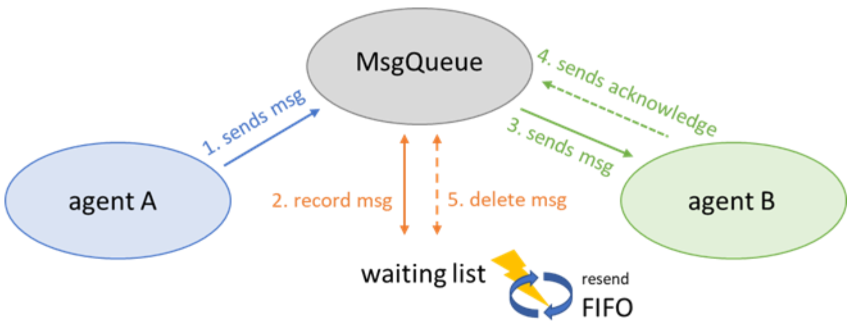


Figure 4.18 - Message scheme to reproduce FIFO function.

The messaging system is built upon the 'CustomMessage' class, which outlines all the types of messages that can be exchanged between agents. When a message is dispatched but not acknowledged by the recipient (for instance, if the recipient is in an unexpected state due to parallel processes in the model), the 'Message_Queue' agent (identified as 'MsgQueue' in the figure) initiates a cyclical resend process. The message remains in the queue until there's a confirmed receipt.

From a coding perspective, there's an internal mechanism ensuring the agent consistently remains in the same state, thereby ensuring all messages are received. This mechanism oversees the functions of receiving, dispatching, and updating the waiting list of messages. Additionally, there's a step to cyclically resend messages from the waiting list (following a first-in, first-out or FIFO approach) if the list isn't empty, with the exception of the most recently added message. The operational flowchart detailing the functions and processes of this agent is depicted in Figure 4.19.

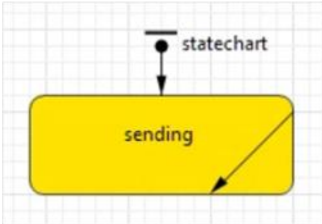


Figure 4.19 – 'Message_Queue' agent´s statechart.

To set up the simulation for the P2P ACS service, it was necessary to add some classes to the model. Table 4.10 lists these classes and provides a brief description of each.

Table 4.10 - Classes within the P2P ACS Module.

Class	Description
AnylogicWeightedEdge	Represents the weights of the edges
CustomMessage	Used as a custom payload for inter-agent communication
OwnerValues	Represents the AV owner
PassengerValues1	Represents the passenger
Shift	Stores the working shifts, for each vehicle
TripsPassenger	Defines the passenger's trips
Vehicle	Represents the aTaxi trips

Throughout the development process, it became necessary to create auxiliary variables. These variables helped track the construction process, detect errors, and measure performance. The performance variables were particularly crucial in analyzing the impact of the P2P ACS service on each participant and the system as a whole.

A specific instance highlighting the importance of auxiliary variables was the need to develop a 'Message_Queue' agent. This need arose due to a discrepancy between the number of messages agents were sending and the number the central system was receiving. It became essential to establish various variables across different agents to count the exchanged messages. At a certain point in the development, many of these variables were either deleted, as they became redundant, or were converted into comments within the code. This ensured they were overlooked during the simulation process.

Variables designed to calculate key performance indicators are assigned to each agent within the model. The guiding principle behind their creation was always to maintain the model's simplicity, avoiding redundant information wherever possible. For instance, the variable 'distance_travelled_empty' for each 'Ataxi' agent represents the distance that agent traveled without passengers.

Within the 'Main' client, one can find the entire process for aggregating and printing outputs for subsequent analysis. Following the previous example: the variable representing the total distance traveled by all taxis, 'distanceRelocation', is invoked at the end of the day by the 'Print_DUMP_Ataxi' event. This event organizes all relevant information about the SAVs in operation that day and prints it using the 'set_output_overall' function. Similar events exist for vehicle owners and passengers.

Other AnyLogic elements that enable the functionality of the P2P ACS module simulation, such as variables, parameters, functions, or events, are identified in the subsequent text.

4.6.2 Owner agent

Individuals have daily activity schedules and choose the best mode of transportation based on their household's socioeconomic characteristics and the features of the transportation system. If the household, which the individual is a part of, owns one or more cars, then the individual can use the car for daily commutes. There's a potential for family members to use the car. The data from population databases assigns a higher probability of car usage to one of the family members, and the transportation mode assignment model allows for carpooling with family members. While conducting their activities, the driver parks the vehicle, leaves it in the same spot, and returns at the end of the activity to use it again. This process repeats throughout the day until they return home.

As mentioned earlier, the assignment of transportation alternatives to individuals (‘Client’ agent) is represented by the ‘full_choice_process’ function. Since the base model uses a 1/20 scale (1 unit represents the mobility of 20 people) due to the computational capacity of the simulation, it's necessary to adjust the number of people traveling by car to simulate the P2P ACS solution with the actual volume of people.

The base model was created based on the utility of modes per trip and lacks some issues associated with this solution; the reconciliation of individual transportation use is done before adjusting the scale. For instance, if one person drives to work, they should drive back home. However, given the probabilistic assignment based on the cumulative utility function, there's a subsequent issue. If the utility dictates 75% use of individual transportation and 25% use of public transportation, in the last step of modal distribution, there might be 16 car trips to work and only 14 return trips by car. To overcome this challenge, the P2P ACS module assumes there are only 14 cars in the system, and the 2 people who used a car for the first trip carpooled.

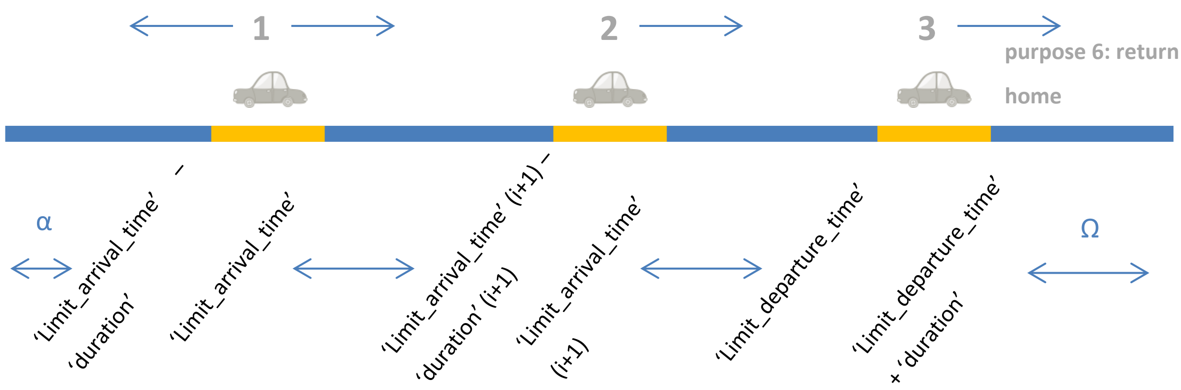
These 14 vehicle owners would be potential peer-providers of the P2P ACS solution in a futuristic scenario where private AVs are in circulation. However, these individuals would first need to purchase an AV, then subscribe to the P2P ACS service, and finally, be willing to offer their vehicle. The ‘establishOwnerCar’ function within the ‘Client’ agent sets the individual's decision algorithm in the model. This algorithm, through the application of three decision levels, narrows down the pool of individuals. Each decision level has an associated factor (parameter): ‘carOwnership’, ‘carSubscription’, and ‘carRent’. In the end, it's possible to identify the group of people willing to lend their vehicle on the simulation day.

The P2P ACS service simulation aims to evaluate the participation possibility of different vehicle owner groups. For this, 4 groups were considered, distinguished by the combination of the following characteristics:

- Living in Lisbon/outside Lisbon - A person living in Lisbon can have their car ready to work without the need for relocation. For someone outside Lisbon, relocating the car to be included in the P2P ACS service will incur costs and travel time.
- Having trips/not having trips - If a person doesn't need to conduct any activities outside the home or doesn't need the vehicle for them, they can offer their car all day; otherwise, they'll only have some free periods that need to be analyzed.

Building availability in the groups brought different levels of complexity. In the group named ‘ownerLiveLx’, referring to Lisbon residents who don't have trips during the day, the SAV's availability is total, making the construction of the ‘aTaxi’ agent straightforward. In the ‘ownerLiveOut’ group, non-mobile people living outside Lisbon, a function is needed to determine the relocation time. This function uses the average travel time between municipalities, stored in the ‘Municipality’ agent. The vehicle moves to a random point within the Lisbon municipality, a process that requires optimization.

Groups of owners with trips are more challenging to model due to the nature of the activities defined in the base model. Figure 4.20 displays a scheme that reproduces how the travel periods are defined using the variable names in the AnyLogic model.



Let i be the sequence of activities.

Figure 4.20 - Calculation of departure and arrival times, where the blue bar represents the allocation to the P2P ACS service.

Consider an individual (belonging to the 'ownerTripLxLiveLx' group) who lives in Lisbon and has two activities during the day in Lisbon, for which they travel by car (imagine a workplace and a supermarket). During the periods when the vehicle is parked - four periods: 1. before going to work, while at home (α); 2. while at work; 3. while at the supermarket; 4. after returning home at the end of the day (Ω) - the vehicle is made available to the P2P ACS service. It's assumed that the vehicle owner always has priority, meaning the vehicle is only available when the owner doesn't need it, and for a specific period. It's also considered that the vehicle is only available if the activities are in Lisbon.

The simulation of the P2P ACS module starts at midnight and lasts for 24 hours. If an individual's trip starts before or ends after midnight (according to their daily schedule), then some adjustments need to be made to availability. If the first trip of the day starts before midnight, the owner doesn't have the car available to put on the market (period α). On the other hand, at the end of the day, the car doesn't work until 24h as usual; it has to end its shift earlier. If the last trip of the day ends after midnight, the owner doesn't have the car available from 12 a.m. as usual, and on the other hand, they can't put the car to work at the end of the day (period Ω).

In the 'ownerTripLxLiveOut' group, people with trips who live outside Lisbon, an additional relocation time needs to be added for the periods of the day when the owner is at home.

To create the vehicle owner in the P2P ACS module, it was necessary to add some elements to the base model. Firstly, the 'Owner' agent was created. This agent represents all the owners that will be used in the P2P ACS service simulation. To construct the 'Owner' agent, an 'OwnerValues' class was created that gathered personal characteristics of the owner. In the 'establishOwnerCar' function, the 'ownersToGenerate' collection is created.

To avoid overloading the P2P ACS service simulation, vehicle owners are created in the system in a staggered manner. That is, all the people who can make their personal vehicle available to the P2P ACS service for the first time that day, between 3 p.m. and 3:15 p.m., are created (as the 'Owner' agent) by the system at 3 p.m. This process is triggered by the 'GenerateOwner' event located within the 'Main' agent and runs every 15 minutes. From this point on, the owner goes through the decision process shown in Figure 4.21.

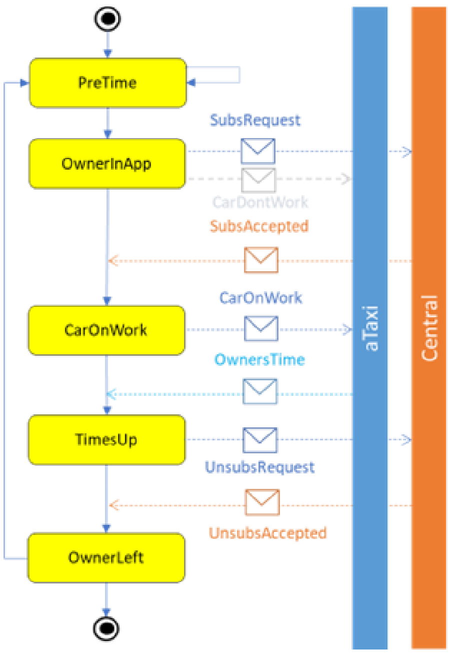


Figure 4.21 - Owner's statechart.

After being created, the 'Owner' agent waits in the 'PreTime' state. When it's time to make the vehicle available, the agent transitions to the 'OwnerInApp' state and sends a message to the central system notifying it that there's an unused vehicle. After receiving a response from the central system, the owner transitions to the 'CarOnWork' state and informs the vehicle that it's now in service for the P2P ACS solution until a specified time. The service's operation was constructed based on the rule that prioritizes the vehicle owner's use: the vehicle must always be at the predefined location and time whenever the owner needs it. When this period ends, the vehicle notifies the owner of its return, and the agent transitions to the 'TimesUp' state. The owner is responsible for informing the central system about the end of the vehicle's availability. After confirmation from the central system, the agent moves to the 'OwnerLeft' state. If the owner has another period during the day when they wish to rent out the car, they transition back to the 'PreTime' state and wait; otherwise, they exit the system.

4.6.3 Autonomous vehicle agent

To model the vehicle that the owner makes available in the P2P ACS module, it was necessary to create the 'aTaxi' agent. This agent represents all the vehicles to be used in the P2P ACS service simulation. To construct the 'aTaxi' agent, the classes 'Shift' and 'Vehicle' were created. The 'Shift' class defines the vehicle's shifts, while the 'Vehicle' class gathers the characteristics of the trips made by the vehicle. The 'aTaxi' agent is created within the 'establishOwnerCar' function, which is nested inside the 'Client' agent.

When the 'aTaxi' agent is created, the owner's ID is associated with it. Thus, each SAV is uniquely linked to one person. However, each individual can own more than one SAV. The state diagram is designed to accommodate this. Messages exchanged between the owner and the central system identify the targeted SAV. And each AV operates independently as an individual agent. The AV agent makes decisions concerning both geographical (relocation and trip) and operational aspects during its available period. Figure 4.22 displays the decision-making process of the 'aTaxi' agent.

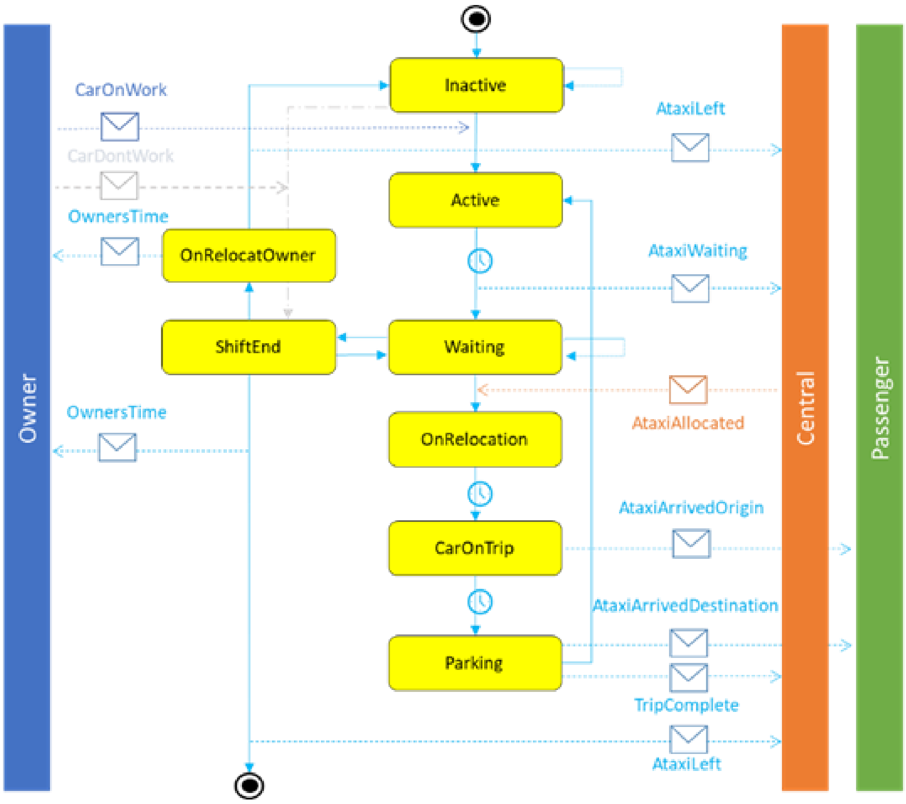


Figure 4.22 - AV's statechart.

The 'aTaxi' agent, upon creation, remains in the 'Inactive' state. When it receives a message from its owner indicating that the vehicle is in service for the P2P ACS solution, the agent transitions to the 'Active' state. It then informs the central system that it's available to transport passengers and waits in the 'Waiting' state. During its service period, the vehicle can be requested at any time. If that happens, the vehicle, upon receiving a message from the central system indicating it has been allocated, moves to the 'OnRelocation' state. This allocation message includes the spatiotemporal details of the trip (starting and ending points of the passenger's requested journey, and relocation and travel times). Once the relocation time ends, the agent transitions to the 'CarOnTrip' state and notifies the passenger of its arrival at the trip's starting point. When the travel time concludes, the agent moves to the 'Parking' state, informs the passenger of its arrival at the destination, and also notifies the central system that the trip was successfully completed. This work doesn't consider the car's relocation after it parks at the destination. Therefore, the car transitions back to the 'Active' state and remains in the same location, awaiting a new trip request.

Once the vehicle's allocated period ends, the agent transitions to the 'ShiftEnd' state. The end time of this period is calculated based on the safety level the owner desires for the return time. For instance, if the owner needs the vehicle by 4 p.m., then the service period ends at 3:45 p.m., the time when the SAV begins its return journey to the owner, unless the owner has specified a longer safety period (the 'onTimeLevel' parameter ranges from 1 to 3 and is multiplied by 15-minute intervals). If the vehicle's owner has set another shift for lending, then the agent moves to the 'OnRelocatOwner' state, notifies the owner of its return, and then reverts to the 'Inactive' state. If the central system doesn't accept the vehicle's subscription request for the next shift or the owner changes their mind about lending it, the agent jumps from the 'Inactive' state directly to the 'ShiftEnd' state. If there are no more shifts for that day, the vehicle exits the system.

4.6.4 Passenger agent

A passenger refers to anyone who utilizes the P2P ACS service for transportation. The choice to use this service is influenced by an individual's personal schedule, including their activities and available time, as well as their interest in this mode of transportation. The 'full_choice_process' function in the base model assigns the mode of travel for each trip and each 'Client' agent.

Within the MNL function, there are various transportation options available. Typically, when simulating new modes, a new alternative is added, along with its respective attributes, to reflect the population's interest in using it. However, this wasn't the case here. For the simulation of the P2P ACS service, since we would be working based on speculative attributes with weak foundations to describe a non-existent service, we chose to use scenario-based modeling. In this context, scenarios could involve either completely or partially replacing one of the existing alternatives. To achieve this, it was essential to develop a function that would assign individuals ('Clients') to the service, either through probabilistic coefficients or randomness.

Given that the base model is scaled at 1/20 (where 1 unit represents the mobility of 20 people), it's necessary to adjust the number of passengers to simulate the P2P ACS solution with the 'real' passenger volume. This adjustment isn't consistent for each unit because the probability assignments for mode usage, considering the positive utility of different transportation modes for that journey, mean that groups of people might choose different modes. For instance, if the utility function indicates that the probability of using a car is 75% and a motorcycle is 25% (totaling 100%), then out of a group of 20 people making this trip, 16 might choose the car and 4 the motorcycle (totaling 20). However, a randomness factor is still applied in the final mode assignment. In the intended simulation, this isn't an issue since there's no distinction between modes. Nevertheless, the P2P ACS module is designed to identify the mode, and if needed in the future, one can easily filter for the desired mode.

The creation of vehicle owners and passengers, which enables the simulation of the operation, is independent. In other words, the same individual can be assigned both the role of a passenger and that of a vehicle owner. This independence is considered a limitation of the developed model. However, if we take into account that the model randomly selects only 10% of passenger trips within the city of Lisbon (representing demand) and 1% of vehicle owners in the Metropolitan Area of Lisbon (representing supply), then the likelihood of dual assignment is relatively low.

To create a passenger in the P2P ACS module, several elements had to be added to the base model. Initially, a 'Passenger' agent was created to represent all passengers using the P2P ACS service. Subsequently, an 'establishPassengers' function was developed within the 'Clients' agent to generate passengers (representing demand) based on certain decision-making algorithms. To construct the 'Passenger' entity, a class called 'PassengerValues1' was created to gather personal characteristics and details of the individual's first trip of the day. Another class, 'TripsPassenger,' was developed to compile features of all the individual's trips.

In generating demand, the model was designed not to preserve the sequence of trips assigned to each individual, as this was deemed irrelevant for the operation of the service. This is a constraint of the model that can be easily modified. Additionally, no adjustments were made to an individual's daily schedule based on changes in travel time from the original mode to the service under study. The only restriction in trip assignment relates to location, specifically the origin/destination (O/D) pair. In this case, all trips originating and ending in the city of Lisbon were filtered. There are no other restrictions on assignment; that is, anyone can be selected to use the P2P ACS service regardless of trip distance, time of day, whether they have a pass or not, etc.

In the demand creation algorithm, three attributes were considered that reflect people's decision-making process regarding the use of the service: (a) subscription to the P2P ACS service; (b) actual use of the P2P ACS service; and (c) requesting a car for the trip. In the P2P ACS module, these parameters ('passSubscription', 'passUse', and 'passUseTrip', respectively) are assigned to the 'Client' agent. This probabilistic assignment process emulates the population's decision-making in choosing to use the service. Each decision is conditional. An individual must first subscribe to the solution, then decide to use the app, and only after that can they request an SAV for their intended trip. The algorithm assigns each person a complete daily schedule related to the use of the P2P ACS service.

In the trip assignment process, there were some details related to time and space that needed adjustment. Individuals (the 'Client' agent) are assigned trips between Grid500. To simulate the movements of the SAVs, the road network is used, meaning the assignment of trip origins and destinations must be made to nodes. In this case, random nodes within the Grid500 (both origin and destination) were assigned. Each node was also associated with Grid200. Regarding departure times, these are set based on rules already implemented for the base model, which depend on the activities leading to the trip. However, a random component was added to the trip assignment at the beginning and end of the day (within a 10-minute window) to compensate for the lack of response from the supply side at the day's boundaries.

To avoid overloading the P2P ACS service simulation, passengers are introduced into the system in a staggered manner. That is, all individuals who will start their journey and use the P2P ACS service for the first time that day, between 3 p.m. and 3:15 p.m., are created (as the 'Passenger' agent) by the system at 3 p.m. This process is triggered by the 'GeneratePassenger' event (located within the 'Main' agent) that runs every 15 minutes. The event accesses the 'passengersToGenerate' collection, where the list of P2P ACS solution passengers for that day is stored, to create each new passenger. From this point, the passenger goes through the decision-making process depicted in Figure 4.23.

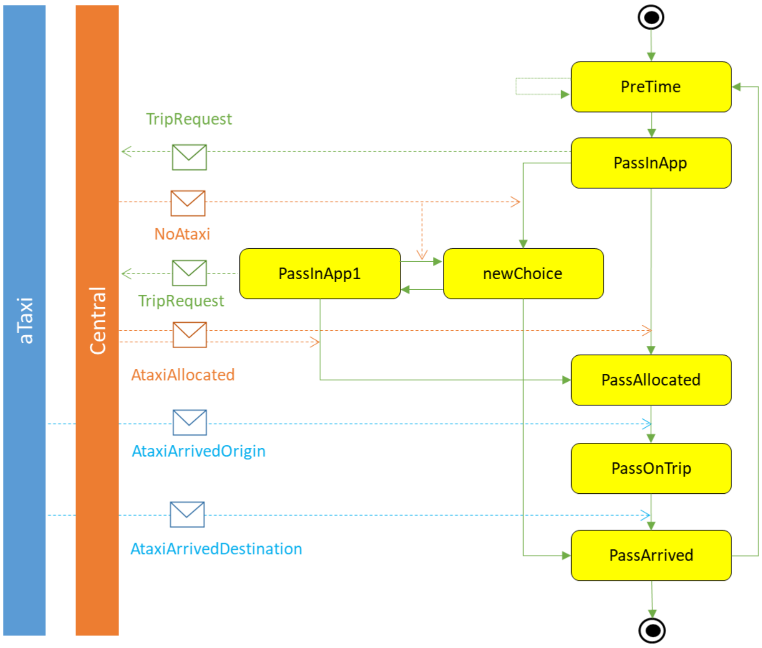


Figure 4.23 - Passenger´s statechart.

The Passenger enters the system and waits in the 'PreTime' state for the passage of time. When it's time to make the trip, the Passenger transitions to the next state, 'PassInApp'. At this point, the trip information (origin, destination) is sent to the central system. If the central system has an available SAV, the Passenger then transitions to the 'PassAllocated' state, based on a message from the central system, and waits for the SAV's arrival. Otherwise, the Passenger moves to the 'newChoice' state. Here, the passenger has the option to request an SAV for the trip again, transitioning to the 'PassApp1' state, or to cancel the request and move to the 'PassArrival' state. There's no assignment of another mode of transport for this passenger's unfulfilled trip since the simulation isn't concerned with analyzing other modes. When the passenger is in the 'newChoice' state, they can only request a new trip a specific number of times, defined by the 'attemptNum' parameter (within the 'Passenger' agent). The time the passenger takes to make a new request has a random component, and the maximum waiting time is defined by the 'X' parameter.

When the passenger is in the 'PassAllocated' state, they only transition to the 'PassOnTrip' state after receiving a message from the SAV indicating its arrival. The shift to the 'PassArrival' state is also triggered by a message from the SAV informing the passenger that they have reached their destination. If the passenger has more trips scheduled for that day, their state changes back to 'PreTime'. Otherwise, the passenger exits the system. Associated with the trips (in the 'tripsP' collection) are two variables: 'tripNumber', representing the sequence of trips, and 'totalTrips', representing the total number of trips the passenger has for that day. The decision to stay in the system and wait for a new trip depends on comparing these variables (‘tripNumber’ < ‘totalTrips’).

This conceptual model doesn't account for future changes, especially those related to population dynamics, transport and mobility planning decisions, and perceptions of AVs. How an individual perceives an AV might differ from their perception of a conventional vehicle. The inherent autonomy of the car allows it to fulfill more household trips.

4.6.5 Central agent

The dispatcher plays a pivotal role in overseeing the subscription and unsubscription processes of vehicles by communicating with vehicle owners through message exchanges. When an owner seeks to subscribe their vehicle to the central system, the dispatcher grants the request automatically, subsequently adding the vehicle to a list termed "currentSubscription". Conversely, when an owner wishes to unsubscribe, the vehicle is promptly removed from this list. Both processes are structured with future adaptability in mind, allowing for potential restrictions on vehicle subscription or unsubscription based on specific rules or criteria.

The dispatcher's involvement is triggered whenever there's a change in one of the four possible vehicle states:

- Subscribed
- Unsubscribed
- Allocated
- Available

Figure 4.24 visually represents the interrelation of these states. For instance, a vehicle cannot simultaneously be in both subscribed and unsubscribed states. Similarly, a vehicle must be subscribed before it can be allocated.

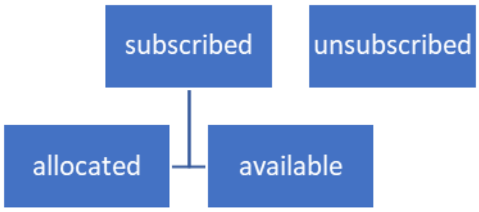


Figure 4.24 - The different states an AV can have within a Central P2P ACS system.

When a vehicle is designated or allocated for a task, it is added to the 'allocatedCars' list. Conversely, once the vehicle completes its task and becomes available again, it is removed from the 'allocatedCars' list and is then added to the 'availableCars' list. Concurrently, the 'grid200Vector' vector undergoes an update through the 'updateGrid200Vector' function. This function is responsible for mapping the grids that currently have available cars.

When a passenger communicates a need for a vehicle to the dispatcher, the vehicle allocation process is initiated. This process triggers the 'getBestGrids' function. The primary objective of this function is to sort and organize the grids containing available cars based on their increasing distance from the starting point of the passenger's trip. To assist this function, there's a variable named 'distanceGrid200Matrix'. This matrix stores the distances between all the centroids of the Grid200. The function employs the following algorithm:

$> 1. build(vectorGridPassenger\ where\ it\ attributes\ 1\ to\ the\ index\ of\ the\ grid200$
$where\ passenger\ stands\ and\ 0\ otherwise\ as\ b_j)$

$> 2. multiply\big(distanceGrid200Matrix\ as\ a_{ij}\ by\ b_j\big)\ which\ results\ in\ vector\ c_i$

$> 3. booleanize(grid200Vector\ as\ d_i)$

$> 4. multiply(c_i\ by\ d_i)\ which\ results\ in\ vector\ g_i$

$> 5. sort(index\ of\ g_i\ ascendent)$

$where\ i, j\ = lenght(grid200)$

After obtaining an ordered list of non-empty Grid200 grids, which is the result of the previously mentioned algorithm, a search process for a SAV commences within each grid. Notably, the search order within each grid is randomized. The assignment of a vehicle to a specific request is contingent upon a time constraint. If the first vehicle doesn't meet the stipulated condition, the system then considers the next vehicle, and this process continues. The algorithms selected for the simulation were specifically chosen to ensure the simulation's runtime remains efficient.

The aforementioned condition pertains to the vehicle's availability. It's imperative to ensure that the vehicle owner retains priority in the use of the car within the P2P ACS service. To achieve this, the system evaluates whether, at the time of allocation, the vehicle has sufficient time to complete the following tasks:

1. Relocate to pick up the passenger.
2. Complete the passenger's requested trip.

3. Relocate to rendezvous with the vehicle owner before the shift concludes.

Another constraint to consider is the maximum waiting time for the passenger. After selecting a suitable vehicle, the dispatcher calculates the time required for the vehicle to relocate to the passenger's location. If this waiting time exceeds a certain threshold, the allocation isn't executed, and the passenger receives a notification indicating 'no Ataxi available'. This restriction, however, was disabled for the simulation.

Upon successful allocation of an SAV, pertinent information is relayed to the Ataxi (this includes passenger details such as trip origin and destination) and to the passenger (confirming the allocation). Subsequently, the vehicle's status is updated to 'allocated'. If no vehicles are available, a 'NoAtaxi' message is dispatched to the passenger. The Ataxi is then tasked with contacting the Central agent at the trip's conclusion to update its status to 'available'.

The potential states that the P2PACS Central agent can assume are depicted in Figure 4.25.

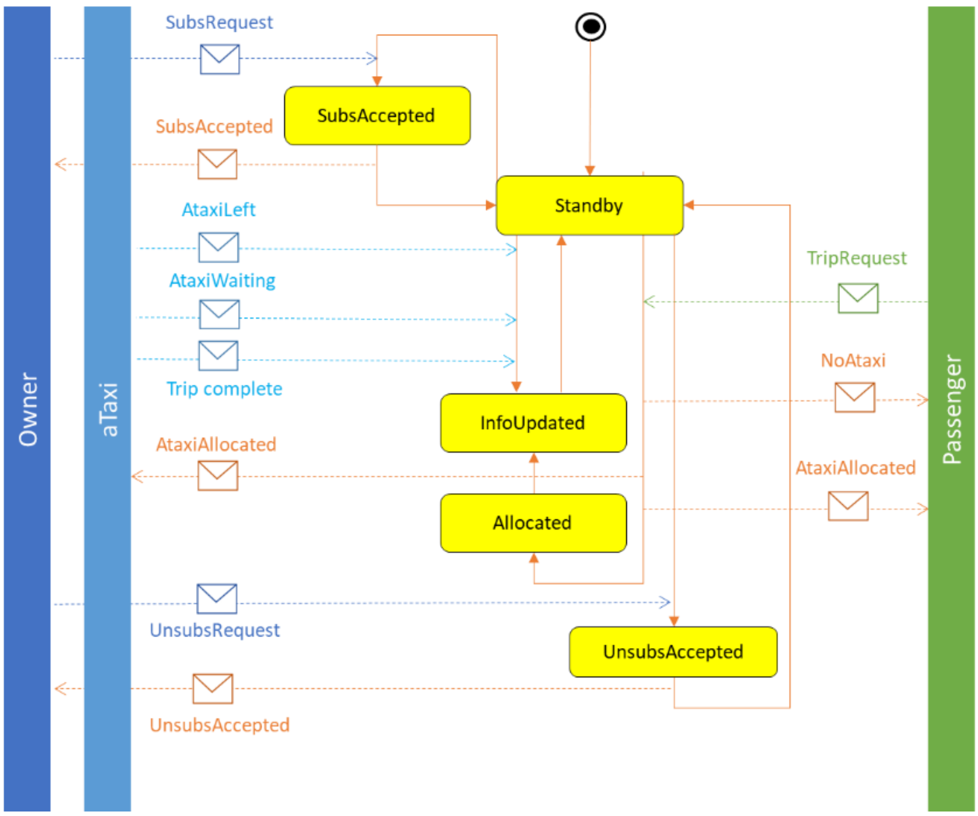


Figure 4.25 - Central´s statechart.

In essence, the central system is initiated at the start of the day as an agent and remains in the 'Standby' state throughout. Its state transitions are triggered by incoming messages from other agents within the system.

When a vehicle owner requests to add their vehicle to the fleet, the central system transitions to the 'SubsAccepted' state, approving the request and adding the SAV to the list of available vehicles for rent. Conversely, when an owner requests the removal of their vehicle from the fleet, the central system enters the 'UnsubsAccepted' state, granting the request and removing the vehicle from the list.

Upon a passenger's request for a vehicle, the central system evaluates the request, checks vehicle availability, calculates travel times, and responds to the passenger, transitioning to the 'Allocated' state. Once a vehicle is allocated to a passenger, it must be removed from the available vehicles list. The central system then moves to the 'InfoUpdated' state to refresh the data and subsequently returns to the 'Standby' state. The 'InfoUpdated' state can also be triggered whenever the central system receives status updates from the SAV, ensuring continuous monitoring of the SAV throughout the day.

4.7 Main Conclusions

There are numerous simulation tools available that consider interactions between agents. Notably among them are the MATSim, SimMobility, and AnyLogic software. All have been employed to simulate scenarios in transportation systems, with numerous academic papers published on the subject. The SimMobility MT model, designed to simulate an AMOD (Automated Mobility on Demand) fleet, laid the groundwork for the design of the P2P (Peer-to-Peer) ACS (Automated Car Sharing) model. However, the theoretical model was eventually tested using the AnyLogic software, and it was integrated with an existing ABM (Agent-Based Model) for Lisbon that was previously developed by Eiró (2015), Martinez & Viegas (2017), Santos et al. (2011) and Viegas & Martínez (2010). This pre-existing model is referred to as the "base model".

The base model was initially crafted to simulate the operation of a car-sharing fleet in Lisbon. It consists of two distinct phases: Phase I - trip generation, and Phase II - service operation. In Phase I, the model starts by creating a synthetic population, then generates an individual activity schedule, and finally establishes the probability of using various transportation options for each individual. During Phase II, the model identifies individuals interested in using a particular mobility solution and simulates the operation of the mobility service.

A thorough analysis of the base model was conducted to understand its structure. Throughout this review process, several modifications were made, primarily aiming to reduce the associated simulation computation time. The main changes involved adjusting the road network to cater to the requirements of the P2P ACS solution in a denser urban area of Lisbon while ensuring the network's validity outside the city. Adjustments were also made to the demand, especially in terms of dispersing transportation demand during the afternoon peak period.

The P2P ACS model was integrated with the original model as the P2P ACS module, and the car-sharing module was deactivated (during Phase II). To operationalize the simulation, we created new agents, classes, functions, and other elements required by AnyLogic. Four primary agents were designed: the vehicle owner, the AV, the passenger, and the control center (often referred to as a "platform" in a two-sided market context). Statecharts were developed for each of these agents. State changes are primarily triggered by message exchanges between agents. To ensure large-scale operation, an additional agent was introduced to oversee the sending and receiving of all messages. The algorithms employed and the process structures aimed to be straightforward yet effective.

Chapter 5. Simulation, and operational and policy implications of the P2P ACS

5.1 Introduction

The previous chapter detailed how the P2P ACS model was implemented as an ABM and integrated with the base model. This chapter delves into the simulation of the P2P ACS operation. Its aim is to provide insights into the impacts of P2P ACS in urban environments, especially from the viewpoints of transportation planners, fleet operators, and users.

The chapter begins by introducing the scenarios that prompted the simulation, as well as all the simulation conditions that were adopted. Following this, we discuss the findings derived from the simulation process. Lastly, the outcomes of the simulation are assessed, and the discussion is centered on some of the key topics highlighted by the results.

5.2 Experimental design and definition of scenarios

Given that the P2P ACS solution we aim to simulate closely mirrors the current taxi system within traditional mobility, we focused on the taxi demand resulting from the base model's simulation. The base model's simulation results, pertaining to the number of trips in the LMA (and even in Lisbon) throughout the day, aligned well with data sourced from INE (2018). However, when examining the taxi demand data, the scenario shifted dramatically (see Figure 5.1). In the overall computation, this discrepancy wasn't evident since taxi usage accounted for only 2% of the transportation alternatives. The comparative data also seemed inconsistent, with each dataset telling a different story. The simulation results indicated a surge in taxi demand at night, while INE (2018) highlighted a distinct peak in the morning and post-lunch hours. In contrast, data extracted from AutoCoop (P. Rodrigues et al., 2020) depicted a steady demand throughout the day, with a noticeable slowdown during nighttime.

Given that it was not feasible to use any of these datasets, nor collecting more detailed information that could better represent taxi usage in Lisbon, we chose to rely solely on the percentage of taxi demand (within the realm of all trips) as a proxy for future SAV demand. The modal share of taxis in Lisbon stands at 2% of the total daily trips (data from 2011, used in the base model). This percentage equates to approximately 21,600 trips/day.

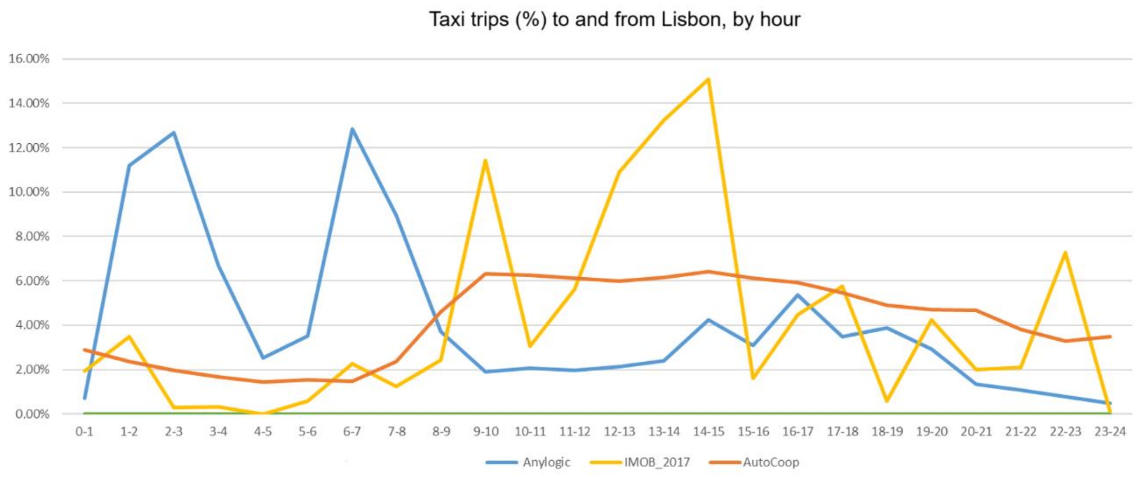


Figure 5.1 - Taxi demand data in Lisbon (comparison of different sources).

To determine the number of passengers (demand), we considered only trips that both originate and end within Lisbon. The simulation aims to replicate a P2P ACS service within an urban core with high demand, catering to first/last-mile needs and short/medium-distance travels, akin to the current taxi system.

With the demand established, a sensitivity analysis was conducted to identify the minimum supply level that wouldn't jeopardize customer service quality (in terms of waiting times and drop-offs). The initial supply value was set at 0.2%, based on the percentage of taxi demand during peak hours, which are the most critical in terms of demand, and on the 1:10 ratio (SAV: conventional cars) cited in literature by Bischoff & Maciejewski (2016b), Boesch et al. (2016), and OECD/ITF (2015). This percentage roughly translates to 658 vehicles/day in the fleet.

As previously mentioned, the P2P ACS module was designed to differentiate between various owner types, based on their residence and daily travel patterns. For the conducted simulation, the vehicle fleet was assumed to consist solely of vehicles whose owners travel within Lisbon during the day. This means two types of groups:

1. individuals residing in Lisbon and engaging in activities within the city; and
2. those living outside Lisbon but traveling to/from the city during the day for activities.

This approach aims to initially assess if the cars operating in Lisbon during the day can meet the city's internal P2P ACS travel needs outlined.

Throughout the simulations, there was always an interest in examining not only the outcomes when fixing supply and demand values but also the potential changes if this balance were to vary (sensitivity analysis).

Scenario 1 is characterized by a demand of 2% of daily trips in Lisbon and a supply of 0.2% of (traditional) vehicles circulating in the city. However, for all indicators analyzed in this scenario, there was a need for a sensitivity analysis that varied the supply between 0.1% and 0.3%, keeping the demand constant. Scenario 2, considered in this study, aimed to assess the shift in the supply-demand balance by varying both demand and supply values. Here, demand values ranged from 1% to 30%, and supply values from 0.3% to 2%. This scenario also sought to test the simulation's robustness in terms of time.

The model was constructed based on set operations, meaning it operates with Bayes' Theorem for intersection: $\mathrm{P(A|B)} = \mathrm{P}\,(\mathrm{A} \cap \mathrm{B})\,/\mathrm{P(B)}$. In other words, passengers will only use the P2P ACS solution if, initially, they have subscribed to the solution, then if they enjoy using the service, and finally, if the service adequately meets their travel needs. It is an action conditioned by a series of preceding actions. To simplify, in the model in question, a single parameter was used to represent all the previous steps - all other parameters were assigned a value of 1. The same approach was applied to vehicle owners. That is, the steps of subscription, use, and provision were all condensed into a single parameter. Table 5.1 displays the parameters used in the simulation, that are related to the decision of demand and supply.

The system assumes that, in all scenarios, vehicle owners prioritize using the AV for their personal needs first. The AV's availability to join the system is contingent upon the period when the AV is parked. Thus, when the owner reaches their destination, they release the vehicle for the duration of their personal activities and specify the time and location where the vehicle should return for the owner's following journey.

Table 5.1 - Parameters related to the 'Client' agent.

Parameter	Description	Values
passSubscription	Factor that translates the number of people who subscribe to the P2P ACS solution to make trips (if equal to 1, then the total universe of people is considered: 100%)	1
passUse	Factor that translates the number of people who, after subscribing to the P2P ACS service, use it to make trips (if equal to 1, then the total universe of people with a subscription is considered: 100%)	1
passUseTrip	Factor that translates the number of people who use the P2P ACS solution for the trip in question (if equal to 1, then the total universe of people with subscription and regular use is considered: 100%)	0.02 (0.01-0.3)
carOwnership	Factor that translates the number of people who buy an AV (if equal to 1, then the total universe of people is considered: 100%)	1
carSubscription	Factor that translates the number of vehicle owners who, while in possession of an AV, subscribe to the P2P ACS solution (if equal to 1, then the total universe of AV owners is considered: 100%)	0.002 (0.003-0.02)
carRent	Factor that reflects the number of vehicle owners who, having subscribed to the P2P ACS service, make their AV available for rental (if equal to 1, then the total universe of AV owners with subscription is considered: 100%)	1

To ensure the solution's effectiveness, an entry rule was established. A vehicle is only considered for the fleet if it's available for a duration longer than the minimum threshold. This duration varies based on the vehicle's location, as detailed in Table 5.2. Considering that our simulations encompass owners with trips from and to Lisbon, only the parameter related to Lisbon is utilized. The chosen value primarily reflects the need to prevent unnecessary entries (actions) into the system, which could hamper the simulation (increased message flow, expanded vehicle list, *etc.*).

It was also considered that all vehicles have an additional relocation time before the end of their shift. The minimum period is set at 15 minutes. This duration can vary. Each owner can opt to extend this base time in 15-minute increments. For this simulation, it was assumed that all owners exhibit the same behavior concerning the risk of vehicle delay, using only the minimum additional time.

Table 5.2 - Parameters related to the 'Owner' agent.

Parameter	Description	Values
minTimeLisbon	Minimum period of AV availability for residents or activities in Lisbon, in order to be accepted as a P2P ACS fleet by Central (in minutes)	10
minTimeOutLisbon	Minimum period of availability of the vehicle, for residents or activities outside Lisbon, in order to be accepted as a P2P ACS fleet by Central (in minutes)	180
onTimeLevel	Coefficient for calculating the additional time it takes to return the vehicle to the owner (α), which can range from 1 to 3, depending on the level of security the owner wants. The center guarantees an additional period of at least 15 minutes to relocate the vehicle at the end of the availability period as a P2P ACS fleet. The last trip is only assigned at time T (in minutes) if $t_{\text{limit}} \leq t_{\text{current}} + T$, where t_{limit} is the return time and t_{current} is the current time: $$T = \text{RelocTime}_1 + \text{TripTime} + \text{RelocTime}_2 + \alpha \cdot 15$$	1

For the passenger, only one behavioral parameter was considered. This reflects the passenger's attitude towards the non-allocation of a vehicle for their journey: it's the number of consecutive trip requests. A passenger can only request a vehicle again up to two times, as indicated in

Table 5.3. Additionally, this parameter is associated with a constant probability function, which sets a maximum interval of 3 minutes between attempts.

Table 5.3 - Parameters related to the 'Passenger' agent.

Parameter	Description	Values
attemptNum	Maximum number of times a passenger is willing to request an AV through the app (due to lack of availability or change in trip characteristics), for the same trip.	3

To evaluate the solution in financial terms, parameters were also included that aim to represent the revenues and costs associated with vehicle trip. The values in Table 5.4 were taken from existing values for the car-sharing solution and do not reflect the P2P ACS solution. A more theoretical foundation should be developed in the future to corroborate with such values. The model is prepared to assess owners’ revenues and the central office based on a payment-per-km model.

It's also worth noting that for the creation of owners, vehicles, and passengers, the scaling factor already present in the base model had to be considered. The value of this parameter remained unchanged when compared to the base model.

Table 5.4 - Parameters related to the 'Main' agent.

Parameter	Description	Values
aTaxiCostKm	Cost of running the AV for its owner, in terms of wear and maintenance (eur/km)	0.1259
aTaxiPriceKm	Price of the journey for the passenger (eur/km)	0.54
Scale	Modeling scale. The model considers a scale factor to speed up the calculation process by grouping together several people with similar mobility choices.	20
ownerRevenue	Revenue factor for the AV owner (compared to the payment made by the passenger). The value must be less than 1 to take into account the fee paid to the platform and travel insurance.	0.7

When an AV owner wishes to lend her vehicle while enduring other activities in Lisbon, she sends a message to the central office inquiring if it would accept a new vehicle into its fleet. At the moment, the constructed model accepts any request, regardless of the existing vehicle quota.

Once added to the list of available vehicles, the car responds to travel requests for trips within the city of Lisbon (both origin and destination in Lisbon). The simulation environment features a dense road network, where vehicles move between nodes and are subject to varying congestion levels throughout the day. Vehicles are assigned based on proximity. All grids (Grid200) surrounding the passenger's trip origin grid are checked in ascending order of distance. The time it takes for the vehicle to reach the passenger (waiting time) is then calculated. The simulation did not consider any maximum waiting time. Instead, a very large number was assigned, serving the same purpose, as can be seen in Table 5.5. This value can be adjusted to test this crucial indicator for passengers and the potential implications it might have on the solution.

Table 5.5 - Parameters related to the 'Central_P2PACS' agent.

Parameter	Description	Values
maxWaitingTime	Maximum time that a passenger considers acceptable to wait for the arrival of an AV at the time of the travel request	10,000

Each simulation can take anywhere from 30 minutes to 3 hours, depending on the number of agents and demand requests – these simulations test between 50k and 550k agents in each scenario. We employed an Intel Core i7-3770 CPU 3.4 GHz with 16Gb of RAM and used the AnyLogic University 6.9.0 software.

Various indicators were used to analyze the four pillars of the solution: the owner, the AV, the passenger, and the system.

5.3 Results

In this section, we delve into the potential advantages of a P2P ACS fleet, presenting a comprehensive analysis based on various experimental results derived from our simulation model.

Distance

As illustrated in Figure 5.2, the mean distance covered during passenger trips stands at 3.7 km. As the fleet size grows, the distance required for vehicle relocation diminishes, given the increased presence of vehicles navigating the city. Specifically, a doubling of the fleet size results in a 20% reduction in relocation distance. On average, for every 2 km that an AV transports a passenger, it travels over 1 km empty. This data is based on a static model where the AV remains stationary at the drop-off point until the next service request. If the model were to mandate waiting in designated city zones, the average relocation distances would likely be even greater.

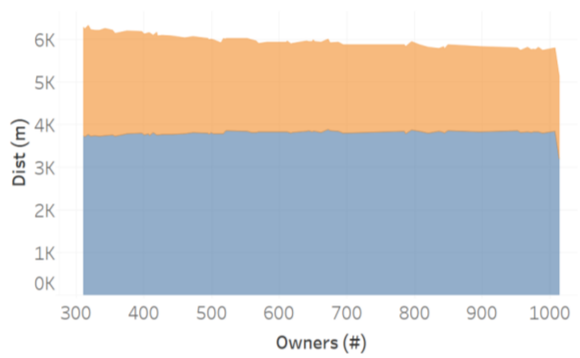


Figure 5.2 - Average distances covered by AVs (orange – km empty; blue – km carrying passengers).

The duration of vehicle utilization, encompassing both occupied and empty trips, predictably diminishes as the fleet size expands (refer to Figure 5.3). For fleets comprising roughly 300 AVs (equivalent to 0.1% of the current cars navigating Lisbon's streets), the active occupancy rate stands close to 50%. This rate plunges to a mere 17% when the fleet swells to around 1,000 AVs

(0.3% of Lisbon's current vehicular count). The proportions for relocation and active service stand at 38% and 62%, respectively.

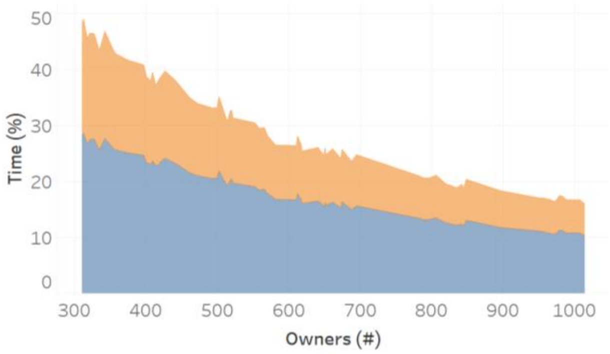


Figure 5.3 - Average duration AVs are in motion during P2P ACS service (orange – % time empty; blue – % time carrying passengers).

As more vehicles enlist in the P2P ACS service, the marginal operational load of each AV diminishes. This reduction results in fewer services performed, decreased kilometers covered, and subsequently, a diminished financial yield for the AV owner.

The distance covered by the AV during its P2P ACS service tenure is also of paramount importance, especially when considering the EV's battery range. Figure 5.4 illustrates that daily travel can peak at a staggering 800km for a compact fleet, a distance currently beyond the reach of most market-available vehicles in terms of EV autonomy.

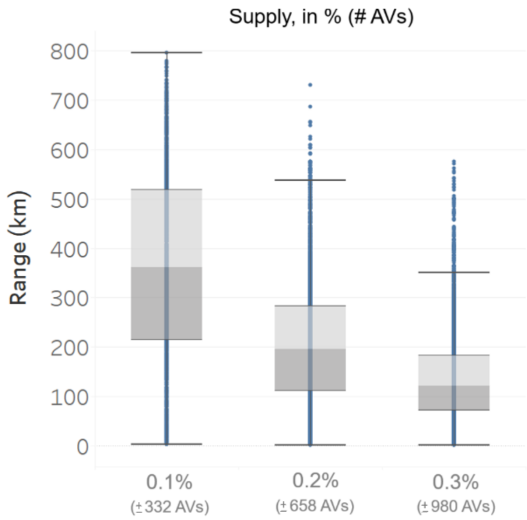


Figure 5.4 - Variety of supply levels (0.1%, 0.2%, and 0.3% of AVs in circulation in Lisbon) responding to a demand equivalent to 2% of Lisbon's total daily journeys.

The median value for a fleet of about 300 AVs (0.1% of Lisbon's prevailing car count) suggests that an AV might need to cover over 360 km without recharging. However, with a larger fleet, this autonomy requirement drops to a more manageable 120 km (at the 50th percentile). Still, it's worth noting that the most sought-after AVs might need to traverse distances exceeding 350 km. It's crucial to remember that these figures exclude the owners' personal trips. This data underscores the imperative to integrate charging logistics into the multi-agent simulation model. As the AV's available operational time shrinks, the service quality of the P2P ACS is bound to be impacted.

Profit

One of the motivations for the vehicle owner to engage in this solution is the potential profit. However, this gain must surpass the vehicle's wear and maintenance costs. The profit for the vehicle owner, through participation in this solution, can be calculated as follows:

$$Profit = Share_{Owner} \times Cost_{passeng} \times km_{passeng} - Cost_{vehicle} \times km_{total}$$

where:

$Share_{Owner}$ is the revenue for the AV owner, considering the fee paid to the platform

$Cost_{passeng}$ is the cost of the trip that passengers must pay (€/km)

$km_{passeng}$ is the total distance of the trips with passengers inside

$Cost_{vehicle}$ is the cost of running the AV for its owner

km_{total} is the total distance of the vehicle (include relocation)

Taking into consideration the scenario where the vehicle travels an average of 120 km per day (see Figure 5.4), of which 40 km are empty miles (see Figure 5.2), and based on the values presented in Table 5.4 regarding platform, passenger, and vehicle costs, the daily profit amounts to €15. The passenger cost used is 0.54€/km (data used for analysing the car-sharing solution in Lisbon). If the profit is halved, referencing values presented by Dandl et al. (2019) or Stephens (2016), while keeping all other factors constant, then the solution no longer brings any profit to the vehicle owner, regardless of the number of kilometers traveled. Furthermore, since the simulation did not account for more comprehensive relocations after dropping off the passenger at the destination, these calculations may suggest that the profit for the owner could cease to exist even with a smaller reduction in passenger costs. This underscores the significant impact that empty miles can have on the model's viability. This analysis is preliminary and aims to highlight the relationship between variables and the need for a more in-depth review of the subject.

Waiting time

As anticipated, the cumulative waiting time for passengers diminishes as the fleet size grows (refer to Figure 5.5). This waiting period unfolds into two distinct segments:

- The inherent delay a passenger must endure due to the vehicle's relocation time within the city (referred to as the waiting time); and
- The potential delay a passenger might experience from multiple attempts to secure a vehicle due to the temporary unavailability of an AV (referred to as the new request time).

Note that a passenger can reinitiate their vehicle request after a brief interval (capped at 6 minutes) and can repeat up to two times. Naturally, as the number of available vehicles increases, the frequency with which passengers need to reissue their requests diminishes. This, in turn, reduces the overall time they spend in this process.

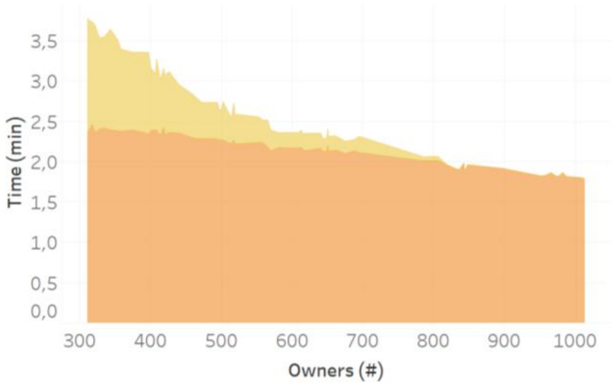


Figure 5.5 - Aggregate wait time for passengers (yellow – “new request time”; orange – “waiting time”).

As the fleet size expands, the waiting time for passengers does decrease, albeit marginally. This is because a larger fleet increases the likelihood of securing a nearby vehicle, given that the vehicles are more dispersed throughout the city. Yet, even with a more limited fleet, the average waiting time remains relatively minimal, even during rush hours. This can be attributed to Lisbon's compact size and the city's myriad alternative routes, allowing vehicles to circumvent congested areas.

The average waiting time is also closely tied to the number of passengers who abandon their requests. As the fleet size shrinks, there's a pronounced exponential surge in such dropouts (refer to Figure 5.6).

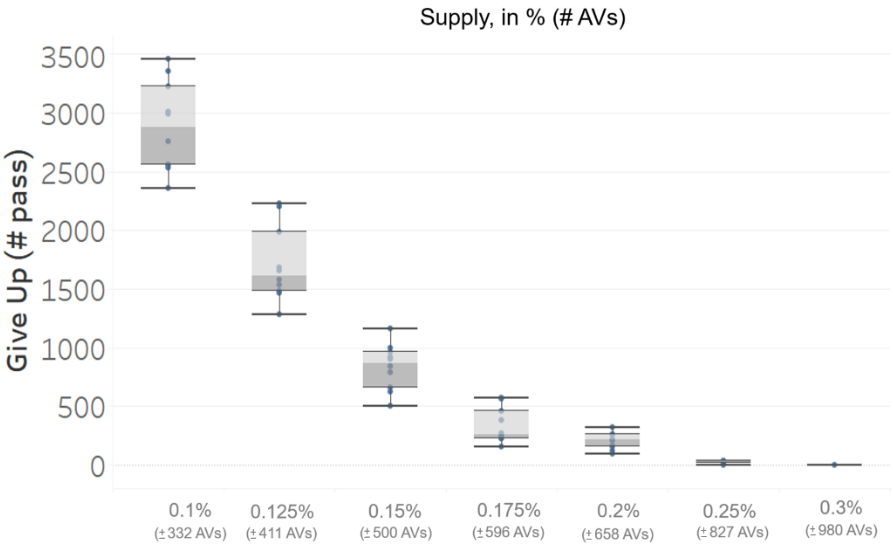


Figure 5.6 - Passenger insights: Count of abandoned requests across various supply levels.

These passenger dropouts are predominantly concentrated during peak hours, reflecting the daily fluctuations in demand and supply (as illustrated in Figure 5.7). The lower the supply/demand ratio, the greater the number of dropouts, a pattern valid for different levels of supply.

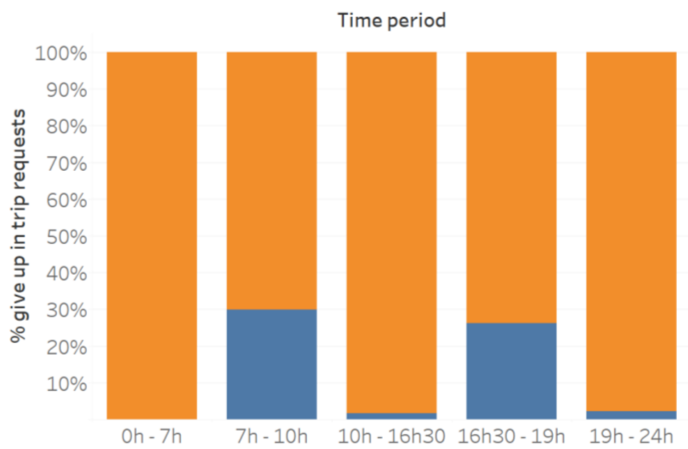


Figure 5.7 - Daily distribution of dropouts for a supply constituting 0.1% of Lisbon's total AVs (approximately 332 AVs) – average outcomes.

Availability

With demand calibrated at a consistent rate based on daily trips, a surge in demand during rush hours was anticipated (as depicted in Figure 5.8). Given that vehicle owners are likely to undertake journeys during these peak times, a dip in AV availability was simulated. Yet, this decline appears to be less pronounced than anticipated based on our findings. This can be attributed to Lisbon's relatively brief average travel durations, often not exceeding 10 minutes.

An intriguing observation further mitigates the theoretically anticipated supply-demand disparity. Vehicles belonging to owners residing outside the city tend to become available precisely during these peak periods. This is because the rush hours for inter-municipal commutes often don't align with the peak times for intra-municipal journeys, creating a beneficial offset.

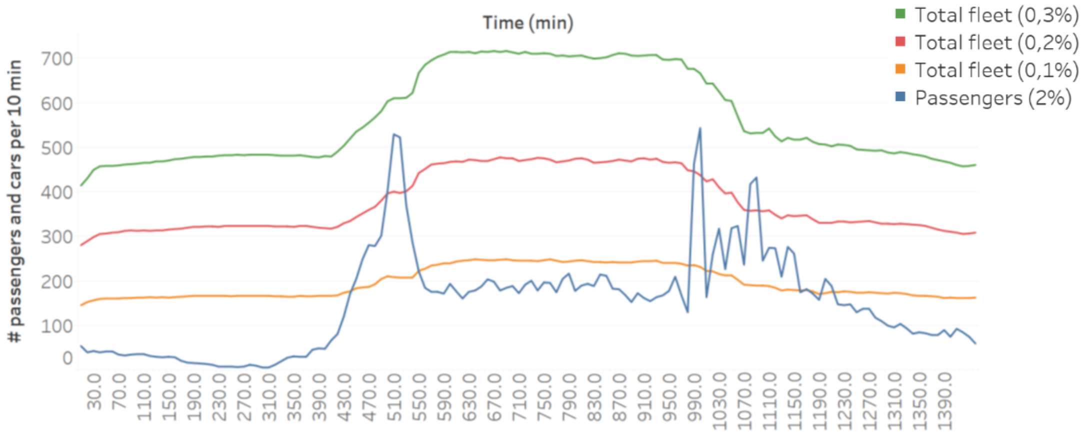


Figure 5.8 - Daily supply-demand equilibrium: A snapshot every 10 minutes showcasing the number of available AVs *versus* passenger requests.

A compelling case for P2P solutions is the lengthy idling periods of private vehicles throughout the day. Our simulations reveal that a staggering 90% of private car owners utilize their vehicles for a mere 1h30 daily at most. This translates to vehicles being inactive for approximately 93% of the day, with the average active use being just 44 minutes. This trend is intrinsically linked to the duration of the working hour shifts. A significant 80% of these shifts span more than 5 hours. The distribution of these idling periods also fluctuates as the day progresses, as illustrated in Figure 5.9 and Figure 5.10.

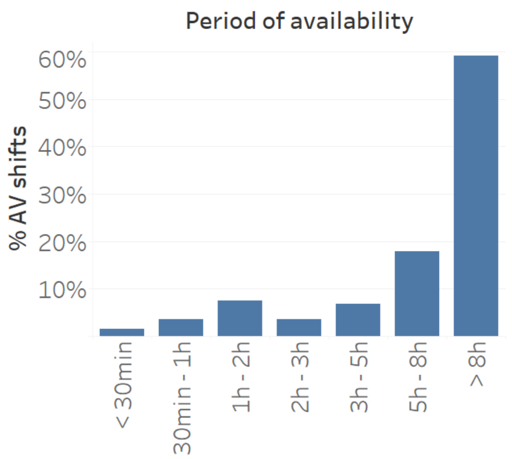


Figure 5.9 - Proportion of idling AVs categorized by their respective availability durations.

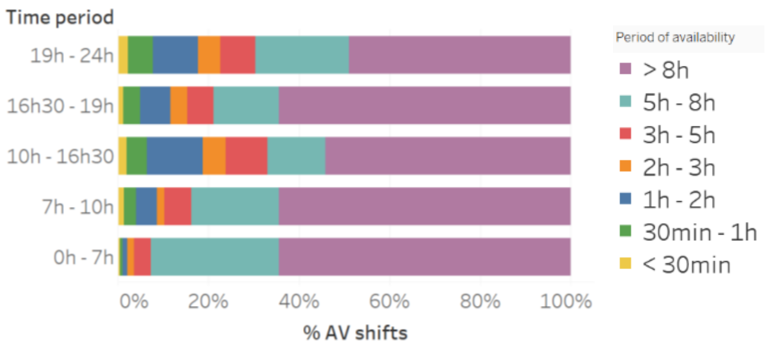


Figure 5.10 - Proportion of AVs idling throughout the day.

The data underscores a pronounced vehicle availability for extended durations, irrespective of the time of day. During nighttime, AVs tend to be accessible for longer periods. The heightened vehicle usage during peak hours results in more pronounced shorter shifts throughout the day. In the evening span (from 19h to 24h), the shifts tend to be more abbreviated due to the 24-hour constraint (as each model test spans only a single day).

Spatial dynamics

Diving into the spatial dynamics of demand, the configurations for morning and afternoon peak periods diverge. Figure 5.11 reveals that during the morning, P2P ACS passengers predominantly hail from more scattered locations (zones in blue in the figure), typically residential zones and the city's primary roads towards the city center (zones in light green in the figure). Conversely, during the afternoon peak, the bustling business and commercial hubs in the city center emerge as the primary departure points. This figure vividly captures the symmetrical nature of departure and arrival locations.

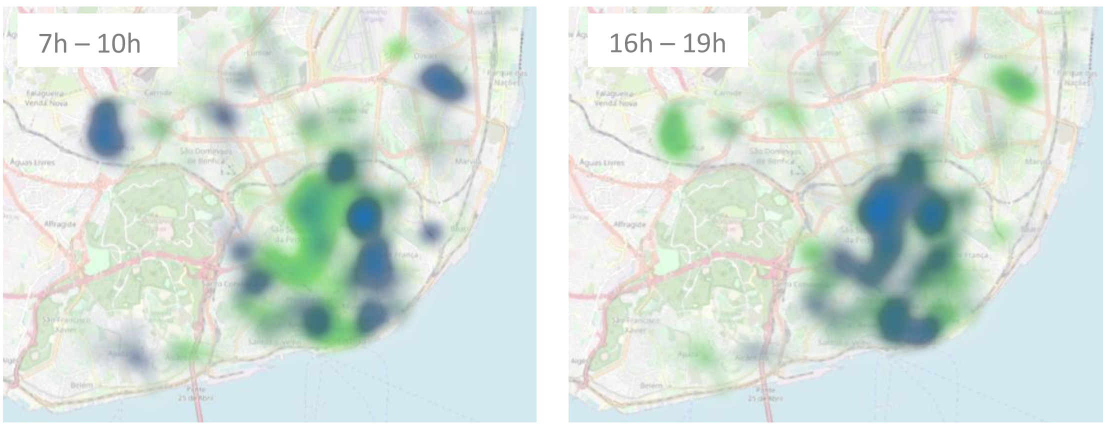


Figure 5.11 - Spatial mapping of P2P ACS starting points (in blue) *versus* destinations (in green) during peak-hours.

The afternoon's concentrated departure locations pose a significant challenge for the P2P ACS service: it amplifies the kilometers AVs travel without passengers and introduces complications for both the AV fleet and the commuters. Vehicles undertaking shorter journeys are in higher demand and more frequently used, leading to disparities in AV workload. Consequently, passengers situated outside this central zone face extended waiting times, given the vehicle concentration in that particular city sector.

Expansion

The preceding analysis endeavored to scrutinize the system's dynamics and assess performance metrics pertaining to the diverse agents involved, all set against a backdrop of a fixed demand constituting 2% of Lisbon's total daily trips. We conducted an auxiliary evaluation spanning various demand-supply equilibrium levels. This was done with an eye towards capturing the inherent unpredictability surrounding the future trajectory of the technology and the rate at which AVs are embraced by both vehicle owners and users. External variables, such as the integration of a branded rental system within privately-owned AVs, could play a pivotal role in the proliferation of the P2P ACS model. Figure 5.12 elucidates the ramifications of varying demand and supply tiers on the frequency of passenger dropouts.

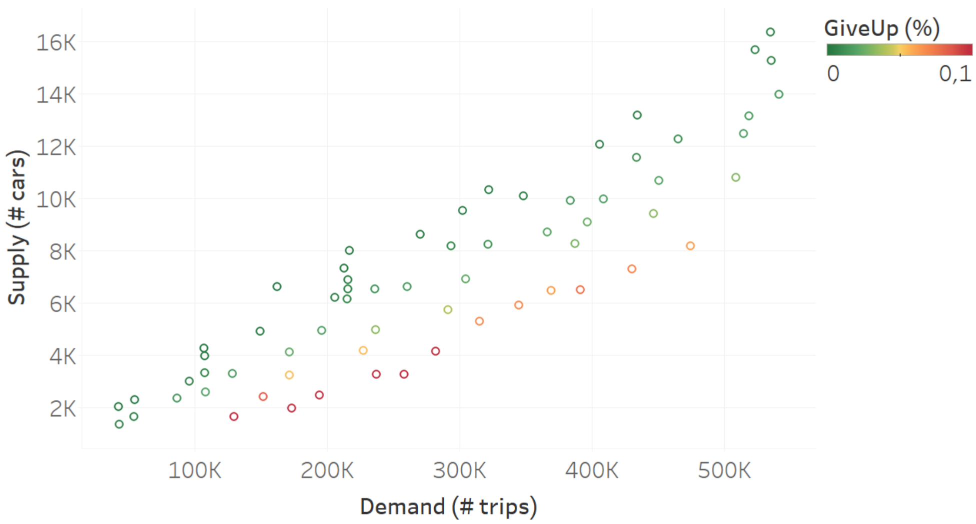


Figure 5.12 - Visual representation of abandonment rates across diverse demand and supply scenarios.

Within this range, a linear relationship emerges between the number of AVs in the fleet and the number of passenger trips, ensuring a baseline level of passenger satisfaction.

5.4 Discussion

The advent of technology in transportation is poised to reshape urban mobility. Yet, the successful integration of these innovations depends on a city's readiness to accommodate innovative mobility solutions, influenced by its size, financial capabilities, and political landscape (Freemark et al., 2019). Current literature reveals a concerning trend: many municipalities, especially at the grassroots level, are ill-prepared for this shift. This unpreparedness often stems from a lack of policies and regulations for AVs (Freemark et al., 2019). Some cities cite a need for more comprehensive data to inform policy-making (Gavanas, 2019), while others point to resource constraints or a knowledge gap about necessary infrastructure changes (Duarte & Ratti, 2018). Furthermore, companies leading policy development often exhibit limited transparency, democratic engagement, and stakeholder participation (Hopkins and Schawnen, 2018). This study aims to spotlight pivotal factors influencing future mobility solutions, suggesting that well-crafted policies can significantly enhance urban value.

Demand-supply balance

Our findings from Lisbon indicate that a P2P fleet comprising nearly 1,000 Avs (supply 0.3%) can efficiently respond to an average of 22,000 daily trips, ensuring waiting times of about 2 minutes and seamless vehicle allocation. However, a 30% fleet reduction, leaving roughly 660 vehicles (supply 0.2%), introduces availability challenges, especially during peak hours. As depicted in Figure 5.6, this reduction leads to a 2% increment in passengers abandoning trips and longer waiting times. A further 30% cut (supply 0.1%), leaving only around 330 vehicles, sees passenger dropouts soar to an alarming 15%.

These data comparisons underscore a crucial insight: the adverse effects amplify exponentially with each fleet reduction. While a 30% decrease from an initial 1,000 vehicles might be manageable, a reduction surpassing 50% poses significant challenges.

Interestingly, while a reduced vehicle count compromises passenger service quality, it boosts vehicle utilization, serving more passengers per vehicle and potentially increasing owner profits. This observation underscores the importance of a holistic evaluation of the P2P ACS solution, considering the perspectives of various stakeholders. A comprehensive cost-benefit analysis should strive for a balance, maximizing mutual benefits for both passengers and owners in these two-sided markets.

The integration of technology into transportation, as depicted in Figure 5.8, reveals intriguing dynamics based on vehicle ownership. At night, most available vehicles belong to Lisbon residents. Come morning rush hour, vehicle availability surges as many commuters arrive in Lisbon for work before residents need their vehicles. During standard working hours, the fleet reaches its peak availability. This trend reverses in the afternoon, with vehicle numbers dwindling during the evening rush.

Interestingly, the figure also highlights that vehicles available only during work hours are fewer than those available for most of the day. Moreover, most travel demands are met by vehicles with longer availability durations. This suggests potential future shifts in the business model to ensure sustainability, growth, or adaptability. For instance, P2P ACS could collaborate with 24/7 Autonomous Mobility on Demand (AMOD) fleets to maintain a minimum fleet size, as Tang (2022) suggests. Alternatively, P2P ACS could purchase vehicles to ensure this minimum or even evolve towards a more professionalized model where owners acquire multiple vehicles to maximize earnings.

This trajectory mirrors the evolution of platforms like Airbnb for the house rental market. By pioneering an online peer-to-peer accommodation platform, Airbnb dramatically expanded short-term lodging options (Dolnicar, 2019). However, this boom brought challenges, including housing shortages, rising property prices, gentrification, and local resident displacement from heavily touristed areas (Benitez-Aurioles & Tussyadiah, 2021; Cocola-Gant, 2018; Cocola-Gant & Gago, 2021; Colomb & de Souza, 2021; Yrigoy, 2019). A study in Porto and Lisbon found that a 1pp rise in Airbnb listings corresponded to a 3.7% hike in housing prices (Franco and Santos, 2021).

To address these challenges, cities updated or introduced regulations. In Portugal, for instance, every rental property requires a registration number, ensuring compliance with vacation rental laws (Franco e Santos, 2021). Both Lisbon and Porto implemented tourist taxes to address tourism-related urban challenges (Franco e Santos, 2021). Notably, regulations have curtailed the professionalization of the market, with a significant 25% drop in hosts managing multiple listings (Bei e Celata, 2023). While regulations might not eradicate the adverse effects of tourism, they can significantly alleviate housing market pressures (Bei e Celata, 2023).

Drawing parallels with P2P ACS, one can anticipate that if the P2P ACS business proves profitable for AV owners, there might be a surge in supply, leading to an increase in trip prices. The growth of the number of AV, participating in P2P ACS, could be proportionally positive (aligned with demand) if it absorbs AV owners who already undertake trips in Lisbon. However, if there's a reliance on external market demand, meaning vehicles coming into the city specifically to participate in the P2P ACS solution, this could result in increased traffic and potentially deteriorating service conditions. To preserve the core value of asset-sharing without distortion, measures like vehicle quotas could be introduced. This would also limit the number of vehicles an owner can possess. Alternatively, progressive rates could be applied to larger fleets, ensuring the spirit of sharing remains intact.

Relocation

Figure 5.2 underscores a significant observation: for every 100km of active P2P ACS services, an AV travels an average of 50 to 60km (on relocation). This is a considerable distance, especially when contrasted with findings from Boesch et al. (2016), which indicate that in a Zurich scenario with 10% demand and 10% fleet, an AV spends only 14% of its productive time relocating. Similarly, Bischoff & Maciejewski's (2016) study in Berlin, which utilized 100k AVs for 2.5 million trips, found that a mere 16% of total driving time was without a passenger. It's worth noting that these studies were selected for comparison because the study area in Zurich closely mirrors that of Lisbon, and the supply-to-demand ratio used for the Berlin case study is similar to the one employed in this simulation. These figures are notably lower than the results from our simulations, suggesting that P2P restrictions might be, in part, influencing these disparities (*e.g.,* relocations from/to the AV owner over the day).

During peak hours, the clustering of SAV owners in destination zones, away from other passengers' journey origins, can exacerbate this discrepancy. In contrast, a corporate SAV fleet, with its centralized management, can proactively relocate vehicles to high-demand areas, optimizing vehicle utilization.

Further, when examining the VKT in Lisbon's SAV implementation, there are notable variances. The OECD/ITF (2015) study indicates a 51% surge in VKT, a stark contrast to the 8.7% increase in the Fagnant & Kockelman (2016) study or the 8% rise in the 1-for-10 scenario by Moreno et al. (2018). This discrepancy suggests unique travel behaviors in Lisbon. The same number of trips might necessitate longer empty journeys, leading to an increase in the average trip duration for all road users, including conventional vehicles (Moreno et al., 2018). This phenomenon could be attributed to Lisbon's unique urban layout and functional organization. The additional mileage isn't uniformly distributed across the city, as highlighted by Bischoff & Maciejewski (2016). Furthermore, some ABM simulations in existing literature might oversimplify the scenario by randomly positioning SAV users on the network, overlooking the city's spatial intricacies.

Relocation needs for AVs present a complex challenge. The cost for passengers should ideally be 1.5 times the vehicle's operating cost per kilometer, when taking into account the ratio of passenger´s trips to empty trips as depicted in Figure 5.2, excluding any profit margins for the owner. This cost, however, is likely to escalate when considering the relocation of the vehicle post-drop-off for parking. In cities like Lisbon, where parking is a premium, AVs can't simply idle anywhere awaiting their next passenger.

One of the touted benefits of AVs is their potential to reduce the need for parking, especially in high-demand areas. They could be directed to park in more affordable zones or even return to the owner's residence where parking might be free. This capability challenges the traditional reliance on parking pricing as a primary tool for Transportation Demand Management, which aims to curtail vehicle usage.

The relocation issue can be unfolded into two perspectives: substitution, which benefits the system, and addition, which burdens it. For instance, if an AV owner drives to work and the car, post-drop-off, returns home to park, this could save significant travel kilometers (Harb et al., 2022) and alleviate congestion. However, the inherent nature of the P2P ACS system means some additional kilometers are inevitable, as vehicles can't remain stationary on roads post-drop-off.

Parking

Parking dynamics in the era of AVs are intriguing. For instance, Zang and Guhathakurta (2017) suggest that a SAV system could reduce parking land by 4.5% in Atlanta with just a 5% market penetration. Harper et al. (2018) indicate that remote parking could save AV users significant daily costs but would increase vehicle travel due to the distance between destinations and parking facilities. The most concerning scenario, where vehicles endlessly cruise, seems unviable due to increased waiting times and operational costs, unless parking charges are exorbitantly high (Bischoff et al., 2019).

To mitigate these challenges, cities could adopt several strategies. Offering free or subsidized parking on the city's periphery, akin to airport cell phone lots, could be one solution (Kramer and Mandel, 2015). Another approach involves imposing fees or taxes on AVs that reflect the congestion, environmental, and other external costs they generate. It's worth noting that even Battery Electric Vehicles (BEVs) can have a carbon footprint if powered by coal-based energy sources. Millard-Ball (2019) suggests a tax based on road occupancy time and another based on distance or energy consumption, with additional charges for zero-occupancy vehicles to discourage endless cruising. Policymakers should also be wary of potential social equity issues, especially in peripheral areas, and consider combining parking policies with other regulations to address these concerns (Zang and Guhathakurta, 2017).

The integration of AVs into urban landscapes presents both challenges and opportunities. Central to this is the issue of parking. While proximity to demand hotspots is ideal for reducing relocation distances and waiting times, the broader vision for many urban planners is to reclaim city spaces traditionally dominated by parked vehicles. This reclamation can facilitate more pedestrian-friendly zones, green spaces, and other community-centric amenities. Thus, the challenge lies in striking a balance between ensuring efficient P2P ACS operations and optimizing urban space utilization.

One potential solution is the development of underground parking silos or designated waiting areas reminiscent of taxi ranks. These spaces could serve dual purposes: they could be hubs for vehicle maintenance, cleaning, and electric charging. Such initiatives, while requiring initial investments, could be undertaken collaboratively between cities and automotive industries. By pooling resources and expertise, cities can ensure smoother integration of autonomous technologies into their infrastructures (Rebalski et al., 2022).

Tailored parking policies could further incentivize vehicle owners to participate in P2P ACS solutions. On-street and off-street parking provisions, universal parking permits, and other measures have been proposed by researchers like Bocken et al. (2020), Cohen and Shaheen (2016), Hampshire & Gaites (2011), and van der Linden (2016) to promote P2P CS. Restricting private vehicles in certain zones or offering subsidies to P2P ACS participants could further bolster these efforts. However, any subsidy should be carefully evaluated to ensure a net positive social impact.

Emerging trends in European cities offer additional insights. Park-sharing platforms, where vehicle and parking space owners collaborate to optimize parking availability, are gaining traction (Mourey & Köhler, 2017). Such platforms could seamlessly integrate with P2P ACS solutions, ensuring efficient vehicle relocations. Furthermore, as more individuals transition to shared mobility solutions and reduce their reliance on private vehicles, there's potential for a significant reduction in parking demand. As referred by Shaheen and Cohen (2013), if each car-sharing vehicle replaces an average of 7 private vehicles, a fleet of 1,000 vehicles could potentially free up 7,000 parking spaces. This could alleviate parking pressures in high-demand areas, further reducing relocation distances and passenger waiting times. By combining innovative parking solutions, collaborative efforts between cities and industries, and leveraging emerging trends, cities can ensure efficient P2P ACS operations while also enhancing urban livability.

Km traveled

The implications of vehicle relocation on daily mileage are indeed significant. As findings suggest, a smaller private vehicle fleet results in a substantial increase in vehicle kilometers traveled (VKT). In the scenario with the smallest fleet, vehicles are traveling a median of 350 km per day, with some reaching up to 800 km. This is a stark contrast to the average taxi in Lisbon, which covers approximately 68 km daily - assuming 16.5 million trips/year (AutoCoope, 2020), a fleet of 3,497 licensed taxis (AML, 2017), an average trip of 5.6 km for taxis in Lisbon (P. Rodrigues et al., 2020) plus relocation (assuming plus 30 %).

This discrepancy highlights a fundamental challenge: the model's assumptions about transportation levels differ significantly from real-world data. While a taxi in Lisbon averages nine rides per day, the model predicts a range of 21 to 68 services per taxi daily. Such a high service rate would place considerable strain on vehicles, especially when considering their range limitations.

Electric vehicle (EV) ranges vary widely based on the model and type. While top-tier electric vehicles can achieve ranges of up to 780 km, many affordable hybrid and electric models are designed for urban commuting and offer much shorter ranges. The study's findings, which suggest a median daily travel of over 500 km for vehicles in a small fleet scenario, are not feasible for most budget-friendly EVs currently on the market.

Furthermore, the model doesn't seem to account for the limitations of vehicle autonomy and the need for periodic charging. Charging not only impacts the vehicle's availability but also the overall quality of service, as highlighted in the work of Zhou et al. (2023). For instance, if a vehicle needs to be recharged during peak demand hours, it could result in longer waiting times for users. Additionally, charging infrastructure, such as the availability and distribution of fast-charging stations, plays a crucial role in the feasibility of such a system. While the potential benefits of a P2P ACS system are numerous, it is essential to develop a more comprehensive model that considers the technical and logistical constraints of current vehicles. This includes accounting for vehicle range, charging infrastructure, and realistic service rates to ensure the system's viability and efficiency.

AV use

The experimental results provide critical insights into urban mobility patterns and the potential implications of introducing SAV as a primary mode of transport.

The average journey length of 4 km aligns with the findings of Rodrigues et al., 2020. Given Lisbon's compact size, this isn't surprising. As SAV is envisioned as a solution for first/last-mile connectivity, integrated with Mobility as a Service (MaaS) offerings, the average trip length might further decrease.

This brings forth a sustainability concern. Cities have been promoting active modes of transport, like walking and cycling, as they are environmentally friendly and promote public health. If SAV starts catering to these short trips, it might cannibalize the modal share of these active modes. Implementing a fixed fee per trip, in addition to variable costs, could deter users from opting for SAV for shorter distances, thereby encouraging walking or cycling for such trips.

The data suggests that while a private vehicle is currently used only about 5% of the day, on average, integrating it into a P2P ACS system could boost its utilization to 23% or even 54% (based on Figure 5.3), depending on the fleet size. This is a significant increase, turning an often-underutilized asset into a more productive one. Such a shift not only enhances the value proposition for the vehicle owner but also benefits passengers through increased availability and potentially the broader system through reduced need for parking and decreased vehicle redundancy.

Earnings

Despite the evident uptick in vehicle usage, there's a notable discrepancy in the earnings observed (see Figure 5.4). Previous experiments with P2P CS have illuminated two contrasting reactions influenced by the potential gain. Dill et al. (2017) found that around 30% of participants, spurred by the potential earnings, began to explore alternative transportation modes, such as active transit and public transport. This shift was something they had contemplated for a while, and they willingly surrendered their vehicles to the shared solution for extended durations. Conversely, during the same study, a segment of vehicles was seldom rented, leading to negligible income. Consequently, 22% of owners remained steadfast in their usage patterns and even resisted frequent rental requests, finding the P2P ACS system no longer beneficial.

Earnings can indeed be a potent motivator for behavioral change. If an owner perceives a high likelihood of profiting during a time when they typically use their vehicle, they might reconsider their vehicle's availability. Such a decision hinges on the perceived benefits of renting out the vehicle outweighing the inconvenience of its unavailability. Owners might opt for alternative transportation or adjust their travel times, ensuring their daily routines remain unaffected.

Such flexibility in availability can be particularly impactful during peak demand times. Ideally, supply should ebb and flow in tandem with demand, ensuring consistent passenger service and maximizing owner profits. This dynamic can be achieved by owners adjusting their availability based on their own travel needs, rather than committing to long, fixed shifts. Introducing dynamic pricing, akin to the models used by ride-hailing services like Uber, can further incentivize owners during high-demand periods.

However, not all owners reap substantial profits, leading to potential disenchantment with the system. The threshold for acceptable earnings will vary among owners, contingent on their vehicle's fixed and variable costs and the perceived value of their time. Those who consistently operate at a loss might limit their vehicle's availability or even withdraw from the system. Such behavior, depending on its prevalence, can strain the supply chain, threatening the system's short-term functionality and long-term viability.

The root cause of these insufficient earnings warrants investigation. If a vehicle is available for extended periods yet remains unrented, its location might be the issue. Certain city areas might experience lower demand, and starting a shift from or traveling to these areas can adversely impact earnings. This observation leads to two potential strategies.

Benefit

Firstly, if the P2P ACS system seeks to serve the entire city uniformly, emphasizing public service and collective benefit, a profit-sharing model might be appropriate. This approach ensures a guaranteed minimum profit for all participating vehicles, allowing for a more equitable distribution across the city. Such a system would eliminate the need for vehicles to gravitate towards high-demand areas and could reduce the attrition rate among disillusioned owners. Research, such as that by Kraft and Ugarković (2021) in Germany and Mitchell et al. (1990) in the US, has shown that profit-sharing can bolster profitability.

Alternatively, if the system's primary objective is profit, the responsability of relocating a vehicle to a low-demand area could fall on the passenger in the form of a fee. This fee would cover the cost of relocating the vehicle to a high-demand area, ensuring consistent demand for the remainder of the shift. However, this approach might exacerbate socio-economic disparities, as areas with robust economic activity typically offer more mobility options. Consequently, trips to less accessible areas would be pricier, potentially undermining the system's inclusivity.

The introduction of AVs and other innovative mobility solutions presents a unique challenge for urban planners and policymakers. The rapid pace of technological advancement often outstrips the ability of cities to adapt and create appropriate regulations. As stakeholders from diverse sectors, including industry, academia, civil society, and government, have pointed out, there's a pressing need to proactively develop mobility planning policies and public transport strategies. The apprehension is clear: without proper guidelines, the deployment of AVs could lead to unintended negative consequences, such as increased traffic congestion and energy consumption (Rebalski et al., 2022).

5.5 Main Conclusions

The P2P ACS constructed model is based on four fundamental elements. First, the vehicle owner, who lends out the vehicle when not in private use; second, the vehicle itself, which operates independently and makes decisions only during its operation, provided they align with the owner's predefined requirements; third, the passenger, who needs transportation; and finally, the central system, which manages passenger requests and allocates them to the nearest available vehicles.

The P2P ACS has a set of constraints to simplify the decision-making processes. Scenarios were used in place of discrete choice models that would dictate the behavior and choices of both the vehicle owner and the passenger. This streamlining allowed for the simulation of the P2P ACS service operation in Lisbon.

The simulation of the P2P model reveals that the quality indicators of the model are sensitive to changes in fleet size, with demand held constant. The observed trends align with existing literature, validating the model's implementation. The base case scenario indicates that the model can satisfy 2% of Lisbon's total daily trips, using only 0.3% of the city's fleet with private AVs while idling. Even in a scenario with fewer vehicles (0.2%), the service quality remains commendable. The average waiting time for passengers increases by just one minute, and the percentage of dropouts rises by around 1%. These preliminary results suggest that such a solution could be beneficial for the city.

The simulation also provided insights into vehicle autonomy and the impact of supply-side variations. While vehicle relocation was simplified in the model, a subsequent discussion explored potential models for this solution. The possibility of the P2P ACS business model evolving and deviating from its initial value proposition was also considered comparing it to the evolution of Airbnb, *i.e.*, investing in wider private car fleets for rental instead of personal use. Lastly, potential measures, such as quotas, taxes, and prime areas, were discussed. These measures could be employed to control distortions in purpose, balance earnings, manage empty runs, and address other challenges.

Chapter 6. Conclusions, limitations and future research

6.1 Research questions and main conclusions

This thesis delves into the potential role of the P2P ACS solution in the future transportation landscape, examining its operational and policy implications for urban settings. The aim of this work is to further enrich the field of shared urban mobility by addressing the proposed research questions:

1. **How does P2P ACS solution fit urban mobility?**

To understand how the P2P ACS solution might fit into urban mobility, it was essential to grasp the main components, the current (and perceived future) context, and the needs of the transportation system. Additionally, it was crucial to discern the value and benefits this solution could bring to the system.

The research started to explore the underlying motivations driving people's mobility choices. It became evident that major decisions, such as where to live or whether to buy a car, significantly influence daily movements. Activities, combined with available transportation options, are the primary determinants of mobility choices. However, choices aren't based solely on rational factors like cost or duration. Personal preferences, feelings, and needs also play a significant role. People's mobility is especially concentrated during morning and evening peak hours, indicating that commuting for work is one of the main reasons people travel. Despite numerous public transport options in cities, a preference for personal cars remains. In the U.S., this preference is attributed to sprawling cities and a lack of regulations discouraging car use. In Europe, car usage varies, but in places like Greater Lisbon, over half the trips are by car. However, within the same city, different groups might have similar travel preferences, which can inform better transportation planning. Car ownership remains popular, especially given the allure of new car features and the associated comfort and status.

Subsequently, the study dissected the three core facets of the P2P ACS solution: the peer-to-peer sharing dynamic, the shared mobility concept, and the autonomy of vehicles. The analysis revealed that shared mobility solutions, like car-sharing, are gaining traction, especially among younger, well-educated, and affluent city residents. Car-sharing aligns with the trend of using something only when needed, rather than owning it. P2P solutions indicate that having a vehicle and making it available to the community prevents the purchase of new vehicles for fleets, while simultaneously leveraging the underutilized resource that is the car. In the future, as AVs gain traction, they might recalibrate residential preferences, potentially intensifying strains on road networks. Yet, shared autonomous solutions like P2P ACS can counterbalance these pressures, proffering flexibility, potential revenue streams for vehicle owners, and overarching system sustainability.

Concluding the study, a plan was outlined detailing how the P2P ACS system might operate and the factors to consider. The P2P ACS system stands out because it connects travelers with car owners willing to share their vehicles. While it faces direct competition from B2B ACS models, P2P has a distinct allure for those valuing community-based sharing, offering tangible financial and environmental dividends for vehicle owners, coupled with a sense of communal contribution. For this system to be effective, a balance between available cars and demand is crucial. This ensures travelers receive quality service and car owners have incentives to share. Launching such an initiative demands a keen understanding of target demographics, stakeholder engagement, and a thorough assessment of operational overheads. While external dynamics like regulatory constraints or evolving perceptions of AVs might present hurdles, opportunities like seamless integration with expansive transport networks can bolster the solution's uptake.

In essence, the study underscores that with adept management, P2P ACS holds the promise of becoming an integral component of the mobility tapestry of the future.

2. What are the operational and policy implications of P2P ACS solution?

To delve into the operational impact and political implications within the urban system, the P2P ACS solution was initially modeled. The P2P ACS solution involves four key players: the passenger, the central hub, the vehicle, and its owner. The inclusion of the vehicle's owner sets the P2P ACS model apart from the AMOD models commonly referenced in academic circles. The model aims to capture the dynamic communication between these players, influenced by each player's behavior.

To validate the constructed model, henceforth referred to as the P2P ACS module, a pre-existing model (from here on termed the 'base model') was used. This base model was originally designed to test a car-sharing solution in Lisbon. It starts by generating a synthetic population, establishes a daily schedule for each individual, and assigns a mode of transport to each individual's trips using a discrete choice model. The entire process was fine-tuned using surveys and studies conducted in the LMA. To simulate the P2P ACS module, several modifications were made to the base model. Some changes addressed computational speed, others adjustments stemmed from the unique operational features of the P2P ACS solution.

The P2P ACS module is designed as both an agent-based and event-based model. The creation of passengers and vehicle owners is based on individuals' daily schedules. To examine the relationship between supply and demand, scenario-based testing was chosen. Initially, the supply was set at 0.2% of vehicles operating in Lisbon (based on a 1 AV to 10 traditional vehicles ratio found in literature), and the demand was set at 2% of passengers seeking daily trips, used as a proxy for taxi demand in Lisbon. All trips originate and end within the city. Subsequently, a sensitivity analysis was conducted to assess variations in supply, aiming to evaluate service impacts and the repercussions for stakeholders and the system. Scenarios for higher levels of both demand and supply were also tested.

The findings indicate that a fleet of roughly 1,000 private AVs, which is about 0.3% of the total supply, can cater to the transportation needs of 22,000 trips, or 2% of the demand, with waiting times averaging around 2 minutes. If this fleet is reduced by half, it can still provide a satisfactory service, though there's a slight increase in service rejections by about 3% and an average waiting time of just under 3 minutes. If demand rises, the number of vehicles must also increase to maintain an acceptable service level. The balance between supply and demand in the operation is crucial. Depending on the fleet size (0.1%-0.3% supply), a P2P ACS system could elevate AV utilization to 23% or even 54% in a day, transforming an often-underutilized asset into a more productive one, in line with the primary goal of P2P ACS.

Vehicle availability fluctuates throughout the day. In scenarios with limited supply (while maintaining 2% demand), there's a noticeable vehicle shortage during peak hours, failing to meet passengers' travel needs. Spatially, various high-demand areas shift as the day progresses. These space-time variations, for vehicles available for the same duration, are the primary reason some vehicles travel significantly different distances throughout the day. For a fleet size of 0.2%, the average distance traveled with passengers is 3.7km per trip, requiring an additional 2km for repositioning. On average, vehicles cover about 200km daily, but this can extend up to 700km, potentially posing battery life challenges for urban electric vehicles.

Public policies will play a crucial role in ensuring operational success. Repositioning vehicles closer to demand hotspots while avoiding central parking or aimless roaming in the city requires municipal intervention. Relocating vehicles far from demand areas results in longer waiting times, diminishing passenger interest. Another vital aspect is the provision of additional city services to address charging and maintenance needs.

There are also internal matters that the P2P ACS solution manager needs to address. These include setting entry quotas, implementing dynamic pricing which might alter the benefit of lending a vehicle at certain times of the day, compensating based on vehicle availability or distance traveled to ensure interest from less profitable owners, and setting a fee for empty trips to compensate vehicle owners for the risk of being stuck in a low-demand area for the remainder of their shift, among other considerations.

6.2 Limitations and future research

The constructed model is a simplification of reality, overlooking certain agent behaviors, which restricts a more detailed analysis of the impacts a P2P ACS solution might have. However, there are several modifications that could make the model more robust, which weren't explored in this thesis.

In the thesis, scenario-building was used to define demand and supply levels. However, it would be beneficial to calibrate each long-term action that influences demand and supply. For instance, applying a discrete choice model for AV purchase, followed by another for its availability and yet another for its lending, would allow for a more detailed analysis of supply variations at different levels and the outcomes of their combination. The developed model was designed to integrate each of these actions. Although declared preference models for the future have limitations due to incomplete information, they could be a useful tool to explore issues like the purchase benefit given the lending gain of the vehicle in this solution, among others.

An interesting line of study, only feasible with modeling the vehicle owner's behavior, would be the owner's willingness to stop using the vehicle for their trips, which the current model doesn't consider. One of the results from the presented model is the challenge of maintaining service levels during peak hours due to the imbalance in the supply-demand relationship during these times. If the benefit for the vehicle owner was higher during this period (for instance, through dynamic pricing), the owner might change their travel time or use an alternative mode of transport; of course, this depends on each owner's individual perspective.

There's also another aspect of the vehicle owner's behavior that needs adjustment. In the model, an additional relocation period was considered at the end of the shift to ensure the owner retrieves the vehicle on time. It's suggested that this fixed value, although designed for three levels of interest, be replaced by a model that, depending on the owner's sensitivity to delay, might have a longer additional period, reducing the lending period (shift) and consequent earnings.

The simulation focuses only on vehicle owners living in Lisbon and those traveling into Lisbon with their vehicles, aiming to avoid bringing more vehicles into the city center beyond those already circulating or present. However, the model is prepared for all vehicles in Greater Lisbon to participate in the solution if their owners wish. It would be interesting to understand the impact of the entry of other vehicles coming from outside Lisbon, especially regarding the benefit it might bring to the vehicle owner since the shift time will be shorter and relocation costs higher.

The model assumes that once a passenger makes a request to the central system, they won't change their trip. However, just like with current ride-hailing solutions, passengers might cancel the trip, delay their departure by a few minutes, or change their starting or ending point. These behaviors weren't considered in the created model. Individual parameters should be assigned in the passenger agent flowcharts for each of these actions.

When a passenger makes a request and the central system doesn't have vehicles to allocate, in this model, the passenger can repeat the request up to two times within a maximum period of six minutes. This behavior was modeled arbitrarily, with a constant probability for the indicated period. This model's weakness should be reviewed and tested (sensitivity analysis) to identify the impact it might have on the main operational indicators.

Another limitation is the vehicle's relocation after dropping off the passenger. The current model doesn't consider any relocation; the vehicle remains stationary at the point where it left the passenger, waiting for a new message from the central system or the end of its shift. Some academic works have explored different AMOD relocation scenarios. It would be interesting to contribute to this topic and compare results with different scenarios: parking lots, home parking, searching for free parking, etc. Moreover, it would be valuable to identify some spots in Lisbon that could be future parking hubs to assist public policies when these solutions are introduced to the city.

Lastly, there's the matter of allocation and rebalancing algorithms. The proposed allocation algorithm was intended to be simple and fast (choosing the nearest grids). However, more efficient algorithms might impact passenger waiting times, especially when using the network and travel times. It's essential to weigh the precision gain against the increased processing time. Moreover, rebalancing vehicles, considering the most sought-after locations for trips, can significantly improve service quality for passengers. As future work, it's suggested to create an additional module, linked to the 'Central' agent, that analyzes trip demand throughout the day. This module could then use the gathered information in the next run to send a set of vehicles to specific hot-spots during the day. This feature could also help determine the starting point for vehicles coming from outside the municipality (which wasn't used in this simulation).

Chapter 7. References

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