Estimation of energy consumption and emissions in aircraft operation and potential for savings

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Aerospace Engineering

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Resumo

Os combustíveis representam uma parte grande dos custos operacionais das companhias aéreas e as emissões de dióxido de carbono estão diretamente relacionadas com o seu consumo; por outro lado, as emissões de poluentes são uma preocupação para as autoridades locais em termos de saúde pública nos aeroportos próximos de cidades. A este respeito, as companhias aéreas e autoridades de aviação têm vindo a desenvolver medidas de forma a reduzir custos e reduzir o impacte ambiental do transporte aéreo. As medidas podem ser tomadas durante as fases de *taxi* (aterragem-*taxi in* e *taxi out*-descolagem) devido ao aumento do tráfego aéreo e congestionamento nos aeroportos que leva a tempos mais longos de *taxi* e ao consumo extra de combustível (e respetivas emissões geradas). Na Europa, esta é uma questão fundamental, as fases de *taxi* representam uma quantidade significativa do tempo total dos voos de médio curso. Novos sistemas emergentes, o desenvolvimento de fontes de energia e as novas tecnologias, oferecem maneiras de reduzir o consumo de combustível e as emissões de poluentes. Neste documento, é desenvolvido um estudo sobre as potenciais poupanças de alguns destes sistemas. Em particular, atuadores (sistemas de bordo) alimentados por baterias, uma célula de combustível ou a APU da aeronave, juntamente com o estudo da utilização de tractores convencionais para mover a aeronave durante as fases de *taxi*. Os sistemas de bordo mostraram bons resultados para rotas curtas, redução de consumo de combustível e das emissões no ciclo LTO. As emissões de NOx para as operações globais mostram pequenos aumentos para rotas mais curtas, e até mesmo reduções nalguns casos, mas aumentaram para rotas longas. A utilizaçao de resultados piores do que em sistemas de bordo.

Palavras-chave

Taxiing alternativo, emissões, consumo de combustível, qualidade do ar local.

Abstract

Aircraft emissions and fuel consumption are a double issue for companies and authorities. Fuel represents a big share of airlines operating costs, and carbon dioxide emissions are directly related to them; on the other hand, pollutant emissions are a concern for local authorities in terms of public health for airports near cities. In this regard, both airlines and aviation authorities join together in an effort to reduce costs and reduce environmental impact of air transportation. Reducing pollutant emissions and fuel consumption during taxi phases (taxi in and taxi out) is an attractive option due to the increase of air traffic and the congestion at airports that leads to longer taxi times and the related extra fuel consumption and generated emissions. In Europe, this is a key issue as taxi phases represent a significant amount of the total time of medium-haul flights. New emerging systems and the development of power sources, as well as new technologies, provide ways to reduce fuel consumption and pollutant emissions; in this document, a study of the potential savings of some of these systems is developed. In particular, on board motor actuators powered by batteries, a fuel cell or the aircraft APU, along with the study of the usage of conventional push back tractors to move the aircraft during taxi phases. On board systems show good results for short routes, reduction in LTO emissions and overall fuel consumption. NO_x emissions for overall operations show small increases for shorter routes, and even reductions in some cases, but increase for long routes. Dispatch towing with conventional tractors shows savings in fuel and some emissions but worse results than on board systems.

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Keywords

Alternative taxiing, emissions, fuel consumption, local air quality.

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List of acronyms

ALAQS - Airport Local Air Quality Studies

APU- Auxiliary Power Unit

BHP- Brake horsepower

CO- Carbon Monoxide

CO_2- Carbon Dioxide

EEA- European Environment Agency

GDP- Gross Domestic Product

GHG – Greenhouse gas

HC-Unburned Hydrocarbon

IATA - International Air Transport Association

ICAO - International Civil Aviation Organization

ICCAIA - International Coordinating Council of Aerospace Industries Associations

ITF- International Transport Forum

LAQ- Local Air Quality

LTO- Landing and Take-Off

Mt – Mega metric tons

MTOW - Maximum Take-Off Weight

NO_x - Oxides of Nitrogen

Pax - Passenger

PEM - Proton Exchange Membrane

PM- Particulate Matter

RPK- Revenue passenger-kilometre

RTK- Revenue tonne-kilometre

SESAR - Single European Sky ATM Research

TBLTs - Towbarless tractors

UNFCCC- United Nations Framework Convention on Climate Change

VOC- Volatile Organ Compound

1 Introduction

This chapter is an overview of the motivation of the Thesis and its objectives, giving a summary of contribution of aircraft to energy consumption and emission to transport sector, how legislation and trends affect aviation sector and how emissions and fuel consumption are related to each part of the flight, regarding local air quality and cruise phases.

1.1 Contribution of aircraft to energy consumption and emissions of the transport sector

Economic and transport growth have been linked historically (Banister & Stead 2003). It is expected a general growth of the global Gross Domestic Product (GDP) along the next years, and also a growth in transportation (The World Bank Group 2015). Due to globalization, air transportation has become a useful link between countries and a fast way to travel. It is easily appreciable that its growth has been great within the last decades in the following figure which shows the evolution of the ICAO RPKs (International Civil Aviation Organization Revenue Passengers-Kilometres), Cargo RTKs (Cargo Revenue Tonne-Kilometres) and also aircraft kilometre (figure 1.1).

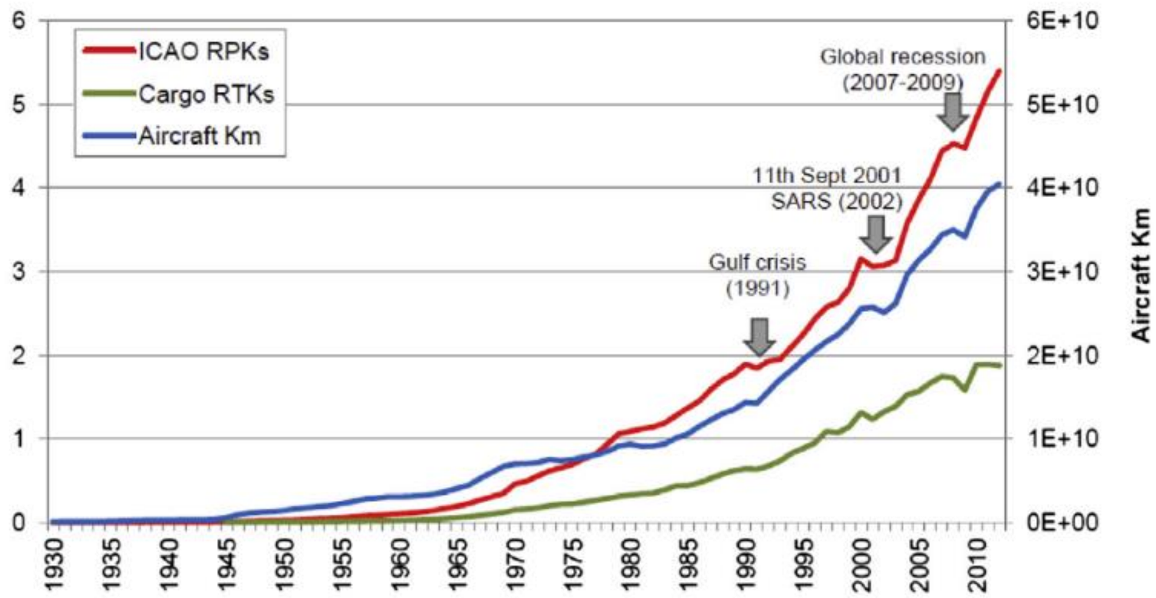

Figure 1. 1-- Global growth of aviation. Order of RPKs is 10^{12} and RTKs is 10^{5}. Source: (Masiol & Harrison 2014)*, originally extracted from ICAO data.*

RPK has been growing since the recovery from global crisis: it started in 2010, set a record in 2011, and now, in 2015, it is expected for the next years a growth of about 5% per year (OECD/ITF

2015). It is known that air pollution is a huge problem for our society nowadays. Although in Europe emissions of many air pollutants have decreased substantially (EEA 2015), it is still necessary to take serious measures in order to reduce air pollutant concentrations. Emissions in aviation come from the combustion of jet fuel, or gasoline for small aircraft with piston engines. Main emissions come from combustion, as CO_2, CO, HC (a type of VOC), NO_x, and SO_2, (which depends on the sulphur level in the fuel). Other species are emitted at relatively low concentrations (PM, N_2O and CH_4) (ICAO 2014).
These emissions can be organized in two categories:

- Greenhouse gas emissions: water vapour (H_2O), nitrous oxide (N_2O), methane (NH_4), ozone (O_3), Chlorofluorocarbons (CFCs) and CO_2 (which is considered the main GHG anthropogenic gas)
- Air pollutant emissions (criteria pollutant): particulate matter (PM), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x), lead (Pb), volatile organic compounds (VOC).

These pollutants could mean a health risk. CO restricts oxygen flow to the vital organs, SO_x produces respiratory illness, NO_x increases asthma problems, particulate matter irritates the lungs, and VOC produces several health problems. As seen, some emissions are related both to environmental issues and to health risks.

The main aviation environmental impacts are aircraft noise and combustion emissions. CO_2 represents the highest emission of aircraft as shown in figure 1.2. Aircraft emissions of CO_2 are proportional to fuel consumed by a factor of 3157 g/kg of fuel (ICAO 2014) .

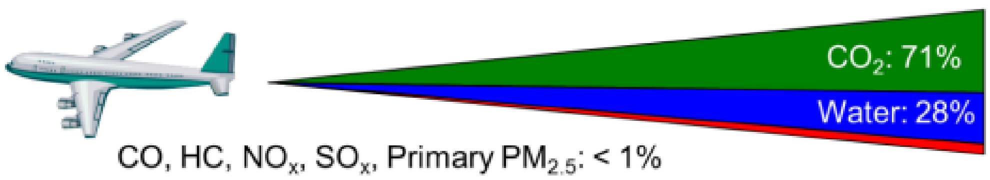

Figure 1. 2- CO_2 and water emissions importance in aviation (Maurice 2013).

On the one hand, talking about air pollutant emissions in Europe. Table 1.1 and figure 1.3 show the percentage of each component of the global emissions by sector.

	Road transport	Railway	Navigation	Civil Aviation	Non-transport
NOx	32.90%	0.90%	19.10%	4.50%	42.60%
CO	26.60%	0.20%	2.30%	0.70%	70.20%
SOx	0.10%	0.00%	20.90%	0.50%	78.50%
VOC	15.40%	0.14%	2.52%	0.40%	81.54%
PM	14.20%	0.40%	11.40%	0.60%	73.40%

Table 1. 1- Air pollutants emissions in Europe per source (EEA 2015)

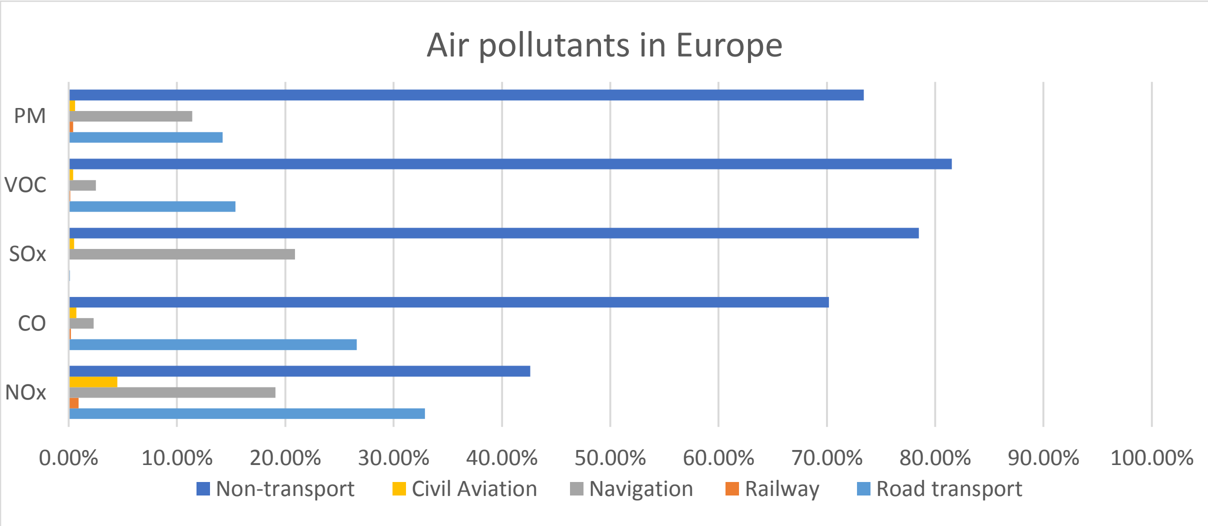

Figure 1. 3- Air pollutants emissions in Europe by source (EEA 2015)

On the other hand, talking about GHG emissions, and so CO_2, in table 1.2 and figure 1.4 are shown the percentages of the global emissions by sector in aviation.

Road transport	Railway	Navigation	Civil Aviation	Other Means of transport	Non-transport
17.47%	0.15%	3.38%	3.11%	0.19%	75.70%

Table 1. 2- GHG emissions in Europe by source (EEA 2015)

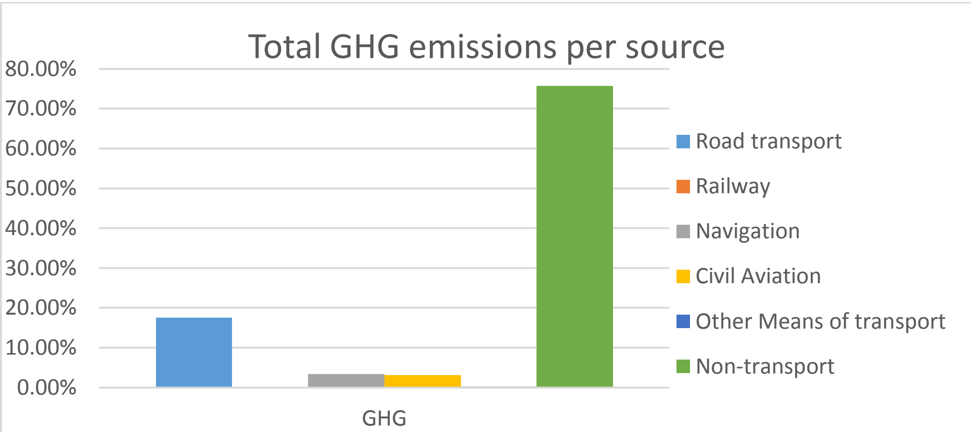

Figure 1. 4- GHG emissions in Europe by source (EEA 2015)

Aircraft emissions are therefore relevant in the total amount of CO_2 and air pollutant emissions that affect population and environment, and although their share is not big, in airports where many aircraft operate and cause these emissions they are a concern.

The evolution of the anthropogenic and aviation emissions of CO_2 throughout last decades is shown in figure 1.5. This figure also shows the percentage that aviation means in the emissions.

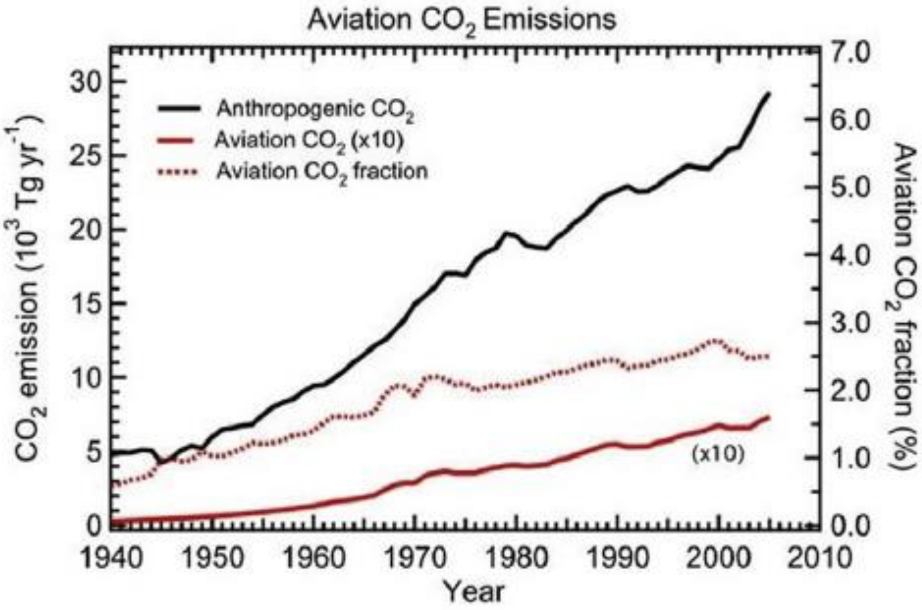

Figure 1. 5- Aviation CO_2 emissions compared to Anthropogenic CO_2 emissions (Grote et al. 2014).

According to ICAO 2013 publications, it is expected a consumption between 216 and 238 Mt of fuel per year for 2020 and a total amount of CO_2 emissions between 682 and 755 Mt. As CO_2 emissions are directly related to the fuel consumption, these emissions only can be reduced by reducing fuel consumption (better efficiency).

As for other emissions, NO_x emissions are a big concern due to the health problems related to them and the high reactivity of these gases (environmental issues related to ozone). These emissions depend both on the fuel consumption and the engine combustor, being related to high power settings and high pressure ratios and temperatures. NO_x and CO_2 emission reduction solutions regarding the engine, can meet or be an obstacle to each other (Watson & Lambert).

1.2 Trends and legislation/goals

Nowadays, reducing consumption of fuel is a goal for aviation. On the one hand, airlines want to reduce costs and on the other, aviation organizations work to achieve a reduction of environmental impact while joining the airlines to try to reduce the costs. Fuel price fluctuates and airlines have to take the risk of the potential rise of fuel prices that already are unstable. This leads to techniques to reduce this risk, as fuel hedging (Ryerson et al. 2011). There is a strong correlation between jet fuel and crude oil price as it is shown below (figure 1.6).

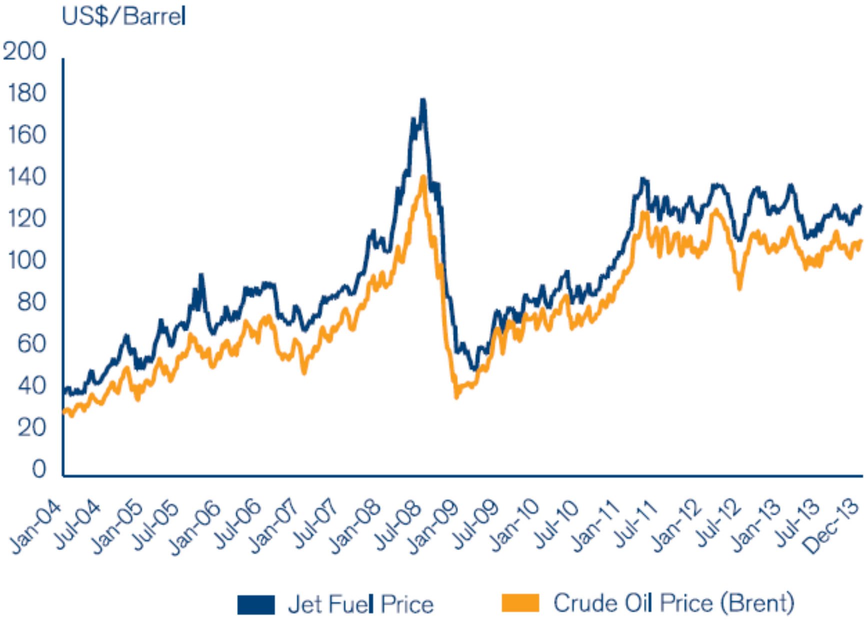

Figure 1. 6- Fuel Prices (IATA 2014).

At the same time governments and international authorities, worried about climate change and air pollution, are making serious efforts in order to reduce CO_2 emissions and air pollutants. There have been several international meetings in order to establish limitations to contaminant emissions. The most important protocol signed was the Protocol of Kyoto (1997) which was ratified by 180 countries. Goals for the next decades are expressed in table 1.3.

2020	**2030**
20% cut in greenhouse gas emissions compared with 1990.	At least 40% cut in greenhouse gas emissions compared with 1990.
20% of total energy consumption from renewable energy.	At least 27% of total energy consumption from renewable energy.
20% increase in energy efficiency	At least 27% increase in energy efficiency

Table 1. 3- EU goals for emissions reductions (Source: European Commission)

Although international aviation emissions are currently excluded from the targets of Kyoto Protocol, it states that the responsibility for limiting or reducing emissions from aviation fuels shall fall to the Annex I parties, working through ICAO. ICAO has established limits that engines have to accomplish (certification standards), as one of ICAO's Environmental Protection Strategic Objectives is to limit or reduce the impact of aircraft engine emissions on local air quality. This concern is focused on effects created during the landing and take-off (LTO) cycle as these emissions are released below 3,000 feet (915 metres) and affect air surrounding airports. One of the initiatives that ICAO has promoted to improve air quality is the creation (and continued updating) of the document Airport Air Quality Guidance

Manual. In this regard, the CAEP (Committee on Aviation Environmental Protection) assists the Council in adopting new standards and policies (ICAO 2015b). Limits and recommendations are included in ICAO annex 16 volume 2, and depend on the aircraft engines. Using sum of emissions from LTO cycle, maximum thrust at sea level and pressure ratio at sea level and maximum thrust, emissions are limited by the two first parameters for HC and CO, and NO_x emissions are limited also by pressure ratio depending on the date of manufacturing of the engine (CAEP standards) (ICAO 2008).

NO_x emissions reduction is the focus of most international effort for pollutant emission reduction, and goals for 2016 and 2026 are 45% of CAEP/6 and 60% of CAEP/6 (Dickson 2014). In Europe, the Advisory Council for Aviation Research and Innovation in Europe (ACARE) has a goal of 75% CO_2 emissions reduction per passenger kilometre and 90% reduction in NO_x emissions in its Flight Path 2050 program (ACARE 2015).

In the frame of the aviation technology and operational improvements, there are several activities and studies that are being developed in order to reach the requirements for emissions, and here is a general overview with examples:

-Solutions concerning airlines business practices. For example, substitution of connecting flights in the United States could lead to a 10% decline of CO_2 emissions each year without changing the fleet (Ryerson et al. 2011).

-Design improvements in the aircraft (Graham et al. 2014)

-Design of more efficient engines (see figure 1.7)

-Taxi solutions, such as the reduction of active engines for the taxi-out phase, electric taxi or operational towing (Wollenheit & Mühlhausen 2013).

-Biofuels possibilities for emissions reduction (Hileman & Stratton 2014).

-Optimized approach methodologies (IATA 2008).

-Ground delay programs (Ryerson et al. 2011).

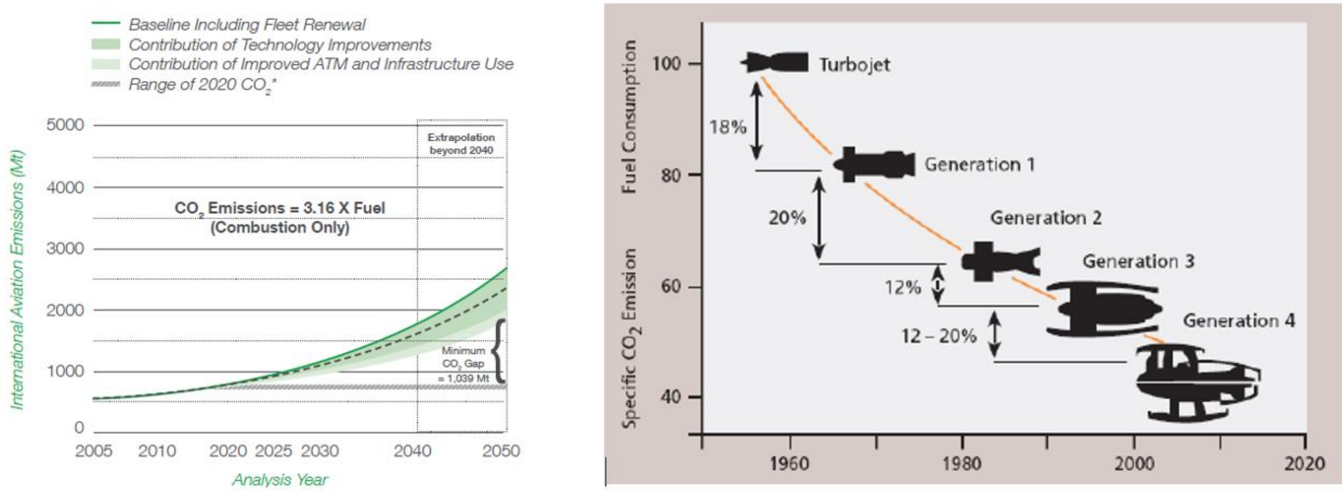

Figure 1. 7- CO_2 emissions forecast, including improvements (ICAO 2013)/Engine improvements (IATA 2000)

1.3 Characterization of flight phases and relevance to overall fuel consumption and emissions

Figure 1.8 provides a global view of a typical profile of flight phases attending to altitude and time of flight.

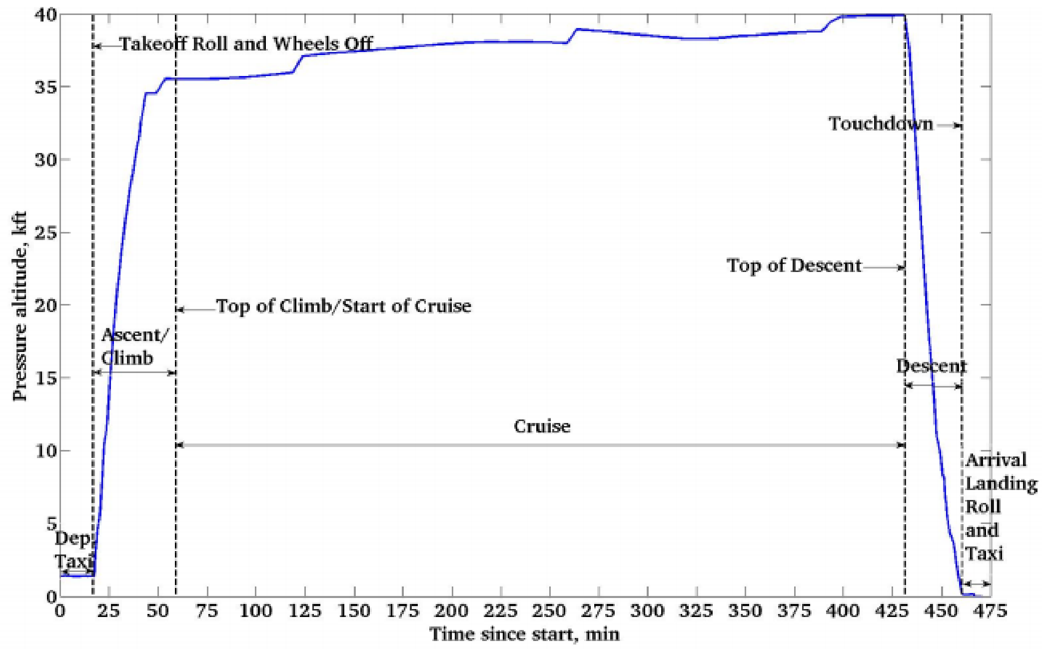

Figure 1. 8- A330 - 223 typical profile of flight phases(altitude vs time) (Chati 2013)

Flight phases can be separated in two main parts: en-route and Landing Take-Off Cycle (LTO).

En-route is the longest phase which takes place at the highest altitude. It includes climbing phase (after reaching 3000 ft), cruise and descent. The reduction of consumption and emissions in this stage is limited for reasons of safety rules (additional fuel, route definitions) and for technological and performance development. Besides it is the most efficient phase, a big percentage of the emissions are produced in cruise.

Landing Take-Off Cycle includes final approach, landing, taxi-in, taxi-out, take-off and climb-out phases as it can be seen on figure 1.9. Emissions in this phase are a concern for the airport surroundings.

Taxi-in and taxi out both includes all movements of the aircraft on ground moving on its wheels when moving from runway to parking and the other way around; this phase and its requirements is further analysed in section 2.2.2.

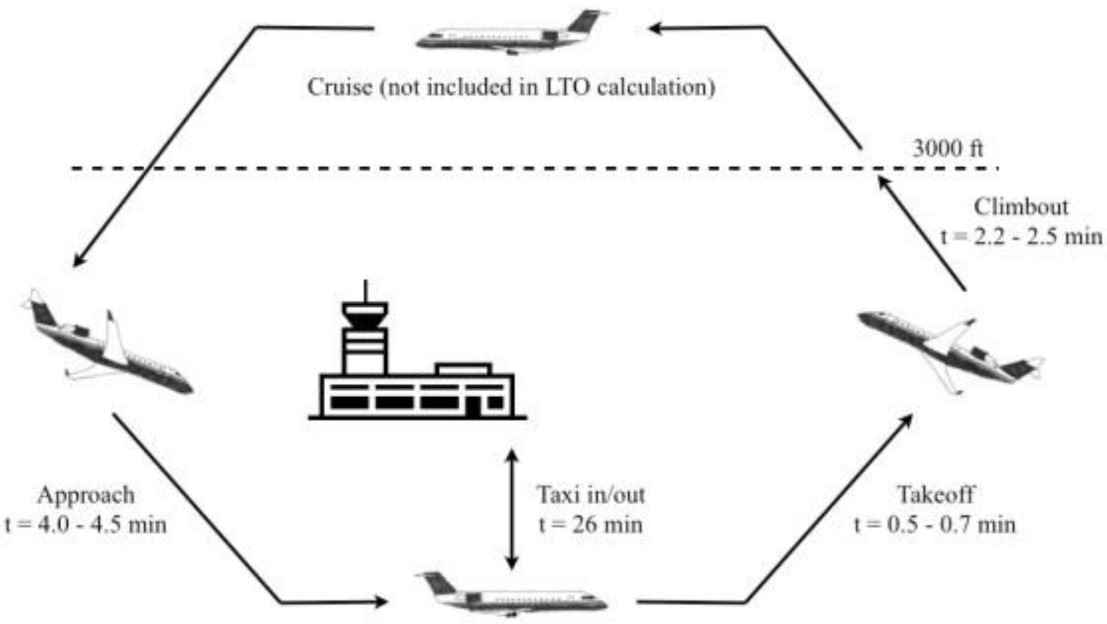

Figure 1. 9- LTO cycle. Source: (Graver & Frey 2009)

As for the LTO cycle, ICAO establishes thrust settings for each part, and also times for each mode (table 1.4). Regarding take-off, thrust setting is usually under 100% unless it is required.

Operating mode	**Thrust setting (% of maximum sea level static thrust)**	**Time-In-Mode (min)**
Take-off	100 % F_{oo}	0.7
Climb-out	85 % F_{oo}	2.2
Approach-landing	30 % F_{oo}	4.0
Taxi/ground idle	7 % F_{oo}	26.0

Table 1. 4-Standard landing and take-off cycles in terms of thrust settings and time spent in the specific mode (Winther & Rypdal 2014) *Original source: ICAO*

Table 1.5 and figure 1.10 present the amount of the main air pollutant due to aviation expressed in Gg (10^9 g) registered in Europe in 2010.

Pollutants	Domestic Cruise	International Cruise	LTO
NO_x (Gg)	40.24	425.33	465.57
SO_x (Gg)	2.91	25.94	28.85
NMVOC (Gg)	1.60	16.38	17.97
CO (Gg)	7.22	44.05	51.27
PM (Gg)	0.71	6.93	7.64

Table 1. 5- Main pollutants due to aviation in Europe in 2010*(EEA 2015)*

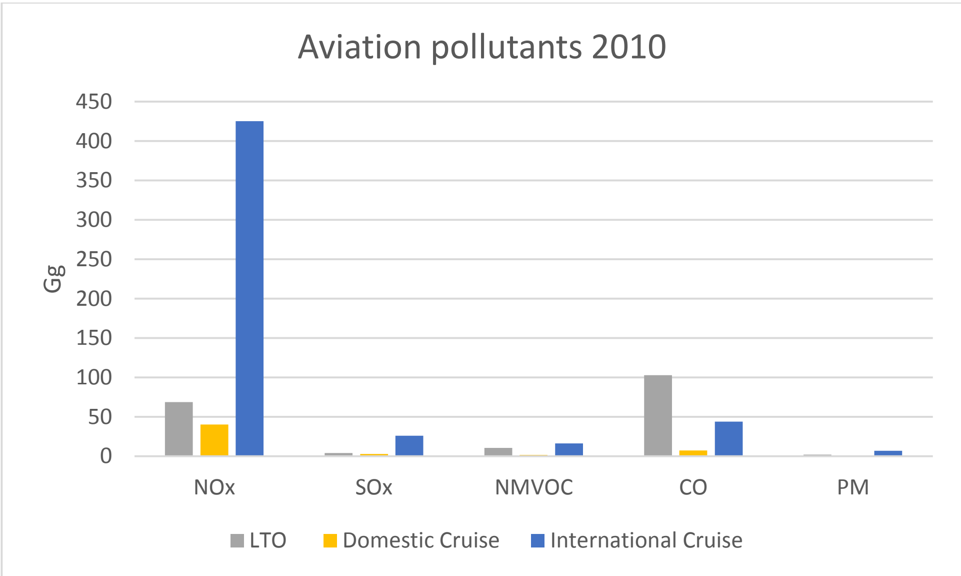

Figure 1. 10-Aviation pollutants 2010 in Europe (EEA 2015)

It is noticeable that LTO cycle means a significant part of the total aviation pollutant emissions. Fuel burned and emissions (CO_2, NO_x, Sulphur Oxides, CO, VOC and PM) during taxi phases depend on taxiing times, as well as on number of operating engines. Due to the cruise phase being the longest one, aircraft engines are designed to be more efficient during this phase, resulting in worse performance during taxi phases; this leads to higher emission index of certain pollutants (CO, HC). The time is also affected by the congestion problems and delays.*" In 2007, aircraft in the US spent more than 63 million minutes in taxiing in and over 150 million minutes in taxiing out. In Europe, aircraft spent 10-30% of their flight inland, which means that an aircraft as the A320 for short or medium range can burn up to 10% of* *its fuel while taxiing''* (Deonandan & Balakrishnan 2010). In this regard, a study from Instituto Superior Técnico shows several alternatives for fuel consumption and emissions reduction in Lisbon airport for all movements during one year(Ribeiro et al. 2011), showing the benefits of several alternatives (dispatch towing, single engine taxiing, taxi times reduction and an innovative system that consists of a fixed rail on the ground for towing aircraft). In this study, as mentioned in next paragraph, the aim is to make the comparison between dispatch towing and three on board system alternatives in several routes.

As mentioned previously, there is a lot of research about improving the aircraft efficiency during en-route phase to reduce consumption. However, these improvements are not the aim of this Thesis.

1.4 Objectives for the Thesis

Based on the need of cutting emissions and jet fuel consumption in aviation, the objectives for this Thesis are to study ways of reducing emissions and fuel consumption in LTO cycle, more in particular during taxi operation, by considering several alternatives: electric motor assistance, towing alternatives (use of a pushback type tractor to perform taxi) and compare those possible solutions with today's conventional procedures.

1.5 Structure of this Thesis

This Thesis is structured in four main parts:

-State of the art: A review of the ways that can lead to achieving less fuel consumption and emissions, with an analysis of the possible alternatives for taxiing (Section 2).

- Methodology: Procedure of calculation/ equations used and reference case for the study of the ways selected to compare with today's standard procedures (Section 3)

- Calculations and results: Results obtained from the application of the methodology (Section 4).

- Conclusions and further development: Main points from the discussion of the data obtained and brief comment on possible future challenges and developments (Section 5)

2 State of the art

This chapter is organised in three parts. Firstly, a brief review of the ways for reducing fuel burnt and emissions in terms of fuels used, aircraft operations and aircraft technology; these will not be considered for this study. Secondly, a review of the taxiing alternatives available, as well as close to market alternatives and a review of the power sources considered for alternatives. This part will be the basis for the methodology developed.

2.1 Fuels, operations and technology

2.1.1 Alternative fuel, biojet fuel

As it was said in the introduction, fuel prices and the environmental issues connected to jet fuel and petroleum are making the solution of cleaner types of fuels more attractive. This leads to the use of alternative fuels. In this field, ground transport sector is a reference; the sector has much more experience in alternative fuels, as bioalcohols, biofuels (biomass, algae-based fuel, biodiesel)(Hileman & Stratton 2014) and both alternative jet fuels and alternative ground transportation fuels share the same feedstocks that can also be used for electricity production. This leads to a competition for the resources but also to a big market, which is an advantage.

The aviation industry has some main requirements for alternative fuels: possibility of mixture with conventional jet fuel, use of the same supply infrastructure and work on aircraft engines, same specifications, environmental sustainability. This excludes several of the alternative fuels used by ground transportation sector, because some of the requirements are pretty restrictive. Once the conditions have been analysed, biojet fuels are a promising alternative (ICAO 2010b; IATA 2015; Hileman & Stratton 2014)

2.1.2 Aircraft technology

During last decades, as can be seen in figure 2.1, fuel efficiency in passenger air traffic has improved significantly, and it is expected that these improvements will continue due to the new generation of aircraft. Last decades results have been achieved thanks to a great development in aircraft technlogy, but also because of better operations and air traffic management.

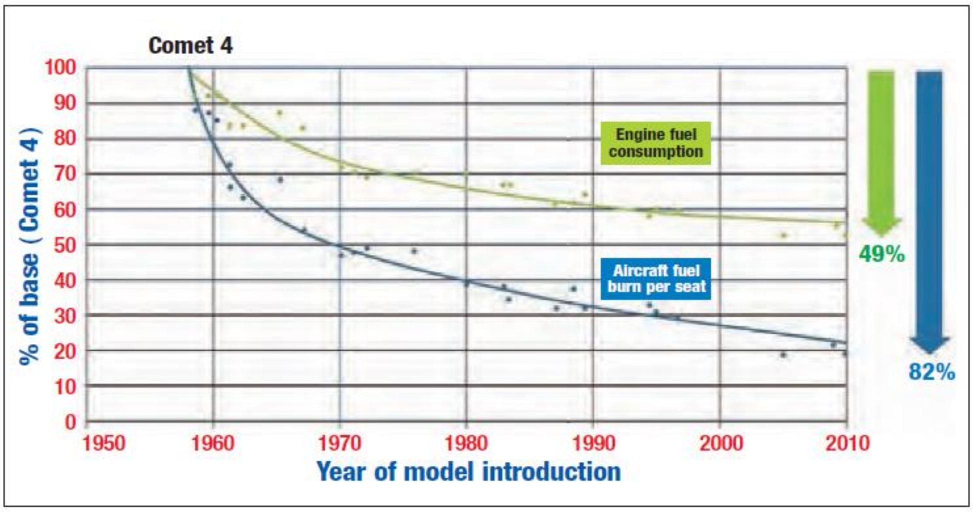

Figure 2. 1-Evolution of passenger air traffic fuel consumption and fuel efficiency (ICAO 2010a).

2.1.2.1 **Weight reduction**

The development of new alloys and advanced composite materials, new techniques and processes have become a source of weight savings in the industry of aviation. For example, the A380 has a 25% incorporation of lightweight composites (Airbus).

2.1.2.2 **Aerodynamic improvement**

Drag reduction during longest phase of flight (cruise) has been very important in efficiency. Examples of the goals in this field are reducing friction, minimizing elements that break the aerodynamic, optimization of surface intersections, etc.

2.1.2.3 **Engine**

Investigation in engine technology is continuously carried out by manufacturers, in order to provide the most reliable an efficient product. Not only in design for better performance, but tests to check the compatibility with alternative fuels are run. As seen in figure 1.2.2, performance of engines is constantly in evolution.

2.1.2.4 **Future aircraft concepts**

Some trends in design promote the idea of new concepts. The Royal Aeronautics Society's Greener by Design initiative, explores the potential impact of new technology and different design for aircraft, including hydrogen considerations. Configurations considered (for current jet fuel): tube and wing, laminar flying wing, blended wing body. (Graham et al. 2014), (Greener by Design 2002)

European project 'New Aircraft Concepts Research', aims to validate and consolidate technologies that will make possible the development of new aircraft, starting from the base that conventional configurations could need to be modified to provide the change needed **(**NACRE). Some similar are the Boeing SUGAR (Subsonic Ultra Green Aircraft Research) concept, the NASA, MIT, and other teams' concepts and the TOSCA project, for example.

2.1.3 Operating improvements

One way to reduce a significant amount of fuel consumption is to optimize the approach phase of flight. Following an optimum profile, has as a result that the number of flight segments is only the needed for the aircraft to prepare to land. Optimization of flight plans is an excellent tool to save fuel consumption. Varying the route, speed, altitude… the savings will be not only in fuel, but in 'time costs'. In airports, delays and excessive taxiing times lead to increased block times and more consumption and therefore, more emissions. In Europe there is the 'European ATM Master Plan', from SESAR, which includes all phases of flight. Continuous Descent Approach is included. A big scheme can be seen in figure 2.2.

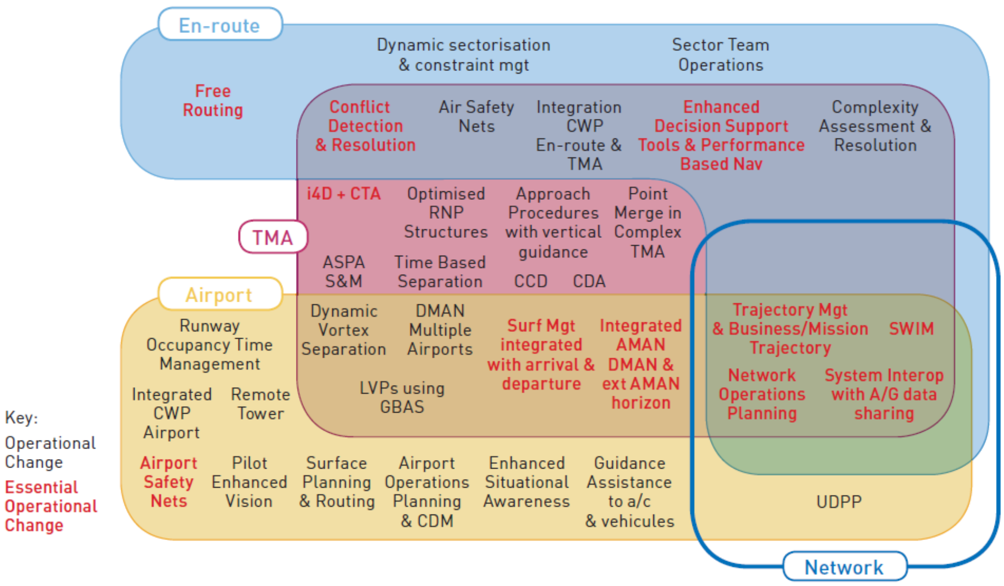

Figure 2. 2-Scheme for ATM Master Plan(SESAR Consortium 2012)

2.2 Taxiing alternatives

This is the main part on which the Thesis will focus in next chapters, more in particular the taxi alternatives without the use of the engines. As said before, this is a source of pollutant emissions for local air and with the increase of air traffic and taxiing times in airports comes consequently the concern about costs and emissions.

2.2.1 Single-engine taxi

One simple way to reduce the emissions, and also the fuel burnt, is the single engine taxi. The use of only part of the engines during taxi would reduce emissions, and as two-engine aircraft would use only one, it is called single-engine taxiing. Due to airport congestion, contribution to air pollution grows, and single-engine taxiing is easy to carry out. Safety has to be considered, because conditions as rain or icing eliminates the possibility of reducing the number of operating engines (Deonandan & Balakrishnan 2010) , (IATA 2015). It is also an issue that if an engine does not work properly (mechanical problems) when pilot turns it on, if the aircraft is in the middle of a taxiway, the equipment and workers won't be there to fix the problem, and the aircraft would have to be taken back to the gate and have another departure time assigned. As not all engines are active, more thrust is required in the operating ones, so foreign object damage and jet blast have more importance, mostly when airport fire service units are not next to the aircraft as in the gates.

Studies made in the USA showed potential air pollutant emission savings of 27% and 45% with this procedure without reducing taxiing time in Orlando and New York- La Guardia (Guo et al. 2014). However, this case is not considered.

2.2.2 Engine alternatives available

Several options to avoid engine use during taxi phase can be compared in terms of fuel consumption and emissions to the conventional taxiing procedure. When considering alternatives for taxiing procedures, they must include push-back from gate (except form particular cases, as no nose-in parking, use of reverse thrust, etc.), moving the aircraft from still with enough force and driving it during the taxi in the taxiway. Taxiing alternatives to engines can be separated in tractor type equipment (external, also called dispatch towing), and in electric motor on wheels (on-board system), which can be on the nose gear or in the main wheels. Performance is a key factor when evaluating alternatives; slower speeds and poor performance mean more congestion in the airport and, as mentioned before, this is a matter of concern in Europe. Costs and logistic viability are also key factors. Main advantages of these alternatives, apart from potential emissions and fuel consumption reduction, are the elimination of jet blast concerns in gate area, less brake wear (due to the permanent thrust) and reduction of foreign object damage.

Alternatives available to engine usage during taxi phases are dispatch towing (a push back type tractor carries the aircraft during taxi phase), performed by conventional tractor, hybrid tractor and all electric tractor considering both fuel cell systems and batteries for the electrical tractor, and on board systems, both nose and main wheel electric actuators, powered by fuel cells, batteries or aircraft's APU.

Apart from complete electrified taxi solutions with on board systems, there is also as option the substitution of conventional pushback.

2.2.3 Tractor type equipment. Dispatch towing

Conventional towing tractors usage can be divided in two, but both of the usages can be performed with the same vehicle: the pushback and the long distance towing. Pushback is a short task, but required, and long distance towing is used for gate to gate movements and operations of maintenance (Canada Transportaion Development Centre 2012). Pushback tractors and tow tractors use the nose gear as link with the aircraft, there are two types of pushback tractors: conventional and towbarless (TBL). Towbarless tractors do not use a tow bar but a device on the vehicle that embraces the nose gear to direct the aircraft (figures 2.3 and 2.4).

Figure 2. 3- Conventional pushback (with towbar). Source: http://www.continental-specialty-tires.com/

Figure 2. 4- Towbarless tractor. Source: http://www.tld-group.com/

External systems for taxiing are vehicles (tractors or ‘tugs’) that are attached to the aircraft in order to tow it along the taxiway (dispatch towing). The power required for the taxi phase does not come from the aircraft, but from the tractor. Tractors have several options of power sources, as hybrid configuration, diesel, all electric (Lektro), while alternative jet fuel is not much available for aircraft (limited stock). Their consumption and emissions will be studied and compared to the conventional taxiing procedure.

However, in terms of viability, acceleration forces supported by the nose gear and the command of the procedure (pilot, tug driver) have to be studied (Wollenheit & Mühlhausen 2013). A logistic problem appears in the movement of the tugs from runway back to gates due to security issues in taxiways; the feasibility of the solution depends on the airport, from a net of roads for tugs to some kind of traffic control system.

Usual tractors for an aircraft of this size have the average load factor of 80% and 175 brake horsepower (BHP) (about 130 kW) for a diesel tug (Webb 1995). Towing speed of these tractors is about 25 km/h (for example, the JBT AeroTech Expediter 160 (JBT AeroTech) is designed to tow from an A320 to an A330 and the equivalent types of Boeing, and has a maximum towing speed of 26 km/h, with a motor of 165 kW, and a maximum starting traction force of 60 kN).

2.2.3.1 **Taxibot**

Taxibot solution is a representative dispatch towing system from the Israel Aerospace Industries, developed with French manufacturer of ground-support TLD Group. It consists of a semi-robotic hybrid tractor (towbarless), controlled by the pilot. This means that the pilot is in control of the movement, using the same controls that are used in conventional taxiing. Braking is performed with main landing gears, which avoids critical loads on nose gear. Simulations made for Charles De Gaulle airport showed compatibility with the infrastructure, no impact on the airport capacity and no perturbation on aircraft flows, just a slightly increase in taxi-out times. This system has been tested extensively, and recently has received approval by the EASA (just the narrow body of 800 HP power). Now it is being used by Lufthansa LEOS, after a presentation at Frankfurt airport on February 19th 2015. Lufthansa expects to save up to 2700 tonnes of fuel per year in its Frankfurt’s hub. Its speed is reported similar to normal taxiing speeds, 42 km/h (Transportation Research Board (TRB) 2015).

The tractor is hybrid diesel-electric, with 8 wheels for narrow body, and 12 for wide body aircraft (TaxiBot International)

2.2.4 On board systems, WheelTug e-taxi and Electric Green Taxiing System (EGTS)

On board systems considered are those in which an electrical motor moves the aircraft. In this particular case, WheelTug e-taxi system is a solution developed by WheelTug and Chrous Motors and consists of a nose wheel motor powered by aircraft's APU. It is an on-board system designed to perform a part of the taxi phase for narrow body aircraft. The device is an electrical motor installed in the nose gear (one on each wheel), showed in figure 2.5, with an electric box in the aircraft and the equipment needed in the cockpit. The aircraft can maneuver on its own (pilot control). This motor does not require additional modification to the APU, and allows movement both forward and backwards, so the system ca perform the pushback. The weight of the system, is around 136 kg (Gubisch 2012).

The problem is, as said, found in speed, as WheelTug does not reach usual taxi speeds. The speed limitations only allows the WheelTug to be useful in taxiing situations where the aircraft has to stop and move.

About aircraft modifications, the attachement point of the nose landing gear may need a modification in the actuator for extension and retraction, structure and stability.

Figure 2. 5- WheelTug system (Source: http://www.fleetsandfuels.com/)

Born by the union of Honeywell and SAFRAN, EGTS system is not certified yet (Transportation Research Board (TRB) 2015). The idea is similar to the nose gear system, but in the main one. The EGTS consists on an electrical motor driven by the APU, but in this case there are also modifications needed in the APU. It can also be used both for pushback and for taxiing, and is permanently fixed to the aircraft, allowing the pilot to control all the process. EGTS has been demonstrated in the Paris Air Show 2013 in an A320, and is expected to enter into service in 2016; the additional weight added is expected to be around 150 kg per wheel, including APU modifications, with a maximum speed of 33 km/h (Norris 2013). Data given by the company estimates the emission savings in up to 50% in nitrogen oxides, 60% in carbon dioxide and 70 % in carbon monoxide in a long taxi out (17 minutes), and substantial fuel consumption savings (SAFRAN 2015). The increase of emission due to the extra weight transported will be addressed in section 3.8. This system has a disadvantage in case the aircraft has to be changed, if the fleet is not equipped equally.

The system includes the cockpit interface unit, the actuators and motors (figure 2.6), the EGTS controller (aircraft), and the modifications in the APU, including the power electronics. The target is to be used in those flights that have long taxi times, short flight range and high flight cycles. The electrical actuator selected is placed between wheels and off axis, in order not to disturb brake cooling efficiency.

Figure 2. 6- EGTS system. Source: http://www.safranmbd.com/egtstm

2.3 Power sources

Here is a review of the characteristics of the alternative energy sources considered for the alternative taxiing systems. This is important when considering future developments. Ground transport sector can use electric energy from batteries or fuel cells. However, that is not possible for aviation in terms of aircraft propulsion. As it is not expected any commercial aircraft of this kind before at least two decades and even then they probably won't have a great range (1500 to 2000 km from IATA estimations), fuel cell and batteries could be useful in order to save fuel and emissions in aircraft movements in airports, as they could be used to power systems to move the aircraft during the taxi phase.

2.3.1 Fuel cells

Fuel cells convert chemical energy from fuel into electricity, but unlike batteries, chemicals are not stored inside; fuel cells require a constant source of oxidant and fuel to maintain the energy supply. Hydrogen and synthetic gases rich in hydrogen are commonly used. The origin of the hydrogen will determine its emissions in the place of production, but using hydrogen as a fuel does not produce emissions (tank to wheel), as reaction product is water (van Vliet et al. 2010). Similarly to batteries, fuel cells have to be combined by cell stacking, due to the fact that a single fuel cell provides low voltages in open circuit, and even less under electrical load (Celikel et al. 2006).

The environmental impact of a fuel cell is low and its electric conversion rate is high, and these are advantages compared to traditional generators. Fuel cells use is limited by price, size and durability, however. Six main classes have emerged as a useful alternative, but proton exchange membrane fuel cell (polymer electrolyte - PEM) is the most promising cell for vehicles (Laminie & Lowry 2012). Fuel cell systems are difficult to make, water balance and temperature have to be controlled carefully, requiring a ‘balance plant’. Fuel cell drivetrains are similar to series hybrid drivetrain, powering an electric motor instead of using a generator. Fuel cells are not limited to hydrogen as fuel; using a fuel reformer, a wide range of fuels can be used to produce hydrogen (methanol, natural gas, diesel, jet fuel, gasoline….), and some types can reform the fuel themselves. However, fuel reformers are expensive, and reduce energy efficiency (van Vliet et al. 2010). In this study, only hydrogen will be considered. Electrical energy required for the fuel systems is assumed to be provided by the APU without appreciable effect on its consumption.

Hydrogen has a specific energy of 33.3 kWh/kg, and a very low energy density, and has to be stored in a certain way, as in liquid state at low temperatures or in a pressurized vessel. Hydrogen storage, due to its density, is a key issue in terms of size and conditions. Stored hydrogen options are shown in table 2.1. It is a matter for further development to study the optimal size, type, performance and maintenance of the systems used.

Storage	kWh/l
Chemical hydride	1
Metal Hydride	0.6
Liquid	1.2
700 Bar	0.8
350 Bar	0.5

Table 2. 1- Storage options for hydrogen. (Kromer & Heywood 2007)

Due to requirements of storage (temperature, size, extraction), pressurized tanks are considered.

2.3.2 Batteries

A battery consists of two or more electric cells connected together. These cells convert chemical energy into electrical energy, and they consist of electrodes and an electrolyte; the reaction between them generates DC electricity. Rechargeable or secondary batteries, in which the chemical reaction can be reversed through the input of current, seem more suitable for these applications. There are several kinds of rechargeable batteries depending on the chemical reaction. Performance criteria are: specific energy and power, energy density, voltages, efficiency (Ah, capacity and energy), availability, operating temperatures, life cycles, recharge rates…. Energy provided by the battery depends on factors such as temperature, charge needs, battery geometry, etc. These factors affect the efficiency of the battery as well as its life.

Even when the chemistry is the same, not all batteries are equal. The main classification is if a battery is either high-energy or high-power; developing in the sector can reach improvements in both characteristics but one is dominant. Cells have low voltages, and connecting them gives us the required voltage. The nominal voltage gives the approximate voltage when the battery is delivering power. However, this voltage changes in practice. It falls when the battery gives out a current, and it rises when the battery is being charged. Charging the battery will be a key factor in its life. The correct way of charging prevents a premature failure. It is important to control carefully the current and the voltage, and maintain the battery in a state of charge over 20%, to avoid a drop in efficiency (Laminie & Lowry 2012). Figures 2.7 to 2.10 show current batteries characteristics available extracted from literature.

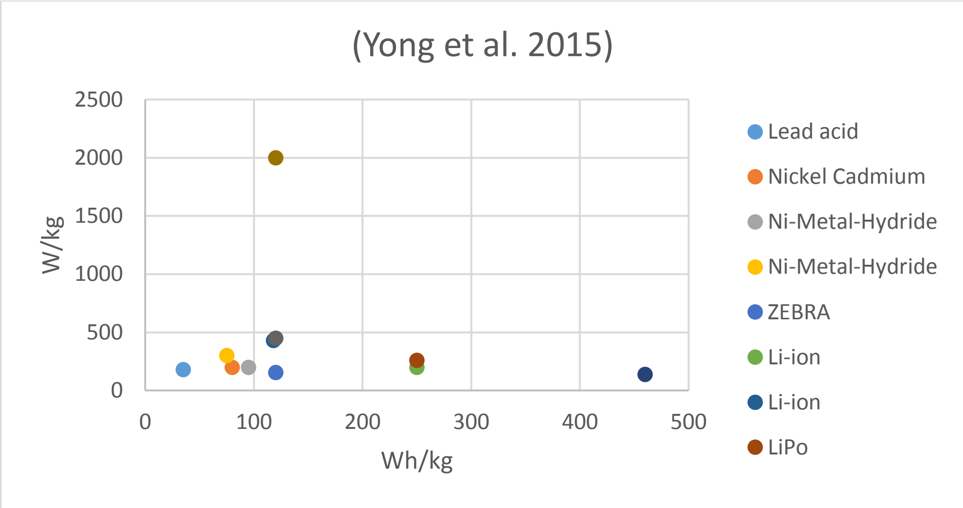

Figure 2. 7- Batteries Ragone plot extracted from *(Yong et al. 2015)*

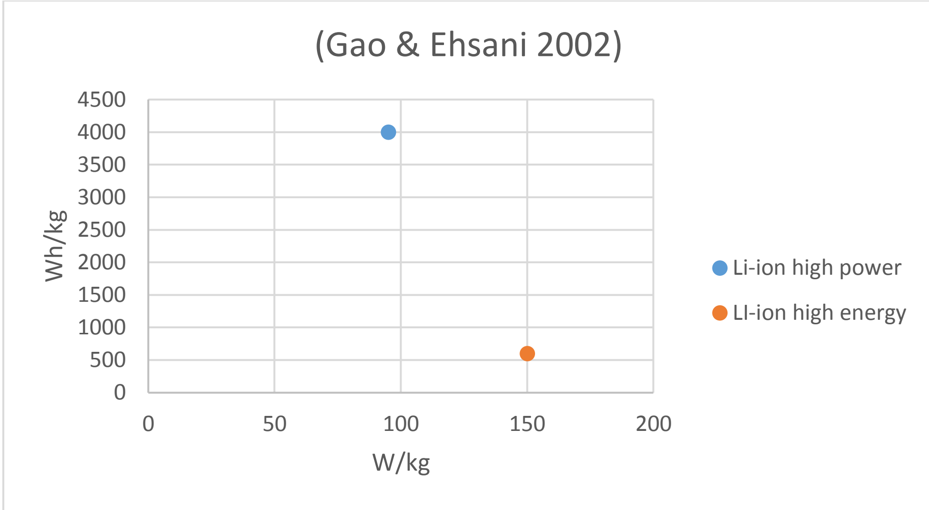

Figure 2. 9- Batteries Ragone plot extracted from *(Gao & Ehsani 2002)*

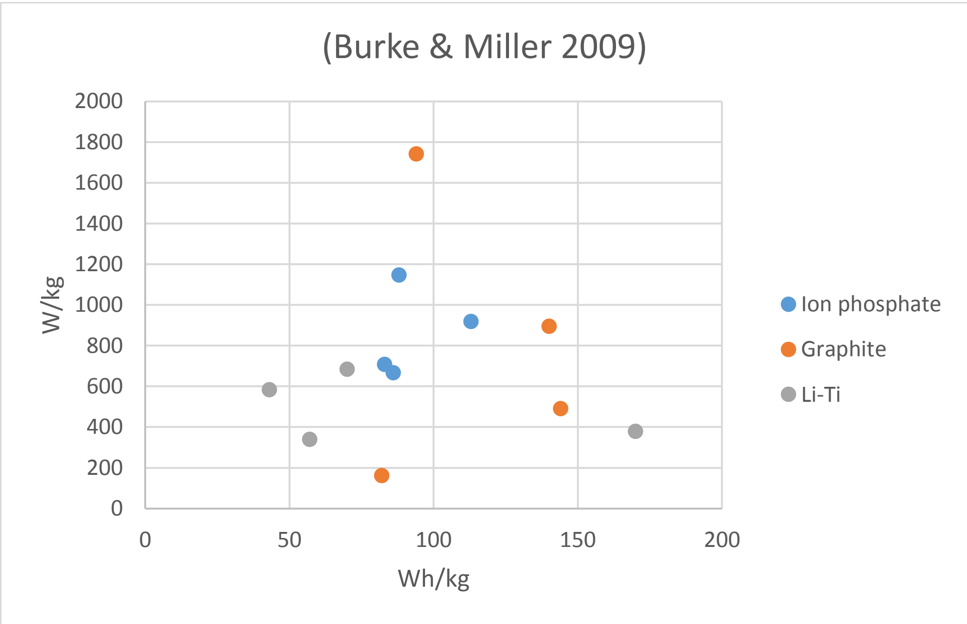

Figure 2. 8- Batteries Ragone plot extracted from *(Burke & Miller 2009)*

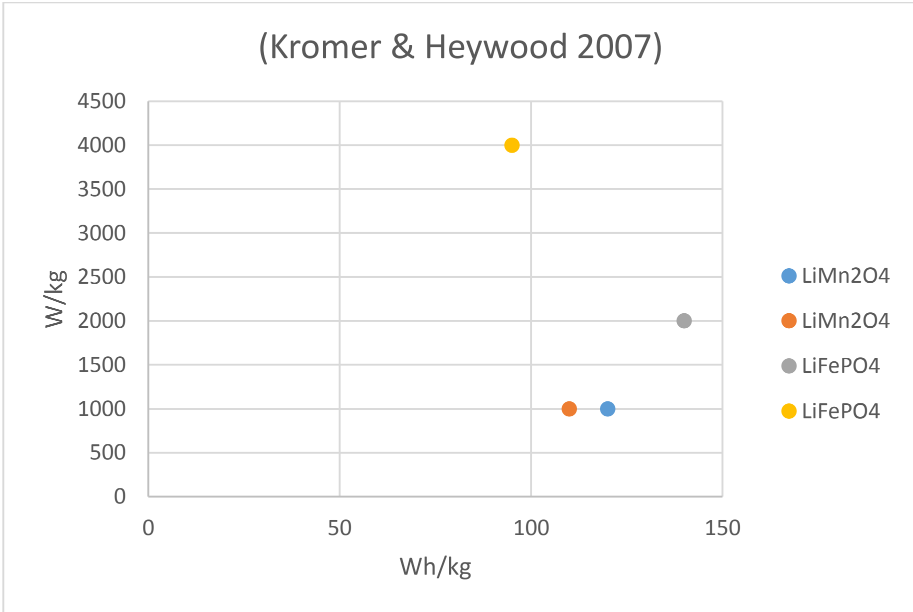

Figure 2. 10- Batteries Ragone plot extracted from *(Kromer & Heywood 2007)*

2.3.3 Auxiliary Power Unit

Auxiliary Power Units (APUs), which are a component of an aircraft, consist basically of a small turbine engine, generating electricity to run the instruments, lights, and also pneumatic and hydraulic energy given the case, as well as the air bleed to start main engines. As mentioned before, APU works when there is no other source of power, meaning that the main engines are off and the aircraft is not connected to a ground power unit. The four APU operating modes (ICAO) are the APU start-up, the normal running for passenger loading, the high load (main engines start) and the normal running for disembarkation. Aircraft APU provides 115/200 V 400 Hz AC, and 28 V DC in some cases of small aircraft.

Auxiliary power unit equipping an aircraft as the A320

is the Honeywell 131-9. This turbine provides up to 300 kW when it is at full load (main engines start). In standard conditions the usage of the APU for the aircraft requirements is about 85 kW, through a generator up to 90/115 kVA, using the bleed air for pneumatic purposes. This means that there is enough energy available for the electrical motors in the wheels. The power that could be available is about 200 kW (Re 2012)**,** and this will be taken as nominal power available for ground propulsion, and considered enough. However, the maximum power, is developed through bleed air for the start of the main engines (APU mode: main engine start), not the electric generator. It is necessary to modify the APU so as to transform all the power developed by the APU into electrical energy, perhaps using a generator and probably a gearbox; however, in this issue just a weight for the extra modifications will be estimated with the electrical motor. The full power will not be needed all the time, but we assume the same fuel consumption given the mode of work of the APU. The weight of the APU is approximately of 165 kg (Honeywell), and uses the same fuel as the aircraft. The period of time during which the main engines are started, checked and the time for warm up is supposed not to affect the aircraft movement.

Data of fuel flow and emissions index for average APUs of each aircraft type are obtained from the report 64 of the Airport Cooperative Research Program sponsored by the FAA (Transportation Research Board (TRB) 2012). Emission index of the carbon dioxide used, however, will be 3157 instead of 3155 (g CO_2/kg fuel), with the same units (annex 1). In this regard, results obtained are related to the election of the APU, and its characteristics vary from one model to another; also the power of the unit is assumed to be enough in order to allow a proper taxi phase performance.

3 Methodology

Figure 3.1 shows the options studied as alternatives to conventional (engine) taxi operations.

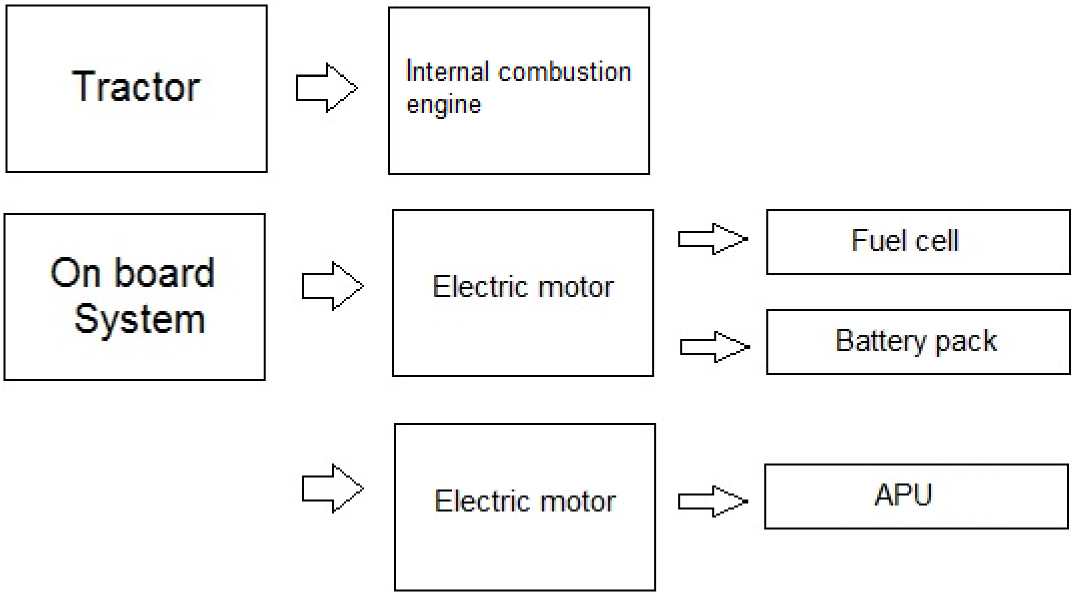

Figure 3. 1- Alternatives studied in taxi operations.

3.1 Aircraft considered

Using the TAP fleet as reference, as most of its aircraft are A319 and A320 types, these will be the aircraft used as reference when calculating the alternative taxiing methods and emissions and fuel consumption impact. Data provided by TAP Portugal, showed in Annex 2, shows the models of the engines which the aircraft are equipped with (CFM International). The engine manufacturer of the considered aircraft engines (CFM) recommends a minimum warm up of 2 min before take-off (CFM 2005), but 5 min will be considered to be conservative and to include start-up and pilot performance of the checklist. Regarding taxi in, it is supposed that after all landings the engines are used for at least 3 min. Figure 3.2 shows the time lapses when alternative systems can be used. These aircraft are prepared in some cases for a different number of passengers, and there are different models for each type, but will focus on the MTOW and the engines. The wing area is obtained from (Butterworth-

Heinemann), 122.4 m² for both. In Europe, A320 an A319 are commonly used and occupy ranks 1 and 3 in the list. The percentage of movements is not necessarily representative of the relative importance in fuel burnt and emissions, as flight distances and aircraft sizes are the most important factors, but gives an idea of the usage of each aircraft (see table 3.1).

ICAO Code	Type name	Nb Engines	Engine type	Percent	Percent International	Cumulative %	Most used engine types
A320	AIRBUS A-320	2	TJ	13.3%	83.4%	13.3%	V2527-A5, CFM56-AB4/P
B738	BOEING 737-800	2	TJ	12.3%	85.1%	25.6%	CFM56-7B26, CFM56-7B27
A319	AIRBUS A-319	2	TJ	9.7%	89.9%	35.3%	CFM56-5B6/P, CFM56-5B5/P

Table 3. 1-Movements per aircraft in Europe in 2011 (A320, B737-800, A319) (Winther & Rypdal 2014) *Original source: Eurocontrol, STATFOR*

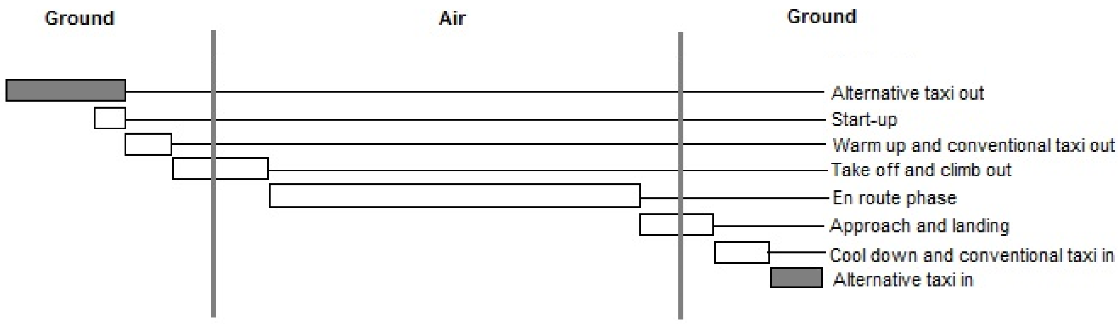

Figure 3. 2-Alternative taxi systems times of usage scheme

Both A320 and A319 aircraft are aircraft manufactured by Airbus, both belong of the A320 family, both are short to medium range narrow body aircraft. For both aircraft, according to Airbus aircraft manuals (Airplane Characteristics), tyres have a diameter of 46 inches for the main gear for the A319 and a diameter of 46 or 49 inches for the A320. For both the nose gear has a diameter of 30 inches. Data of the wheel radius when loaded and static is extracted from tyre manufacturers (Michelin). Data can change depending on the width of the tyre and de load distribution in the aircraft, but as the load can vary the number is used as representative. Radius taken for the 46 inches (diameter) wheel when loaded is 57 cm, 61 cm is taken for the 49 inches wheel and 38 cm for the nose gear tyres. These values will be used to calculate the torque needed in the wheel axis.

3.1.1 Reference scenario

Routes considered for the case studies are Lisbon- Porto, Lisbon-Geneva, Lisbon-Paris (Orly) and Lisbon-Milan (Malpensa). As said before, data is obtained from TAP, including average flight lengths, fuel consumption, load factor (no freight is transported in these routes) and number of movements (annex 4). Two options are considered for the calculations. Firstly, a round trip in which the aircraft has to carry all the weight for the taxi phases in case it is used an on-board system, and any battery changes and refuelling are done in Lisbon (which is the base and is where the company would have a better infrastructure and equipment). In this case, those routes in which the number of flights slightly differ in each direction, the lowest number of round trips is taken. Secondly, the single trips between the airports are used, considering that batteries can be changed in each destination without extra delay and so does happen with the fuel cell's hydrogen supply. Taxi times for airport considered are extracted from Eurocontrol (EUROCONTROL 2015), and appear in annex 6. Relevance of taxi fuel consumption and emissions results for routes considered are displayed in section 4. Reference emissions for LTO cycles (annex 7) are extracted from ICAO engine emission databank *(ICAO 2015a)*, and for en-route phases (annex 3) from EMEP/EEA inventory guidebook (European Monitoring and Evaluation Programme/European Environment Agency).

3.1.2 Engine comparison

Figures 3.3 and 3.4 show the engines, sorted by certification date (EASA 2012), for aircraft considered in TAP fleet . Engine data are described in annexes 5, 6 and 7.

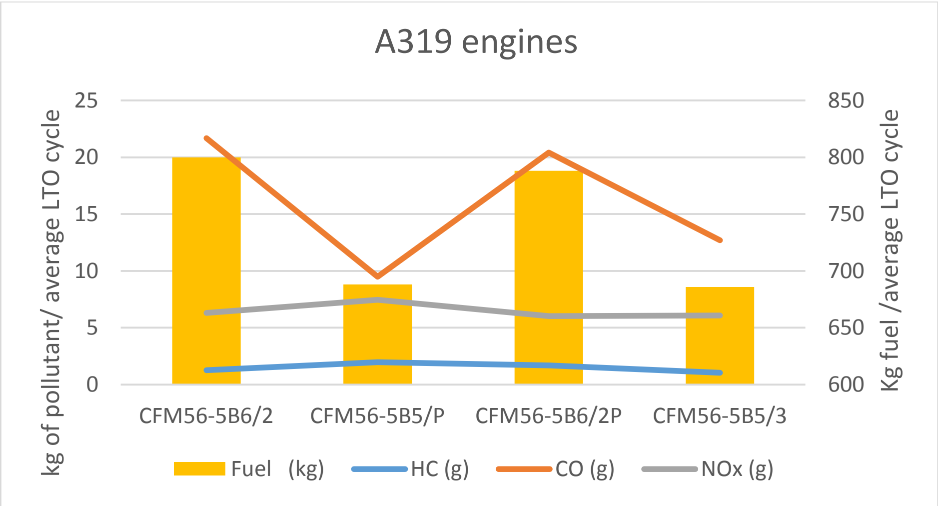

Figure 3. 3-A319 engines in TAP fleet, pollutant emissions and fuel consumption on average LTO cycle for 2 engines (ICAO 2015a)

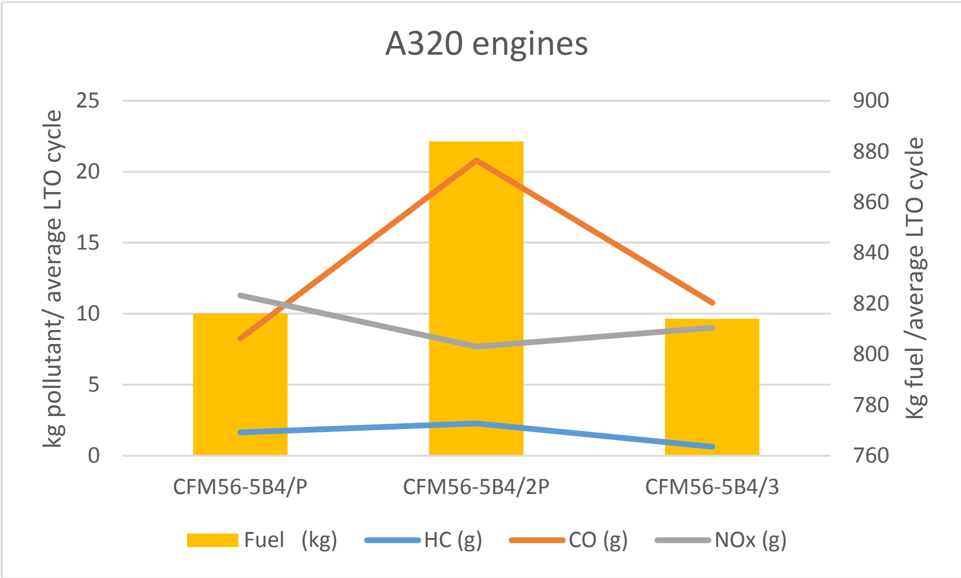

Figure 3. 4-A319 engines in TAP fleet, pollutant emissions and fuel consumption on average LTO cycle of 2 engines (ICAO 2015a)

As can be seen, emissions and consumption are interesting, more in particular for NOx and fuel, due to ICAO Annex 16 normative (CAEP regulations) and the interest on more efficient engines. For future considerations, lower emissions in the engine during LTO phases and the rest of the flight will suppose less emissions associated to the use of an on board alternative taxiing system. Engines considered to study the alternatives, due to its spread of usage, are the 5B5/P for the A319 and the 5B4/P for the A320.

3.2 Taxiing requirements

Taxiing speeds are limited to 46 km/h in taxiways (Wollenheit & Mühlhausen 2013), however, this speed differs from actual speeds as during the taxi phase aircraft have to turn, stop and slow down in several situations. As reference to estimate the energy and power required by the aircraft in the taxi phase, runway crossing rules are applied. ICAO prescribes a minimum of 90 m in a common approach procedure, between the holding position and the operation itself; other authorities are more cautious (Re 2012), considering this distance and a safety time to cover it twice. It is also assumed that the taxiway has no slope (maximum permitted by ICAO is 1.5%) to calculate the average taxi needs, but it is considered in case of the maximum force required. The acceleration considered is 0.25 m/s² (Re 2012) taking into account the safety needs of acceleration.

Usual taxi range from 6 m/s to 10 m/s, although depending on the airport they vary and in some long straight taxiways speeds are higher (Desart)(Schrier et al. 2011). This can be used to estimate the requirements of the taxiing system. If the average speed of taxi considering stops and turns is taken 5 m/s, in a 10 min taxi out, this means 3000 m covered, an accurate distance. Some examples of taxi simulations show similar speeds in samples of taxi procedures (Khadilkar & Balakrishnan 2012).

Total force required for driving a vehicle at a constant speed can be calculated as follows (Gerssen-Gondelach & Faaij 2012):

$$F_{friction} = C_{rr} \times m \times g \quad (1)$$

$$F_d = \frac{1}{2}\rho \times v^2 \times C_D \times S \quad (2)$$

$$F = m \times a + F_d + F_{friction} \quad (3)$$

$$F_{slope} = m \times g \times sen\, \phi \quad (4)$$

$F_{friction} = force\ needed\ to\ overcome\ rolling\ resistance$

$F_{slope} = force\ needed\ to\ overcome\ a\ slope$

$F_d = force\ needed\ to\ overcome\ drag$

$C_{rr} = rolling\ resistance\ coefficient$

$m = mass\ of\ the\ vehicle\ (kg)$

$g = gravitational\ acceleration\ constant\ (9.81 m/s^2)$

$v = velocity\ of\ the\ vehicle\ (m/s)$

$\rho = density\ of\ air\ (1.225\ kg/m^3)$

$S = reference\ wing\ area\ (m^2)$

$C_D = coefficient\ of\ drag$

$\phi = angle\ of\ the\ slope$

For coefficients, it is assumed a rolling resistance coefficient of 0.01 (trucks) and a non-drag lift coefficient of 0.017, to be conservative. Rolling resistance, however, may be less (0.006 - 0.01). The inertia of the motor is not taken into account, as electric motors provide instant torque. Towing forces are shown in figure 3.5.

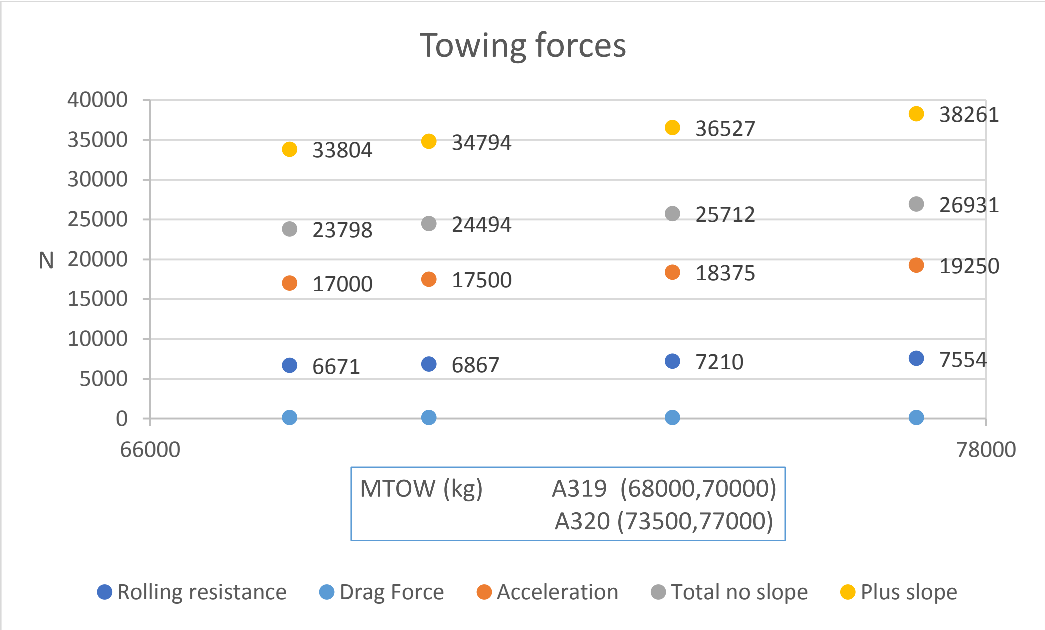

Figure 3. 5- Maximum forces required in taxi

After the calculations, it can be seen that in a case of maximum acceleration, supposed to be needed of 0.25 m/s²), forces are up to 24- 27 kN, which in case of a slope of 1.5 % would be incremented up to 35-38 kN. Drag forces are negligible. However, actual towing forces are not that high during all the taxi. Considered average forces for taxi are from 6 kN to 10 kN. The forces needed to maintain the speed are about 6-8 KN as can be seen, but there are events of acceleration and deceleration in which the requirements for the motor/motors will be higher, being forced to deliver more power. Towing measurements for several A319, made during the study of a prototype for a wheel hub motor are shown in figure 3.6; those measurements are made under the condition being towed by a conventional tractor. As can be seen, average force does not reach 8 kN, and movement can be maintained with 6 kN. However, this was performed at low speeds (due to the tow bar) so it is expected a higher force in average.

Torque needs and speeds are calculated through the equations below:

$$T_{axis} = F_{wheels} \times r \quad (5)$$

$$T_{axis} = T_{motor} \times Gear\ ratio \times \eta_{transmission} \quad (6)$$

$$V_{vehicle} = 2\pi r \times \frac{1}{Gear\ ratio} \times 1/60 \times n_{motor} \quad (7)$$

$$P_{avaliable} = P_{motor} \times \eta_{transmission} \quad (8)$$

Where:

$T_{axis} = torque\ delivered\ in\ the\ axis$

$F_{wheels} = force\ avaliable\ or\ required\ to\ move\ the\ aircraft$

$T_{motor} = torque\ delivered\ by\ the\ motor$

$n_{motor} = speed\ of\ the\ motor\ (rpm)$

$V_{vehicle} = speed\ of\ the\ vehicle\ (tractor, aircraft)$

$P_{motor} = power\ at\ the\ output\ of\ the\ motor$

$\eta_{trans} = efficiency\ of\ the\ transmission\ (axles, gearbox, etc.)$

Transmission efficiency will be considered as 0.95, as transmission method is supposed to be selected as the available optimum. Different gear ratios are calculated for torque and speed (figures 3.7 and 3.8). As for minimum torque, in Frankfurt airport tests of alternative taxiing systems, a 47 tonne A320 required a breakaway torque of 3,500 Nm on a level surface in dry conditions, torque that could reach a value of 5,800 Nm (Gubisch 2012).

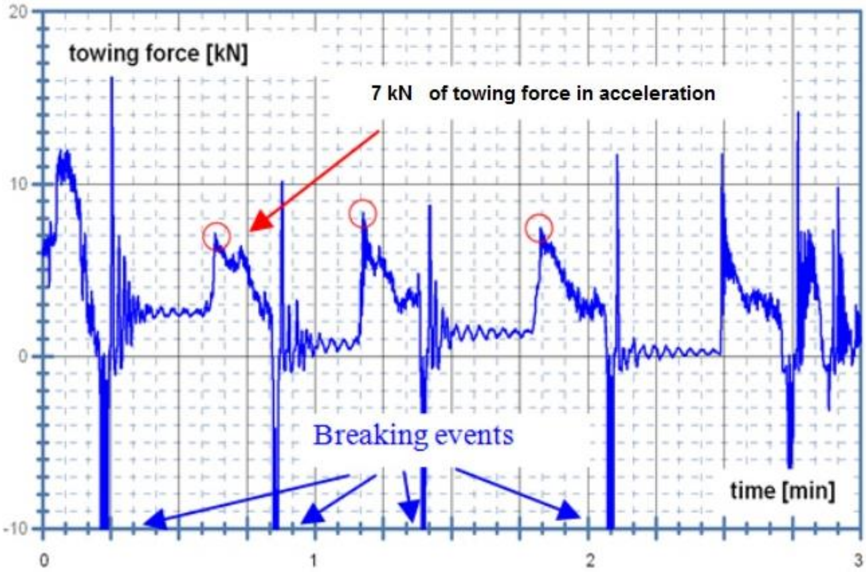

Figure 3. 6- Example of towing forces required for an A319 (Schrier et al. 2011)

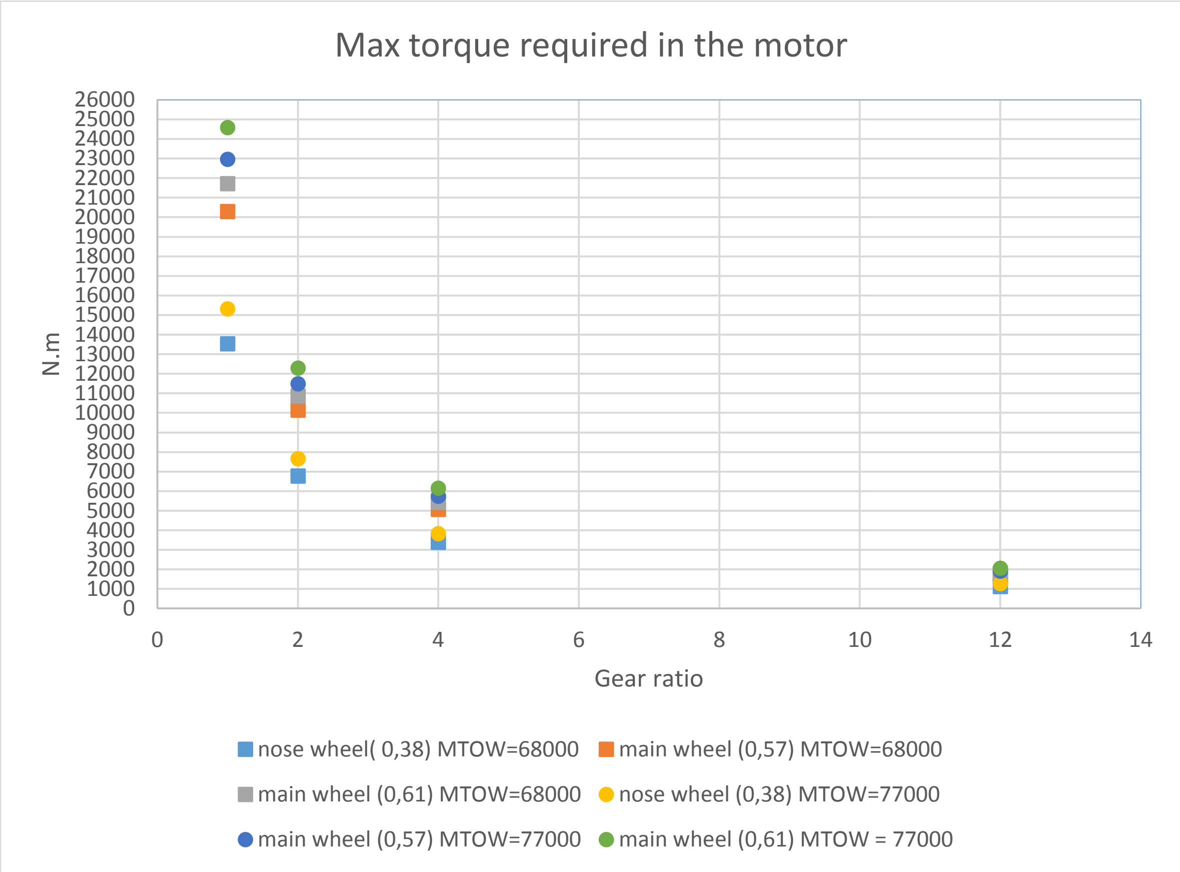

Figure 3. 7- Maximum torque requirements in the motor for the heaviest and the lightest aircraft considered

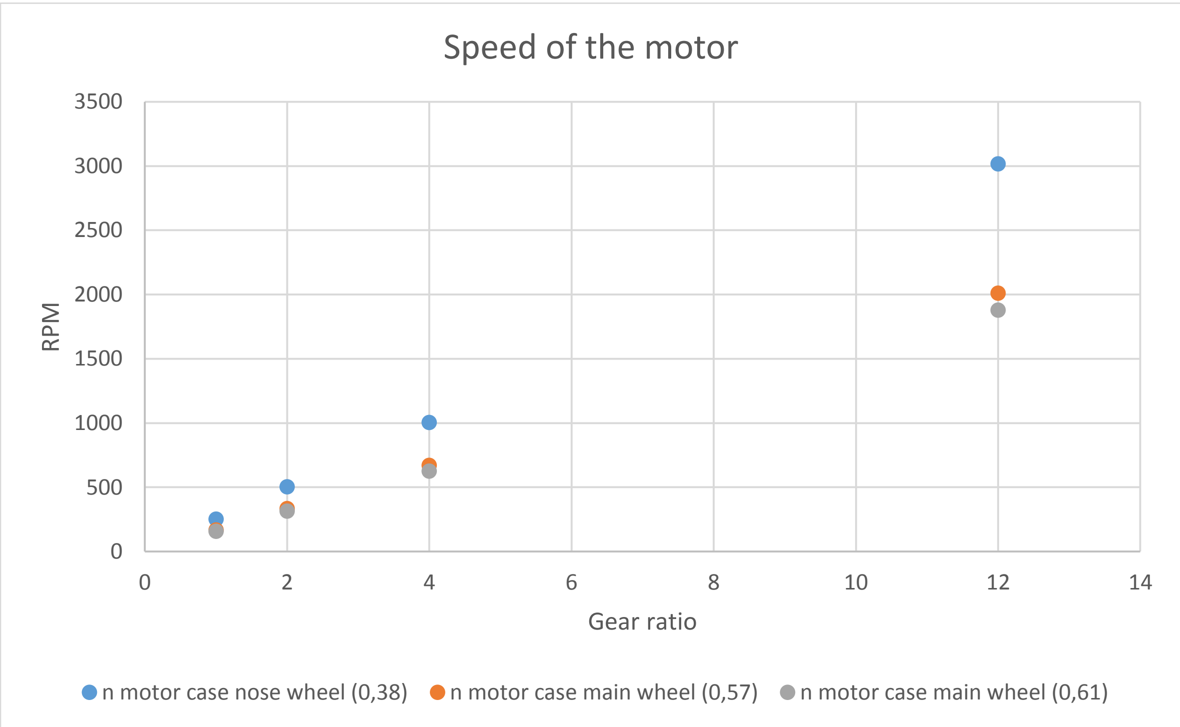

Figure 3. 8- Motor rotation speeds requirements with each gear ratio

These rotation speeds give an accurate approximation of the maximum speed that the motors required for this purpose have to achieve with enough torque.

To make an approach to the needs of energy:

$$P_{avg} = F_{avg} \times v_{avg} \quad (9)$$

Where ‘avg’ is ‘average’.

Considering a force of 16k N in average (similar to idle thrust) and 7 m/s of speed, results are an average power from of 112 kW; this is assumed to represent the performance of a taxi out and a taxi in, in conventional conditions considering acceleration events. The maximum power required, in order to fulfil the requirements of security used as reference, would have to be enough for the aircraft to move 107 m (90 plus extra 17; code F in the ICAO recommendations, although it is no necessary) twice in a time interval of 40 s. In a first approach it is assumed an average speed of 5.35 m/s under maximum traction force of each aircraft, power needed is about 200 kW (210 kW in the output of the motor) for the 77000 MTOW A320, and this will be used as a reference for the power source. Given that narrow body aircraft in European flights are usually under 80% pax load factor (ICAO 2014), and they don’t take off at MTOW, it is considered enough. However, performance is assumed not as good as conventional taxiing, as the thrust of the engines is far more powerful.

3.2.1 On board electric actuators

In order to test the viability of a wheel hub motor for the A320 nose gear, the Institute of Vehicle Concepts has designed and built a prototype for the German Aerospace Centre DLR (Schrier et al. 2011) . Using a gearbox of three gear stages, it has a translation stage with a ratio of 1:12 for taxiing on ground. The system is integrated in the wheel and the axis because of the absence of brakes. The results showed the possibility of a torque up to 10 kN, with a maximum rotation speed of the motor of 2000 rpm (Schrier et al. 2011). Considering the curves of the motor (figure 3.9), and the requirements in terms of motor torque for the considered aircraft and taxi requirements, the nose wheel motor option has to be rejected for a complete taxiing procedure, which will be studied, but currently the system could besuitable for a substitution of the conventional pushback and the movements of stop and go.

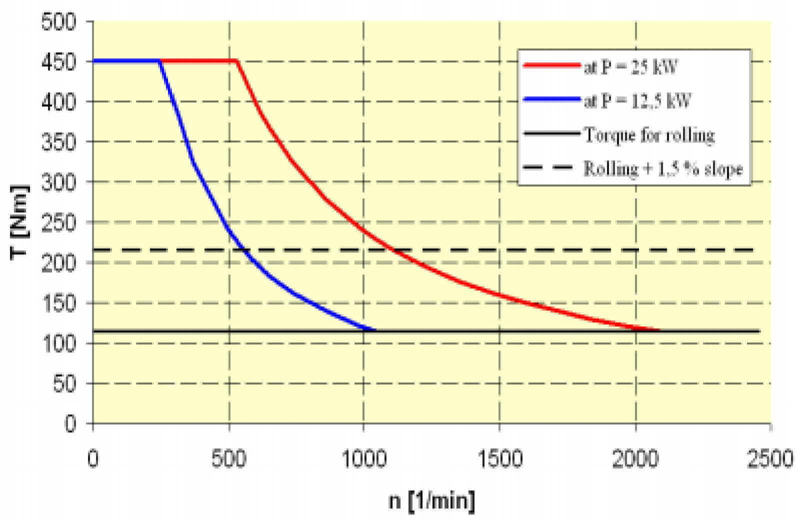

Figure 3. 9- Performance of a wheel hub motor prototype for A320's nose gear (Schrier et al. 2011)

As for the main wheel system, it can be considered a direct drive wheel actuator that, given that there are 4 big wheels, it may be feasible to achieve the performance requirements for ground movement of the aircraft with direct drive, which will increase the reliability of the system as they would not have a gear box. In this case, a study of the viability of the Green Taxi solution (EGTS), mentioned before, but without gearbox, shows a device between 65-75 kg (Raminosoa et al. 2011) capable of performing as showed in figure 3.10.

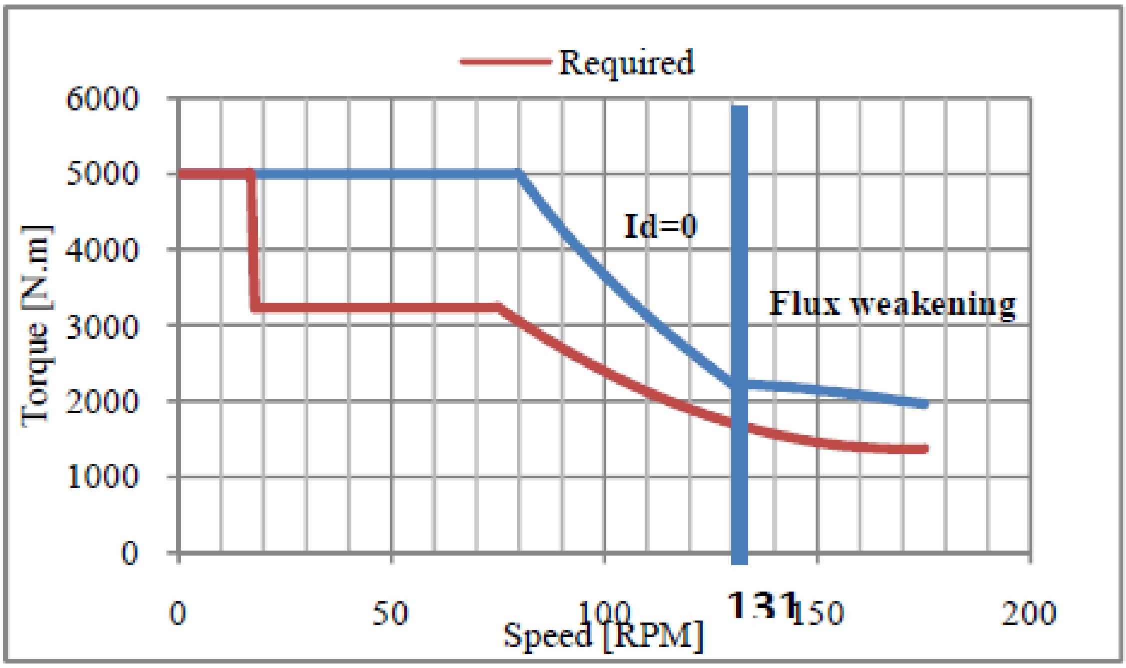

Figure 3. 10- Performance of a wheel actuator for the main gear (Raminosoa et al. 2011). *Blue line represents the maximum performance, and red line the one required for the taxi procedure studied (A320-B737).*

This motor speed, according to equation 7, allows a maximum speed of 7.8 m/s before the flux weakens, so in theory maximum speed is higher. In on board actuators, controllers required to use the electrical motor are supposed to have an efficiency of 98%.

3.3 Emissions calculation methodology and fuel burnt.

The EMEP/EEA (European Monitoring and Evaluation Programme/European Environent Agency) air pollutant emission inventory guidebook (Winther & Rypdal 2014) provides technical guidance to prepare national emissions inventory. It includes a chapter for aviation, where there are defined several proceedings of estimate the emissions and fuel consumption depending on data available. It separates the civil aviation traffic into international and national and into LTO cycle and cruise. Thrust considered by ICAO as reference for taxi phases is 7% (table 1.4)

However, this is the standard, in (Chati 2013), for example, using flight data recorder data, they extracted an amount of 10% of the maximum thrust during taxi, and reductions in the percentage of the rest of the LTO phases from 15 to 30%. Taxiing times in different airports can be found in Eurocontrol (CODA). As the thrust depends on several factors, the calculations will stay attached to the ICAO standard value of 7% of maximum engine thrust at ground idle (taxi).

In our case, aircraft consumption during taxi phases will be estimated by using taxiing times and the data obtained from the ICAO Aircraft Engine Emissions Databank. This databank contains information on exhaust emissions of aircraft engines. The information was provided by engine manufacturers.

The emissions will be estimated for CO, NO_x, CO_2 and HC. CO_2 is directly related to the fuel burnt, with a relation of 3157 g/kg fuel (ICAO 2014), and the rest are in the ICAO database.

Equations used to estimate emissions during taxi phases:

$$FB = t \times 60 \times FF_{idle} \times N \qquad 10$$

$$E_i = t \times 60 \times FF_{idle} \times {EI_i}^{idle} \times N \qquad 11$$

Where

$FB = fuel\ burned$

$t = time\ (min)$

$FF_{idle} = fuel\ flow\ at\ idle\ conditions\ (kg/s)$

$E_i = emissions\ of\ pollutant\ i$

$N = number\ of\ active\ motors\ (2)$

${EI_i}^{idle} = emission\ index\ for\ pollutant\ i\ at\ idle\ (g/kg\ of\ fuel)$

3.4 Auxiliary power unit emissions

Equations used to estimate the emissions and fuel consumption of the APU are similar to the ones used for the main engines in conventional taxiing. Extra fuel required for taxi in is supposed to be taken from the reserve fuel so this fuel is not an extra weight but has to be replaced when refuelling.

$$FB_{APU} = t \times 60 \times FF_{MES} \quad (12)$$

$${E_{pollutant_i}}^{MES} = FF_{MES} \times {EI_i}^{MES} \times t \times 60 \quad (13)$$

Where:

$FB_{APU} = fuel\ consumed\ by\ the\ APU$

$FF_{MES} = fuel\ flow\ of\ the\ APU\ in\ the\ main\ engine\ start\ mode\ (kg/s)$

${E_{pollutant_i}}^{MES} = emissions\ of\ pollutant\ i\ in\ main\ engine\ start\ conditions$

${EI_i}^{MES} = emissions\ index\ of\ pollutant\ i\ in\ main\ engine\ start\ conditions\ \ (g/kg\ of\ fuel)$

$t = time\ (min)$

3.5 Conventional tractors emissions and fuel consumption

Main engines start up and warm up time do not affect this alternative, as it can be performed during movement. Conventional tractors used to perform pushback considered for towing are both wide and narrow aircraft type powered by diesel and gasoline internal combustion engines. Table 3.2 shows performance characteristics in terms of consumption and emissions for narrow body and wide body type pushback tractors to move reference aircraft are obtained from literature (Webb 1995)(Deonandan &

Balakrishnan 2010). The connection of the towing vehicle for the taxi in phase is a problem in terms of time and logistics, so in this case only taxi out is considered; even when with a good planning the tractor used to tow a departing aircraft could be used to tow an arriving one, this solution seems too difficult to carry out (considering that aircraft would have to stop and also that usually aircraft only use a part of the runway for decelerating), and departure and arrival are situated at opposite runway ends. Emissions and fuel are based on power measurements at the output shaft of vehicle's engine (break horsepower, BHP).

		BHP/kW	Fuel consumption (l/(BHPh))	Emissions (g/(BHPh))			kg/litre of fuel
				NO_x	CO	HC	CO_2
Narrow Body	Diesel	175/130	0,231	11	4	1	2,672
	Gasoline	175/130	0,337	4	240	4	2,321
Wide Body	Diesel	500/373	0,201	11	4	1	2,672
	Gasoline	500/373	0,337	4	240	4	2,321

Table 3. 2-Conventional pushback tractors characteristics (Webb 1995)(Deonandan & Balakrishnan 2010).

Taxi procedure performed by narrow body tractor type is considered slower than conventional taxi. The time of dispatch towing in these cases is assumed to be 2.5 times the current taxi time for narrow body type (round trip), to be conservative, and usual times for wide body, both working at its usual load factor of 0.8 (Webb 1995) to carry the aircraft, but 0.5 for the wide body type tractor when not towing. Structural requirements for accelerating and breaking events are considered solved by a system connecting the main gear brakes to the tug (see section 2.2.3). Otherwise, maximum forces supported by the nose gear could not allow great acceleration and breaking actions.

As for electric powered tugs, considering two electrical models commercially available for the aircraft type considered (Anon)(Lektro), have modest characteristics for towing. The average speed is taken 5km/h, which is about 5 times slower than the speed considered for an average taxi (7m/s). These speed and power characteristics do not allow to perform a suitable taxi phase.

Equations that define fuel consumption and emissions of conventional (diesel and gasoline) pushback tractors are shown below. The taxi in procedure is not considered feasible due to logistic constraints.

$$FB_{Tractor} = Load\ factor \times BHP \times FF_{BHP} \times t/60 \quad (14)$$

$$E_{pollutant_i} = Load\ factor \times BHP \times t/60 \times EI_{pollutant_i} \quad (15)$$

$$E_{CO_2} = FB_{Tractor} \times EI_{CO_2} \quad (16)$$

Where:

$FB_{Tractor} = fuel\ consmumtion\ of\ vehicle\ (l/BHPh)$

$BHP = average\ rated\ horsepower$

$FF_{BHP} = fuel\ flow\ (\frac{l}{BHPh})$

3.6 Batteries

The solution selected to the problem of battery charging times is to take the batteries from the vehicle, put a charged pack instead, and store the discharged one while charging. This way of proceeding could have several logistics issues, adding complexity to the system, and because of the needs of space for storage and design for a quick swap, but may be worth implementing it in case of a place where all the vehicles stop, such as an airport.

Batteries considered to make the calculations are a lithium ion cell manufactured by EIG (Graphite/ Ni CoMnO2), with 140 Wh/kg (at 300 W/kg) of specific energy and 895 W/kg of specific power and the Lithium Iron Phosphate LiFeO4 (140Wh/kg, 2000W/kg) (figures 2.7 to 2.10). The mass extracted will be used as a reference for the aircraft extra consumption in case of the on board electric motor powered with batteries. The efficiency of lithium ion batteries is high, sometimes over 95%, but a value of 0,9 is taken with the forecast of improvement in the future (Gerssen-Gondelach & Faaij 2012), as the battery performance depends on several factors. Tank to wheel emissions related to this kind of power system are considered 0 in the place of usage (Aguirre et al. 2012; Van Vliet et al. 2011), but emissions in the place of energy production (or hydrogen) vary from source and are a concern in those places.

However, in the field of batteries, a lot of research and development is required to reach a point near the theoretical energy capacity of the cells (Adelhelm et al. 2015). As for future development, it is expected a better performance and the development of possibilities that are currently under development; it is also expected that cost for batteries will decrease as the market of electrical vehicles grows and the manufacturers find methods and materials with less cost associated (Kromer & Heywood 2007), which would make these solutions much more attractive.

3.6.1 Approximate battery sizing

Battery sizing for a complete taxi phase is made based on the assumption that it has to bear the energy and power required for the time that is expected to work multiplied by a factor (1.2). This is due to the needs of the battery to stay in a state of charge between 20% and 80% in order be as efficient as possible (Laminie & Lowry 2012). As well, it is assumed that battery pack occupies the same volume in each case, and so the same weight for each aircraft, which means that, as happens with the electrical motors, the battery weight will be slightly oversized for the A319, resulting in a better performance because of lower weights. The specific sizing depending on each aircraft model and configuration is left for further development.

$$Battery\ pack\ weigh = factor \times \max\left(\frac{Energy\ required}{Specific\ energy_{Battery}}, \frac{Power\ required}{Scpecific\ power_{Battery}}\right) \quad 17$$

$$Energy\ required = Average\ power\ in\ taxi \times\ time\ \times 60\ \times 1/\eta_{tot} \quad 18$$

$$Power\ required = Maximum\ power\ required/\eta_{tot} \quad 19$$

$$\eta_{tot} = \eta_{transmission} \times \eta_{motor} \times \eta_{battery} \times \eta_{controller} \quad 20$$

3.7 Fuel cells

. Fuel cells used for the study are selected from available transport fuel cells currently used for buses and trucks, or assumed from its characteristics. As said before, only compressed hydrogen is considered as fuel. Available fuel cells for transportation data is extracted from the U.S. Department of Energy (see table 3.3), and the weights are extracted from the manufacturers.

Manufacturer	Name	Output (kw)		Weight	Efficiency (%)	Size* (m)
Ballard Power Systems	FC Velocity-HD6	75	150	350/404		1,5x0,9x0,5
Symbio FC	ALP	80	100	-	-	-
US Fuel Cell	Model 80 APU	80		248	56	0,9x0,9x0,6
	Model 150 APU	150		474	59	1,5x0,9x0,5
	UTC's PureMotion	120		900	46	1,2x1,5x1

Table 3. 3- Available fuel cell systems for transportation (all PEM fuel cell) (U.S. Department of Energy 2013)(UTC Power 2012)(US FuelCell 2013)(Ballard 2011)

Consumption of the FC Velocity is extracted from (Canada Transportaion Development Centre 2012), and it is of 15 kg/hour working at full power. In the case of Model 80 APU and Model 150 APU consumption indices are obtained from (US FuelCell 2013), 5.1 kg/h at full power for the 80 kW model and 8.4 kg/h at full power for the 150 kW model (these consumptions are estimated for continuous peak power, 80 kW in the first case and 130 kW in the second). It is assumed that these fuel cell systems can power an all-electric pushback tractor, as electric motor technology allows a performance good enough to reach taxi speeds while towing an aircraft, but this is left for further research. Regarding energy storage, carbon fibre tanks offer a solution less heavy than steel tanks, offering ranks between 0.035-0.055 kg of hydrogen per kilogram of storage weight, but maximum ratio recommended for transportation is 0.045 kg of hydrogen per kg of storage system (Canada Transportaion Development Centre 2012).

A theoretical fuel cell of 230 kW (equation 24) is extracted from mixing Model 150 and Model 80 for the main gear wheel actuator case. This one is assumed to consume as the other two and have the worst performance. These systems' consumption is extracted from literature review, and so the calculations are based on performance reports of the cells systems instead of cell efficiencies. Hydrogen weight consumed during taxi phases is not considered eliminated during rest of the flight due to its low value (the storage weight is what is significant). Calculations for hydrogen requirements are made with the following equations.

$$Total\ weight\ required = fuel\ cell\ weight + Hydrogen\ tank\ weight \tag{21}$$

$$Hydrogen\ required = hydrogen\ consumption \times time \tag{22}$$

$$Hydrogen\ tanks\ weight = mass_{hydrogen\ required}/(\frac{kg_{hydrogen}}{kg_{tank}}) \tag{23}$$

$$Power\ required = Maximum\ power\ required/(\eta_{transmission} \times \eta_{motor} \times \eta_{controller}) \tag{24}$$

3.8 Extra fuel consumption and emissions due to added weight

Extra fuel burned due to the extra weight added by on board systems is estimated using ICAO's Carbon Calculation Methodology adapted for fuel consumption (ICAO 2014). The methodology is based on distance to estimate the consumption and emissions of a single passenger, using public data available for fuel consumption. ICAO has a database with pairs of airports and its distances based on EMEP/EEA Emission Inventory Guidebook (Winther & Rypdal 2014), but in this case average distances of the routes provided by TAP are used.

$$\frac{Fuel\ consumption}{pax} = \frac{total\ fuel \times pax_{fregiht}}{n_{y_{seats}} \times pax_{load}} \tag{25}$$

Where:

$pax_{freight} = pax\ to\ freight\ factor, ratio\ calculated\ from\ ICAO\ statistical\ database$

$n_{y_{seats}} = number\ of\ equivalent\ economy\ seats\ (aircraft)$

$pax_{load} = ratio\ calculated\ from\ ICAO\ statistical\ database\ (passengers, avaliable\ seats)$

Pax to freight factor is calculated given the number of passengers and the tonnage of another cargo, for a route group. Pax load factor is based on the passengers transported and the seats available. However, from data obtained from TAP, flight routes considered are hardly ever used to transport neither freight nor mail, so total cargo will be considered as passengers, and average load factors (pax load) are also given. Total fuel burnt in average per route is also available from TAP, and fuel consumption and emissions relation per phase of flight are obtained from statistical data of EMEP /EEA Emission inventory guidebook for flying distances of equivalent aircraft (see annex 3),. The information is prepared in several distances so each route flight distance has to be interpolated. Data are separated in LTO cycle and en-route phase. Data for LTO cycle is changed according to the engines considered for each aircraft among the fleet possibilities, as data are available from ICAO emissions databank for ICAO standard times, and changing standard taxiing times modified for each airport case. En-route phase fuel consumption and emissions are estimated using the equivalent aircraft and average load factors, included in the guidebook, due to the lack of data available.

Extra weight is estimated from seats available in each aircraft (annex 2) and average load factors per route, calculating fuel consumption per passenger and expressing the on board systems weight as a number of passengers (and so the extra fuel consumption). This is a first approach as the fuel consumption is not proportional to the number of passengers, but differences in load factor are considered not great and this estimation is more conservative. Each passenger has an estimated weight of 100kg plus 50kg of aircraft infrastructure and equipment (ICAO's methodology), but due to this not being representative for the whole aircraft, weight used to compare system with number of seats and fuel consumption is extracted from A320 maximum landing weight (maximum weight allowed in landing, see annex 2) without cargo divided by available seats (see also annex 2). Each seat's related weight is this way 300 kg, and this is used to estimate the number of seats equivalent for the added weight, and obtain extra fuel consumption per route. The extra fuel required to carry the on board systems will be counted against the potential savings.

4 Results

Results for the reference scenario and alternative scenarios comments are in the following sections. Regarding the nomenclature, as compressed hydrogen was selected for the fuel cell, this alternative will be mentioned as hydrogen. Routes are mentioned by airport initials or an abbreviation of its name (e.g., Lisbon-Porto may be mentioned as L-P or LIS OPO (IATA airport codes), and L-P RT, where RT is round trip) in order to fit in the graphics.

4.1 Taxiing emissions and fuel burnt compared to standard LTO cycles.

Emissions of conventional taxi phases (taxi in and taxi out) show the relevance and the potential savings in terms of pollutants (figures 4.1 and 4.2) for the routes considering as reference the standard LTO cycle for the engines considered. Each route considers the taxi out emissions of the departure airport and the taxi in emissions of the arriving airport. As mentioned previously, due to the direct relationship between CO_2 and fuel burnt, one of them will be used as representative for both. In figures 4.1 and 4.2, each pair of cities has four columns related, one for each pollutant considered and one for fuel consumption (also representative for CO_2); first airport in each label is departure airport.

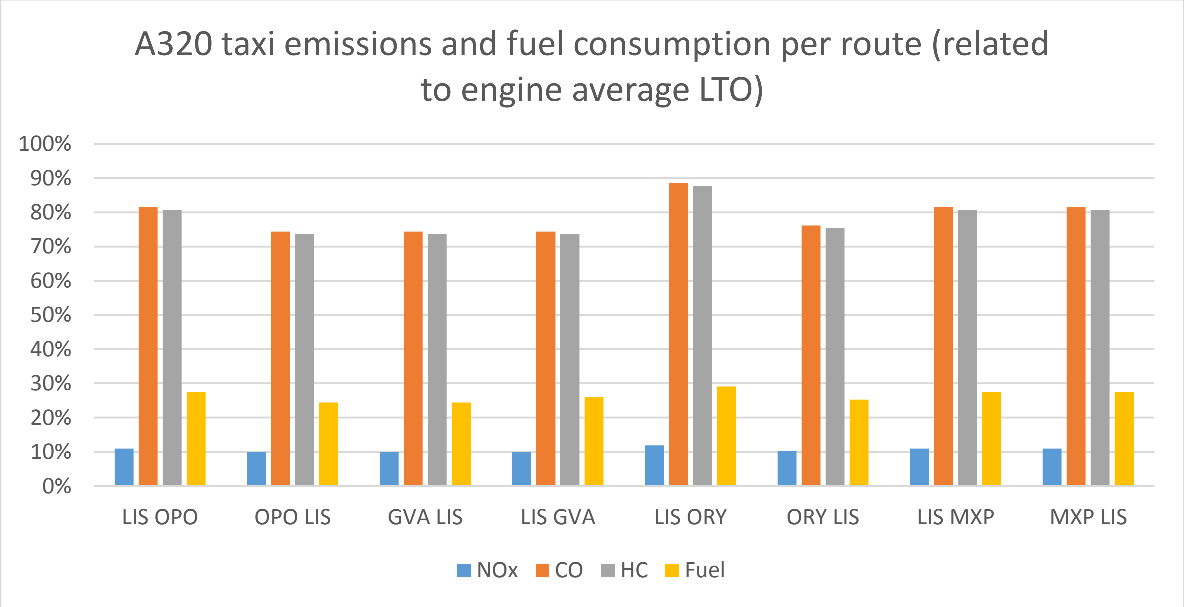

Figure 4. 1-Taxi emissions and fuel consumption per route for the A320 considering the 5B4/P engines and airport average times, as well as LTO cycle ICAO standard values.

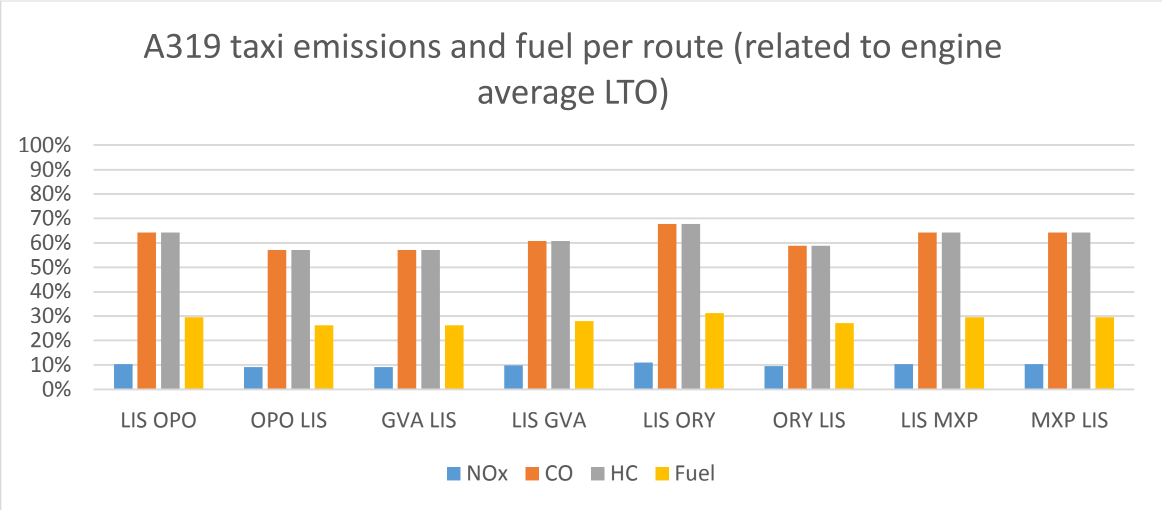

Figure 4. 2-Taxi emissions and fuel consumption per route for the A319 considering the 5B5/P engines and airport average times, as well as LTO cycle standard values (ICAO).

In figures 4.3 and 4.4 total taxi emissions are compared to those that can be eliminated. It is not feasible to avoid all emissions and fuel consumption during taxi phases because, as said before, engines require some time to start up (2 min), warm up (3 min) and cool down (3 min); cool down occurs in taxi in phase. During these times, engines are working, and performing the taxi phase, except from the start up, when the alternative system is still working. Those emissions and fuel consumption that can be supressed are those labelled as 'avoidable'. As calculations are based on taxiing times, the percentages are the same for both emissions and fuel consumption, and will differ from one airport to another due to their different average taxiing times.

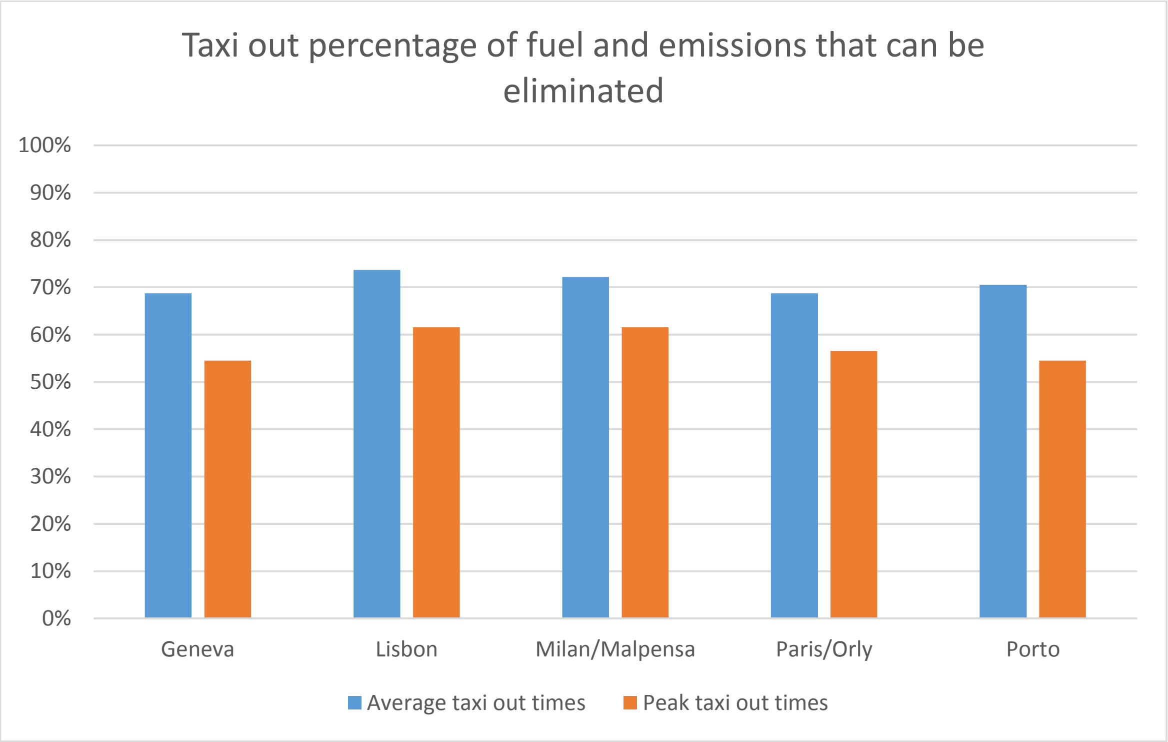

Figure 4. 3-Emissions and fuel consumption that are avoidable as a percentage of the total for the taxi out phase.

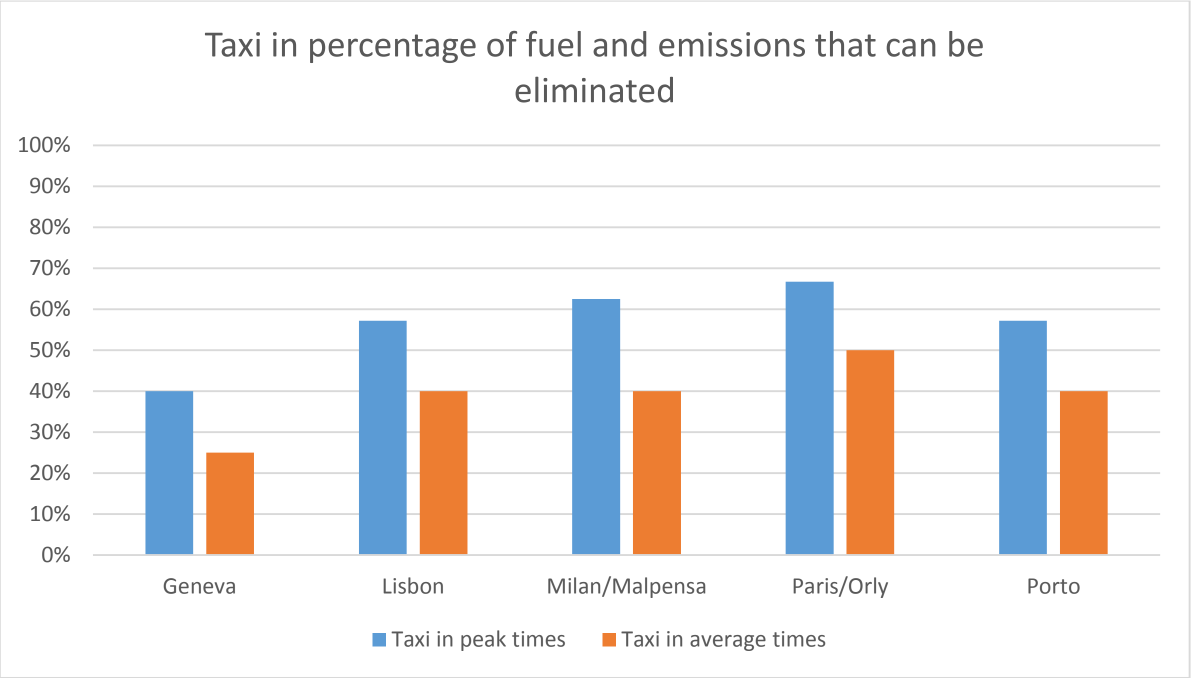

Figure 4. 4-Emissions and fuel consumption that are avoidable as a percentage of the total for the taxi in phase.

Figure 4.5 shows the fuel consumption per operation in each taxi phase for aircraft considered in kg; this gives an idea of the amount of fuel that can be saved. This is a significant quantity, considering the number of operations per airport a year. However, each case studied has its disadvantages in terms of fuel consumption, and the differences and total savings between them are showed in next sections. In figure 4.5 each airport has four columns related, two for each aircraft considered (one for taxi in and one for taxi out).

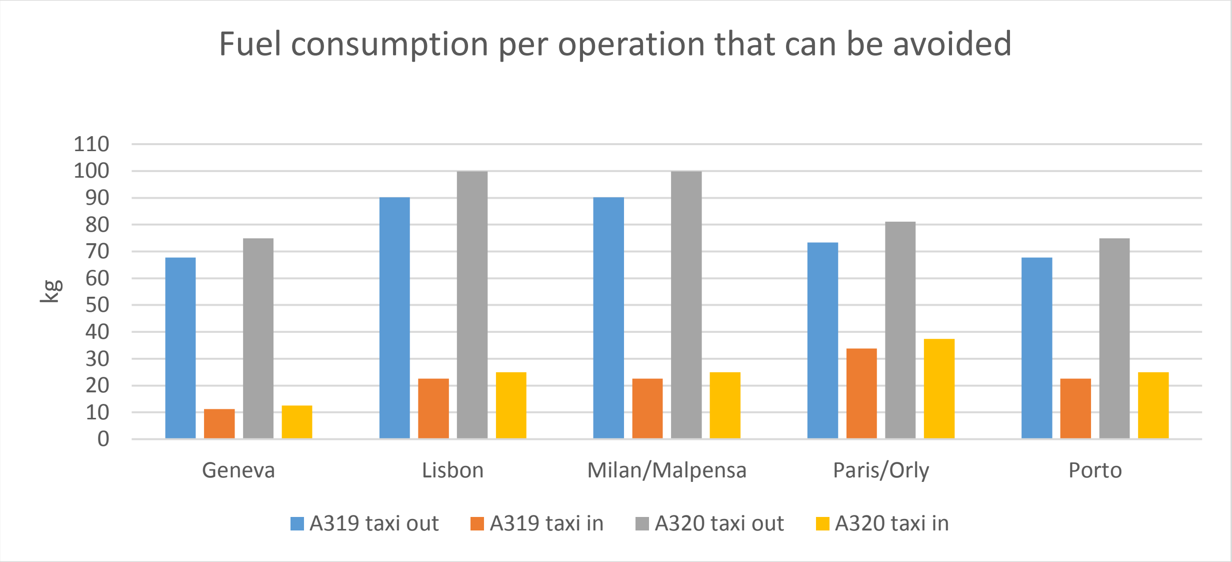

Figure 4. 5-Maximum fuel consumption that can be saved in case of an alternative taxiing, per operation (average taxi times).

4.2 Tractor type equipment. Dispatch towing

As calculations are based on aircraft taxi times, dispatch towing solution shows the same reduction of emissions and fuel consumption for each airport in terms of percentage. This solution has no impact on the rest of the flight phases, as it does not require any extra weight in the aircraft, apart from some equipment for control purposes; however, this weight was assumed negligible. Figure 4.6 shows the influence of using dispatch towing in the taxi out pollutant emissions. Figure 4.7 shows the same for taxi in. Pushback tractors for wide body aircraft appear as WB (Wide Body), and narrow body as NB (Narrow Body). In order to summarize the results in two figures, results showed are related to taxi time that engines are not active for warm up and start up (maximum emissions savings mentioned in section 4.1, figure 4.3). So to obtain the percentage of savings related to total conventional taxi procedure, this percentages have to be multiplied by the percentage of time that engines are not operating of the total taxi procedure (figure 4.3) However, comparison for total ground emissions is in section 4.4. In figures 4.6 and 4.7 each tractor type considered has a column for each pollutant. Negative percentages represent an increase of emissions.

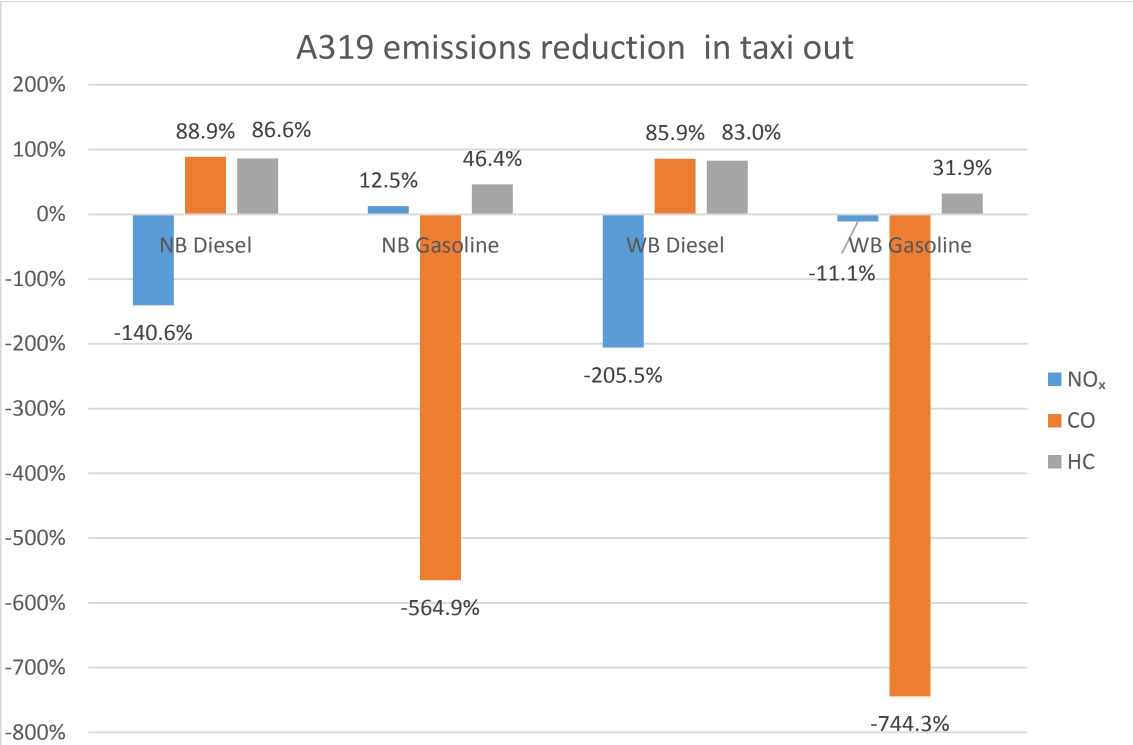

Figure 4. 6-Emissions reduction from maximum avoidable considering conventional tractors for A319 dispatch towing. Negative percentages mean an increase of the pollutant emissions.

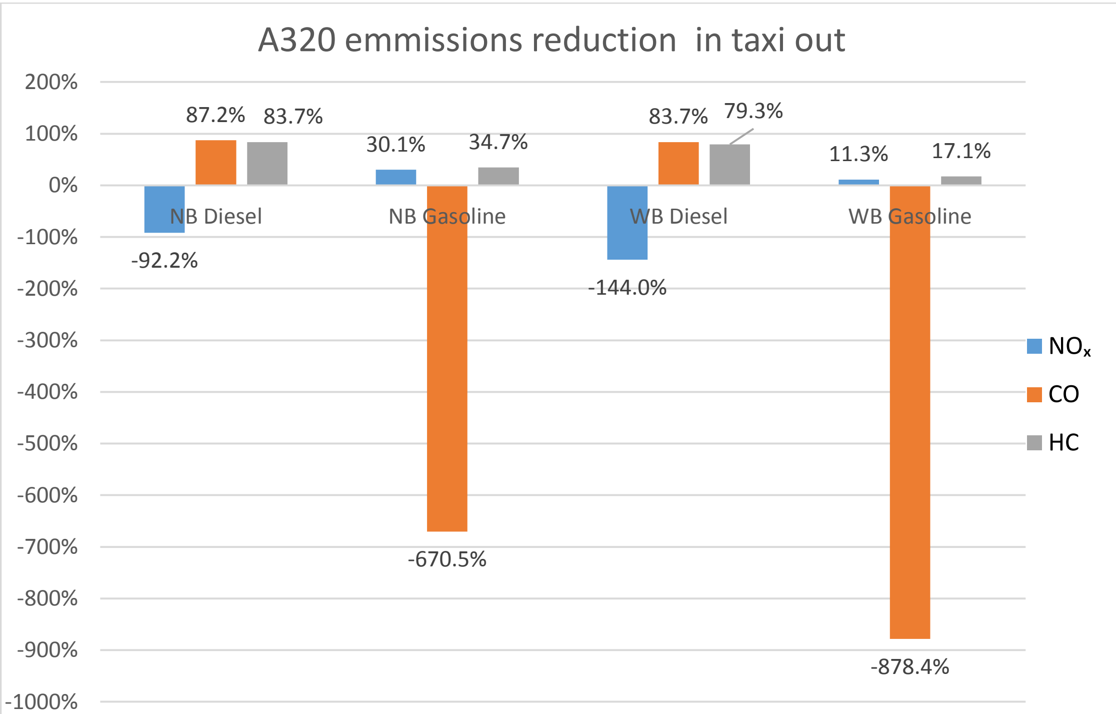

Figure 4. 7-Emissions reduction from maximum avoidable considering conventional tractors for A319 dispatch towing. Negative ratios mean an increase of the pollutant emissions

Carbon dioxide emission savings from the total possible due to the warm up times of the aircraft engines (figure 4.8) show the difference of efficiency between aircraft engine and tractors, which are designed to work in a more efficient way in ground operations. 100% will be a total clean system, as electrical motors powered by batteries, which do not have direct emissions related.

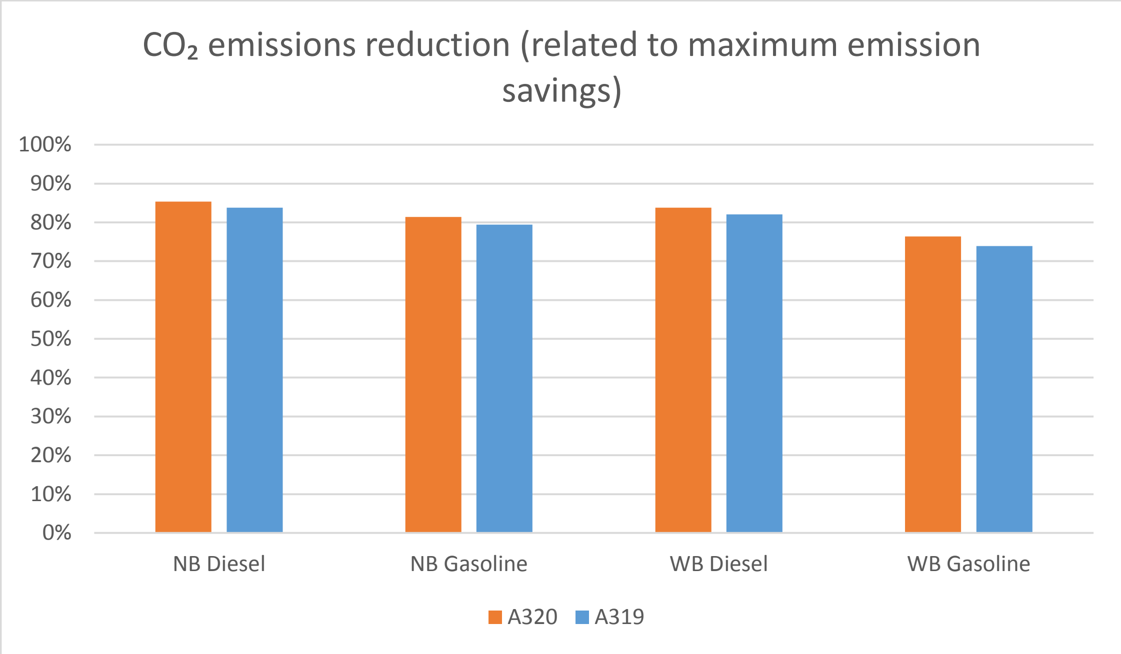

Figure 4. 8-CO_2 emissions reductions from maximum avoidable using conventional tractors for dispatch towing

Figure 4.9 shows the potential savings of jet fuel for a year in selected routes using dispatch towing and average taxiing times. These results are significant in terms of emissions, but potential economic benefits depend on the cost of dispatch towing infrastructure as results do not include tractors' fuel consumption. However, in terms of fuel consumption comparison, CO_2 emissions shown before (figure 4.8) are a good indicator, even though gasoline and diesel tractors have lower CO_2 emissions indices. Results (figure 4.8) show better results for NB tractors but in any case both options have important CO_2 emissions reduction in the time that tractors are used (between 73% and 85%). While NB shows more CO_2 savings, speed and therefore taxi times could be greatly increased.

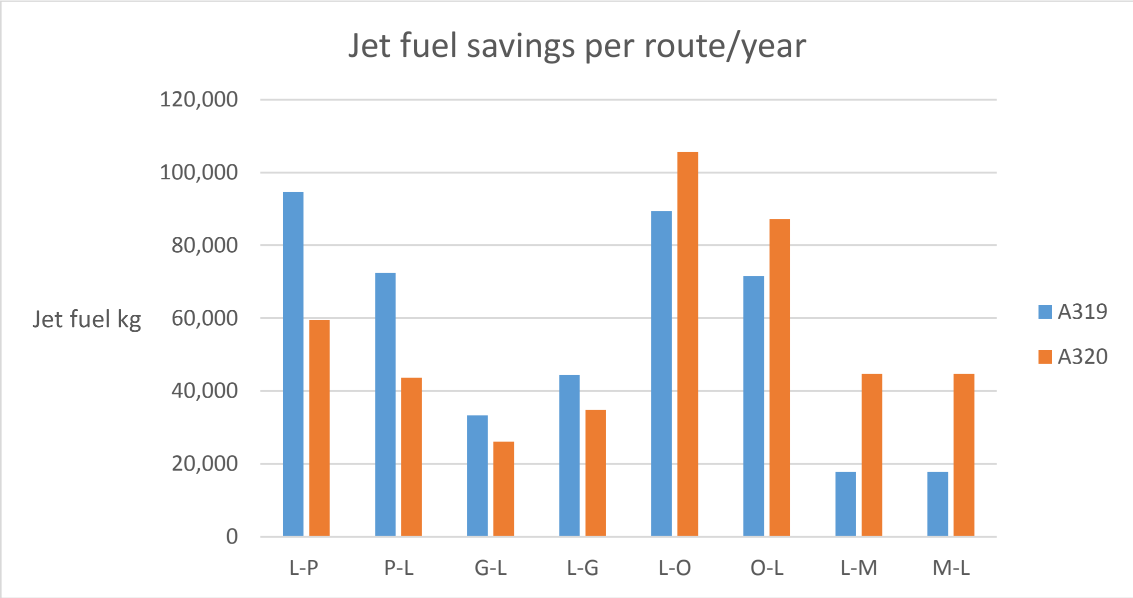

Figure 4. 9-Total jet fuel savings in kilograms per route/year.

Results show very important reductions in carbon dioxide and in some pollutant emissions. Even so, results in diesel tractors show (figures 4.6 and 4.7) an increase of NO_x emissions (from 92.2% to 144% comparing to the same time interval with operating engines in conventional taxi), and gasoline tractors produce a great amount of CO (up to 8 times more than those from conventional taxiing); the usage of these systems therefore is charged with an increase of one pollutant while others are greatly reduced. A320 and A319 savings results are different as can be seen, and this is because their emissions related to taxi phases differ as they use different engines with different emission indices, resulting in more savings for A319 in CO and HC and less in NO_x (in case of wide body gasoline tractor, NO_x emissions increase). In this case it is interesting to further study how hybridization could help to reduce pollutant emissions that can limit this alternative. Times, as mentioned (in section 3.5), are a key factor in the election between a NB and a WB tractor, as NB times are assumed to be much higher (2.5 times)

4.3 On board systems for full taxi phase

4.3.1 On board systems weights

On board systems are composed of three main parts, the weight due to the electrical motors, the weight of extra components for transforming the energy stored into electricity and the weight of the storage. APU's fuel weight is not relevant when calculating the extra fuel consumption for the rest of the flight, as it is consumed during the taxi phase. As mentioned before, hydrogen weight is considered negligible compared to the weight of the whole fuel cell system. The differences between these weights considering one flight and a round trip, using ICAO standard times for taxi in and taxi out phases (19 and 7 min) but considering the warm up and cool down times. Figures 4.10 and 4.11 show the variation of the weight for each case.

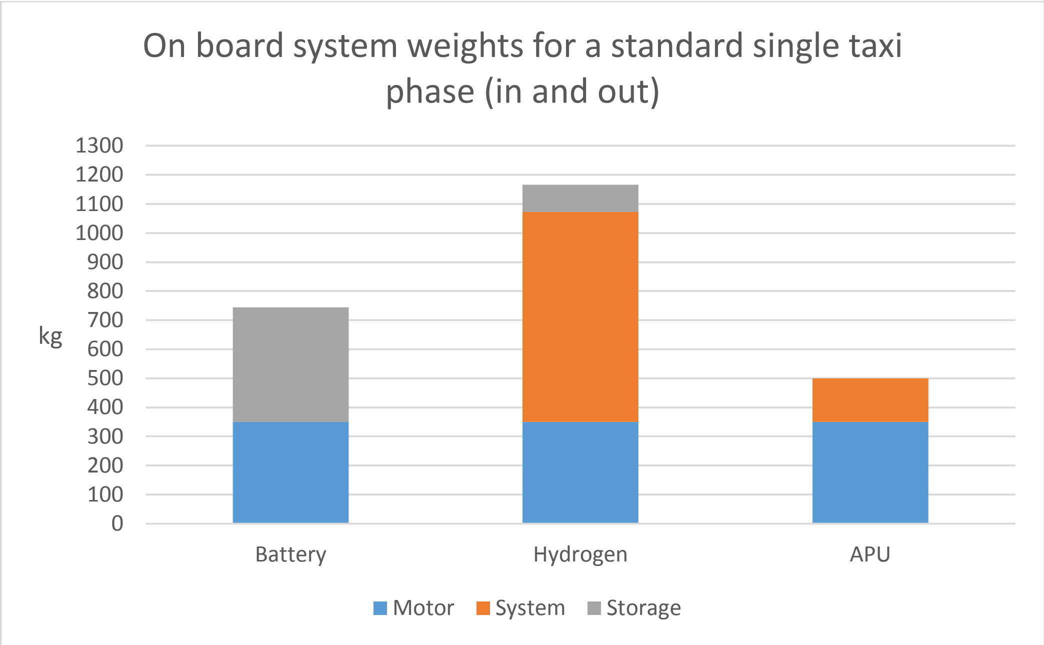

Figure 4. 10-Weight per component for each on boar system. Case of a complete taxi phase

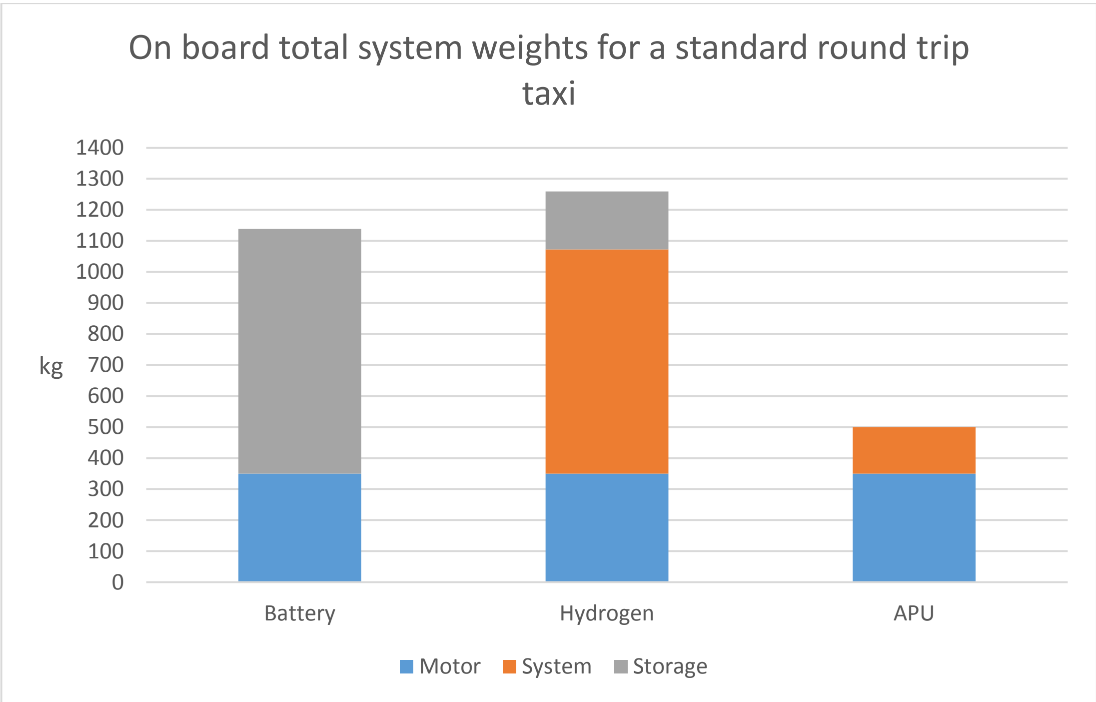

Figure 4. 11-Weight per component for each on board system. Case of round trip

As can be seen, battery pack weight increases proportionally to taxi times, but fuel cell system powered with hydrogen does not, as only the hydrogen storage changes in weight, not the fuel cell. In the case of the APU, weight is always the same. This will affect results in terms of the importance of taxiing times and the emissions and fuel consumption due to the extra weights, which depend on flight distances as well.

4.3.2 Cost in emissions and fuel burnt for carrying the extra weight.

Figures 4.12 to 4.15 show the cost in terms of pollutant emissions related to the extra weight of the on board systems, for both aircraft and considering average times and peak times, for whole operations (LTO cycle plus en-route phase) Positive values mean an increase of emissions for the whole operation, while negative values mean savings. Results include savings for taxi out and taxi in phases. Each graph includes the direct routes and the round trips, and for each case three groups of columns are displayed, one for NO_x emissions, one for CO emissions and one for HC. Each group of columns has one column for each on board system considered (each power source option for the electrical motor: battery pack, fuel cell named as hydrogen and APU), and there is a figure for each aircraft and taxi times (average or peak). These emissions are related to the complete flight but, in any case, the additional weight, regardless of the savings, will produce more emissions during the en-route phase in most cases.

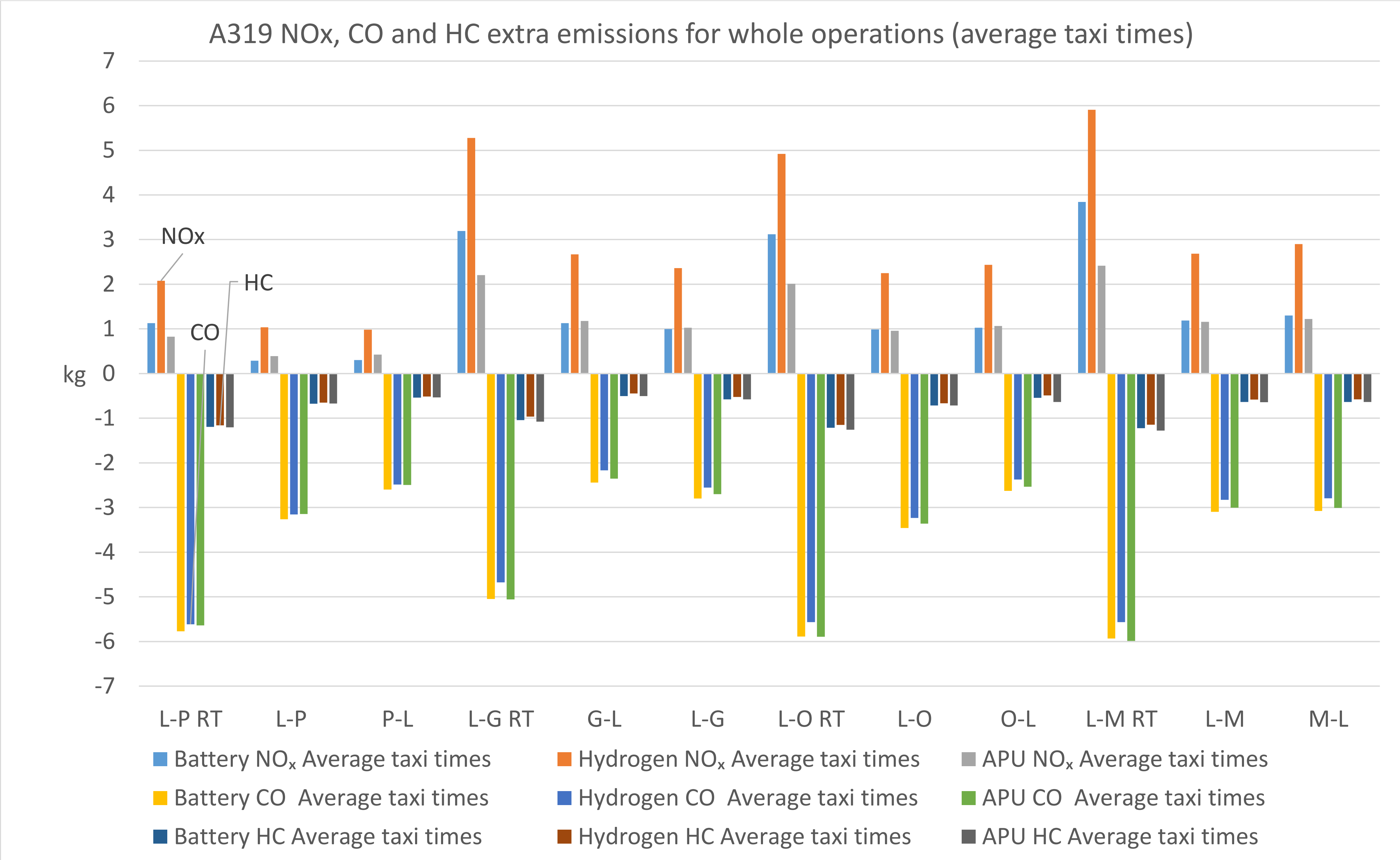

Figure 4. 12-A319 pollutant emissions due to on board systems weight for complete routes and round trips (average taxi times)

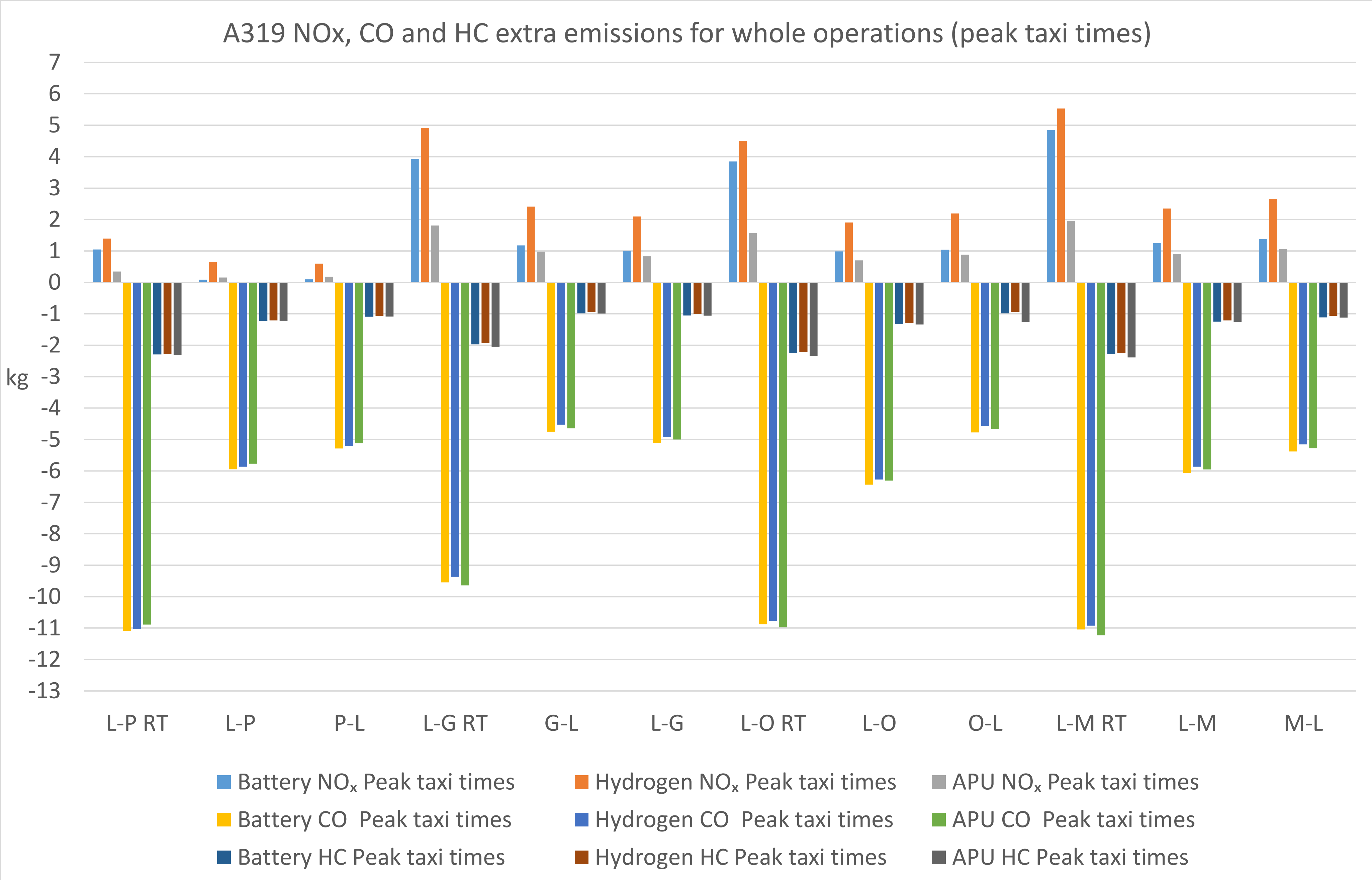

Figure 4. 13-A319 pollutant emissions due to on board systems weight for complete routes and round trips (peak taxi times)

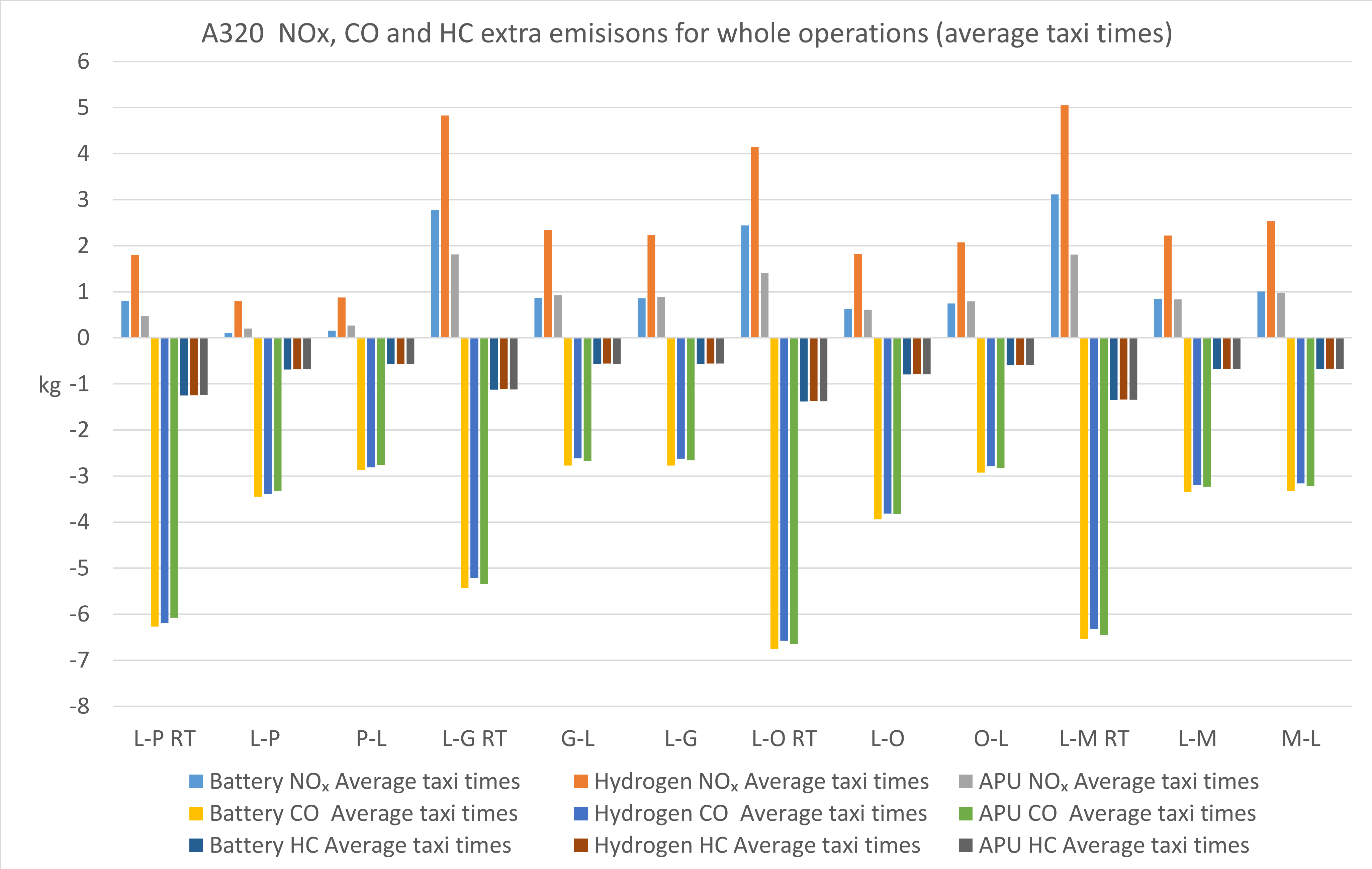

Figure 4. 14-A320 pollutant emissions due to on board systems weight for complete routes and round trips (average taxi times)

Figure 4. 15-A320 pollutant emissions due to on board systems weight for complete routes and round trips (peak taxi times)

Figures 4.16 and 4.17 show NO_x emissions for EMEP average operations (modified table for engines considered LTO cycles), in order to compare with extra emissions generated by the extra weight added.

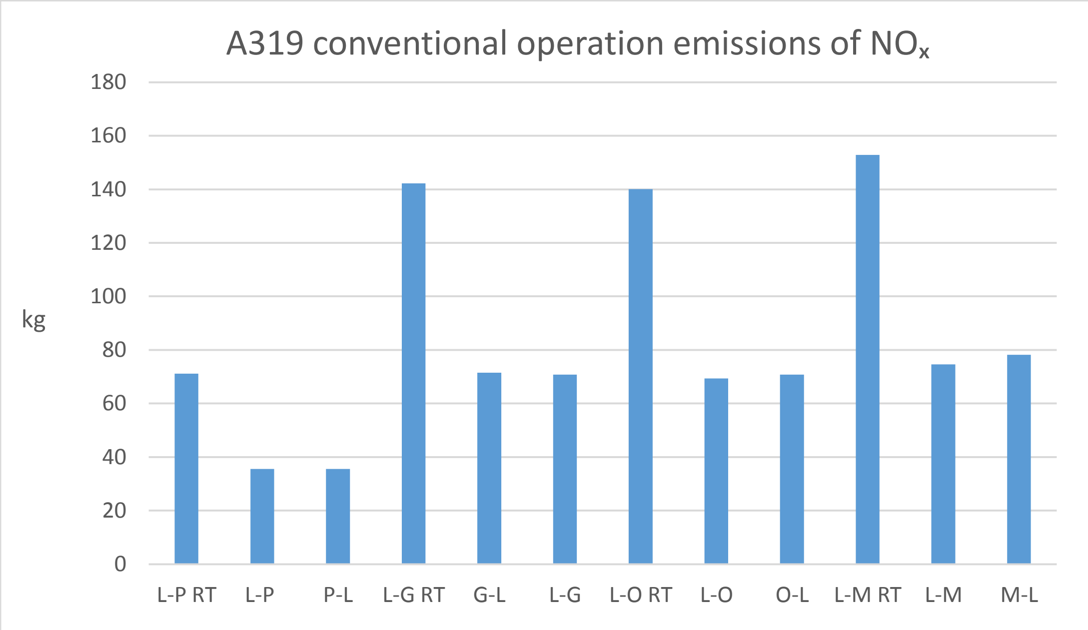

Figure 4. 16- Emissions of NO_x for A319 considered in conventional operations

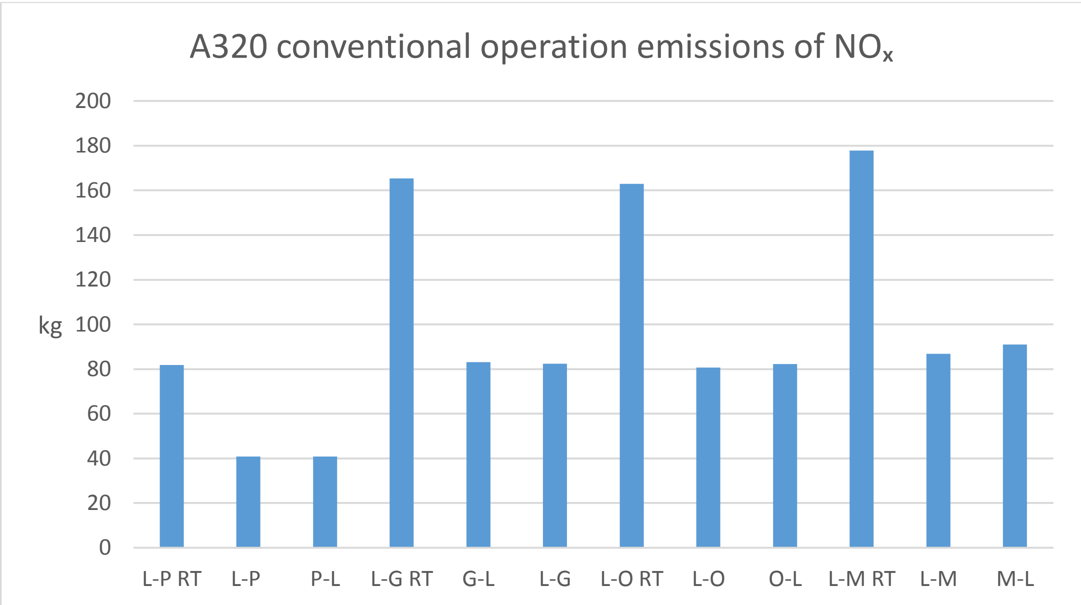

Figure 4. 17- Emissions of NO_x for A319 considered in conventional operations

As NO_x emissions are the only pollutants that increase with the use of on board systems, figures 4.18 and 4.19 show comparison only for these kind of pollutant emissions between average and peak taxi times, for complete operations. Results for average taxi times are the left group of three columns for each route or round trip and results for peak taxi times are the right group, with one column for each on board system considered. As total NO_x emissions depend mostly on en-route phase and extra weight, it is important to notice that in round trip cases using batteries or hydrogen (same storage for both trips), emissions are higher than adding the two single routes, due to the extra weight, but this is more visible in the battery case (as explained in section 4.3.1) . APU option is not affected by this issue. This will also happen in some cases in fuel consumption (figures 4.20 and 4.21). Regarding comparison with conventional operations (comparison between figures 4.16 and 4.18, 4.17 and 4.19), results show increases under 5% in worst cases, and around 1% in best cases, even very small savings (for example, in direct route Porto Lisbon using APU for the A320 and peak taxi times, extra weight is not relevant enough to produce extra emissions to overcome the savings, even though en-route emission index is far higher). This increase depends on route length. In terms of NO_x direct routes with lightest systems do not have high emissions increase related, and have even slight reductions (really low, figure 4.15, most favourable case), but heavier systems are much more penalised.

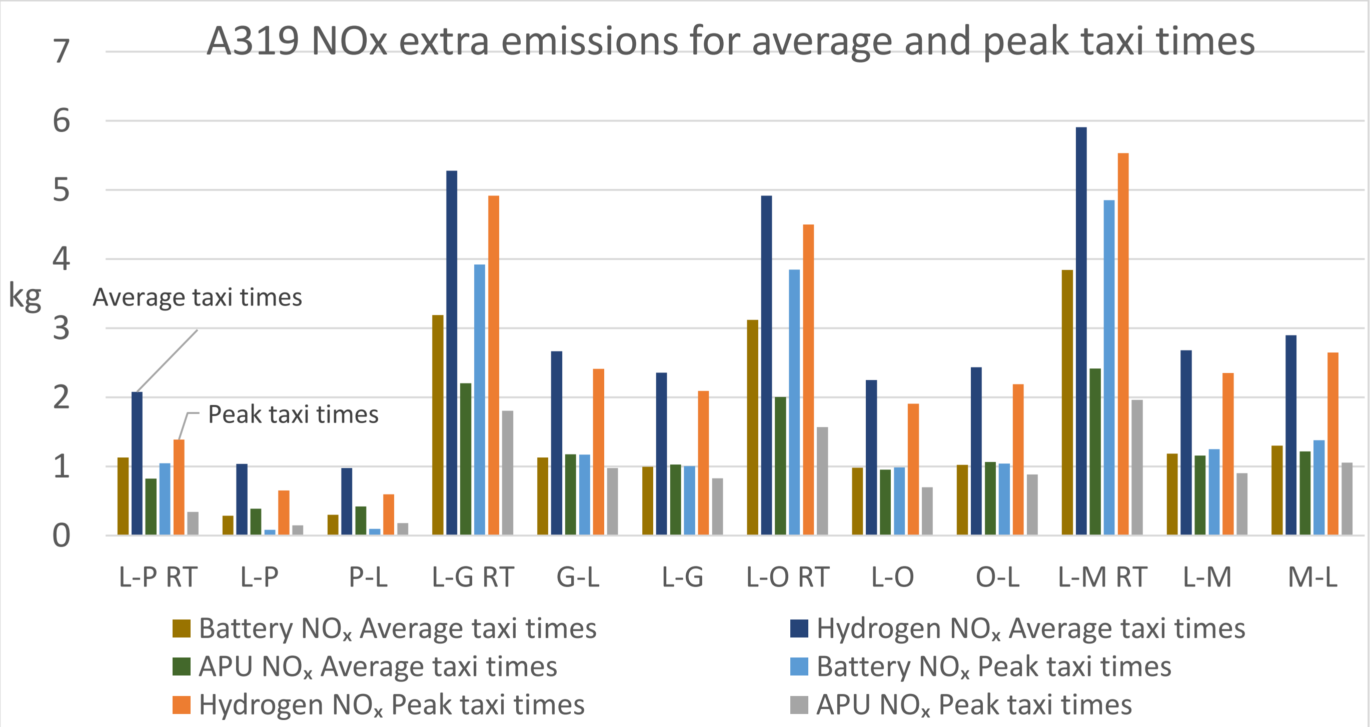

Figure 4. 18-A319 NOx extra emissions comparison between average taxi times and peak taxi times

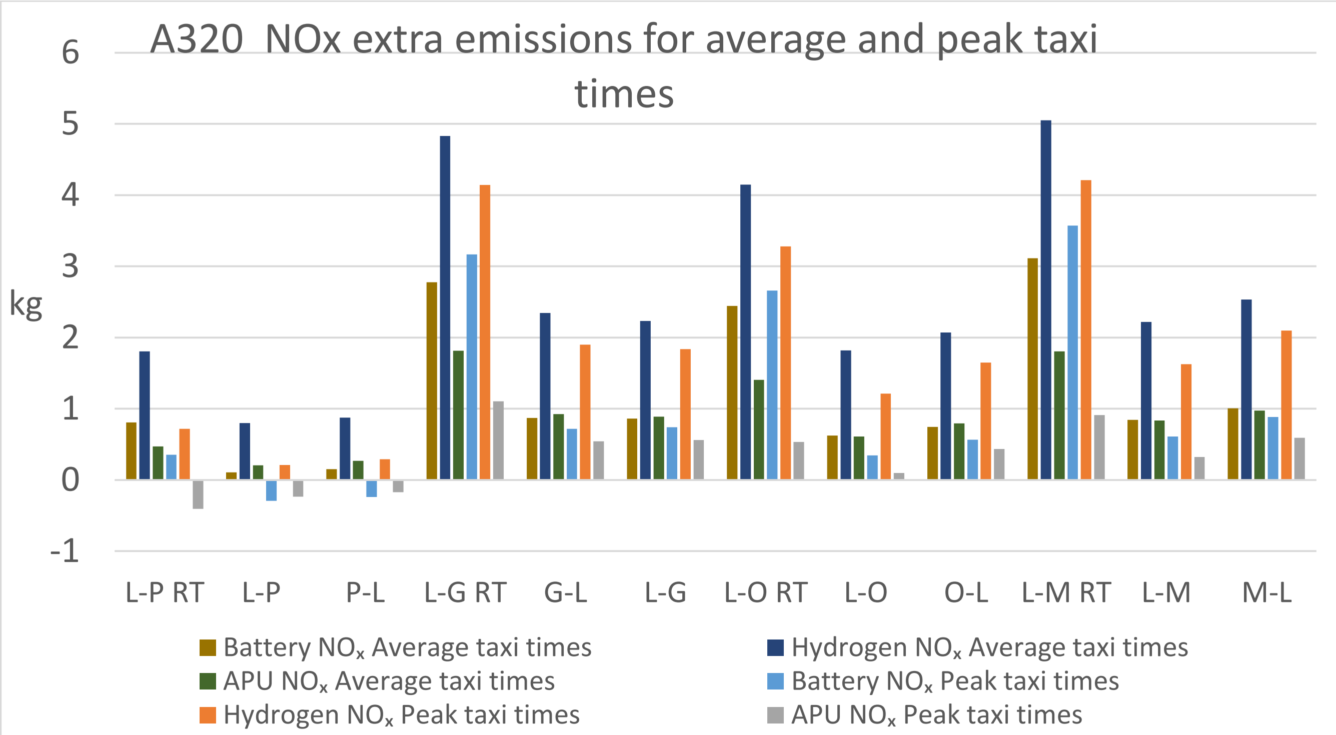

Figure 4. 19-A320 NOx extra emissions comparison between average taxi times and peak taxi times

Results for complete operations show savings in CO and HC emissions in all cases considered (figures 4.12 to 4.15); these emissions occur mostly in taxi phases (taxi in and taxi out), and so they are reduced the most with the usage of on board systems, showing similar reductions for all alternatives considered. However, NO_x emissions are almost always greater (as can be seen also in figures from 4.18 and 4.19) when adding extra weight due to engine emissions of NO_x being higher in en-route conditions (Winther & Rypdal 2014), and despite the savings during taxi they will increase in case of longer flight lengths. For longer taxi phases, reductions in CO and HC emissions are more significant, as savings increase when taxi times do for the routes (flight length) selected, because as mentioned before HC and CO emissions are most important in taxi phases. NO_x emissions are less reduced for longer taxi phases or even increased (batteries) due to the fact that the extra weight can generate more emissions that those saved. In the particular case of the battery-powered motor, as batteries mass is directly related to time, results show an increase of NO_x in every round trip, except for the two shortest (Lisbon Porto and Porto Lisbon) (figures 4.18 and 4.19). This means that as battery weight increases (with taxi times), NO_x emissions will increase with taxi times when flight is over a certain value, as these emissions are lower during the taxi phase. For APU and Hydrogen, the increase of mass is less severe so in all routes considered there is a reduction in extra NO_x emissions when taxi times increase. In this regard, as an example, Lisbon Geneva and Lisbon Paris routes are of interest; Geneva is almost 21 NM farther from Lisbon in air distance that Paris/Orly. Paris airport has the same taxi out times as Geneva, but greater taxi in times (average). Results show that therefore NO_x emissions are higher for Geneva Lisbon, Lisbon Geneva and round trips due to the distance, while HC and CO emissions are lower for

Lisbon Paris than for Lisbon Geneva, as well as round trips, but the same for Geneva Lisbon and for Paris Lisbon (as can be seen on figures 4.12 and 4.14).

Regarding the aircraft, the A320 shows less extra emissions (comparing between figures 4.12 and 4.14), as well as more improvement or (or less increase) in extra emissions when taxi times are higher (figures 4.13 and 4.15); this is due to the fact that, apart from the A320 being bigger, as mentioned in section 3.2, systems characteristics are selected for A320 aircraft, and studied for A319 in order to check its viability in a smaller aircraft. This leads to systems that are lighter in comparison with the total aircraft for the A320, meaning less extra consumption and emissions related for the A320 than for the A319. However, aircraft engines are also key factors in extra emissions, as they have different emissions indices (section 3.1.2), and the evolution of these indices will be of importance.

Considering total NO_x emissions, APU seems to be the best option because it implies less extra weight and this means less related emissions during en-route phase. However, during taxi phases APU's NO_x emissions will be greater than those from the other two alternatives (ground emissions), as those do not have direct related emissions (as well as HC and CO, but these two have low emission indices in APU as seen in annex 1). Particular study results for LTO cycles emissions is in section 4.3.3.

Regarding fuel consumption, figures 4.20 and 4.21 show the extra consumption per route or round trip, considering each on board system. Fuel consumption is a key factor in the application of alternative systems; if fuel consumption for the overall operation is increased, there is no advantage in using the system in terms of fuel costs and carbon dioxide emissions. Negative values of fuel consumption mean savings, in raw values, and positive results mean an increase in fuel consumption for that system and route. Results are separated in each case in two groups of columns, one for average taxi times and one for peak taxi times. Figures 4.20 and 4.21 show significant differences between average and longer taxiing times.

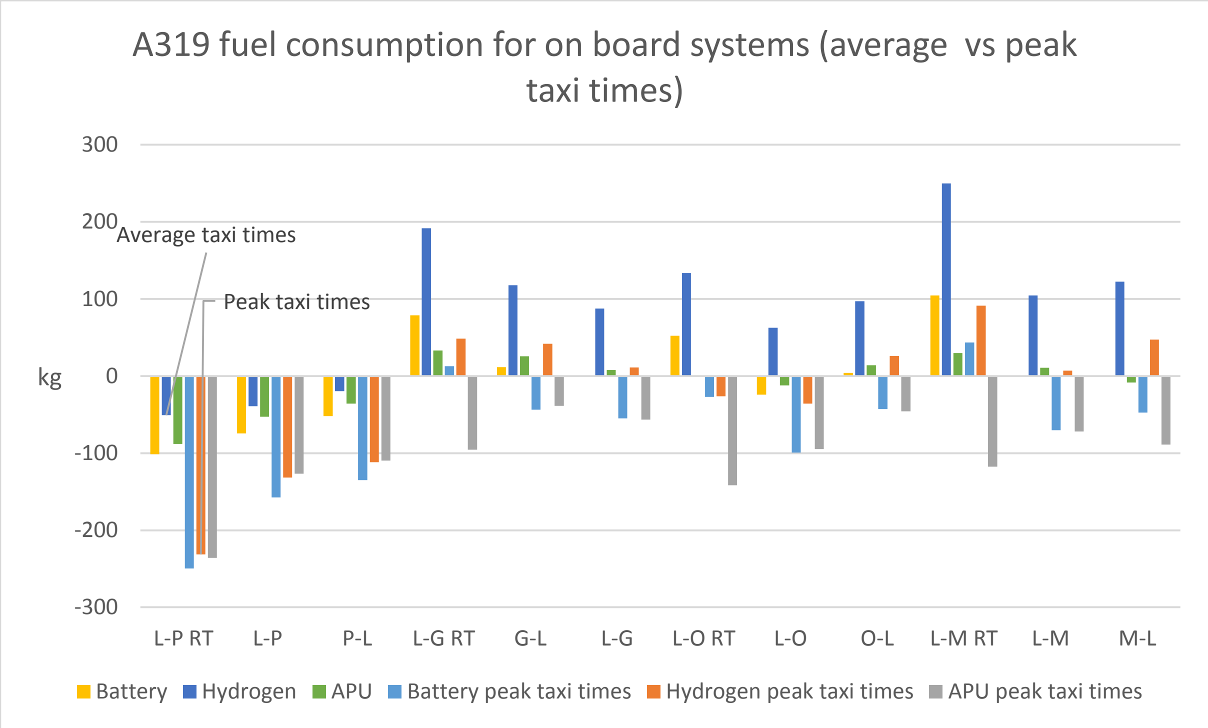

Figure 4. 20-A319 extra fuel consumption due to on board systems weight for each system and route/ round trip (average and peak taxi times)

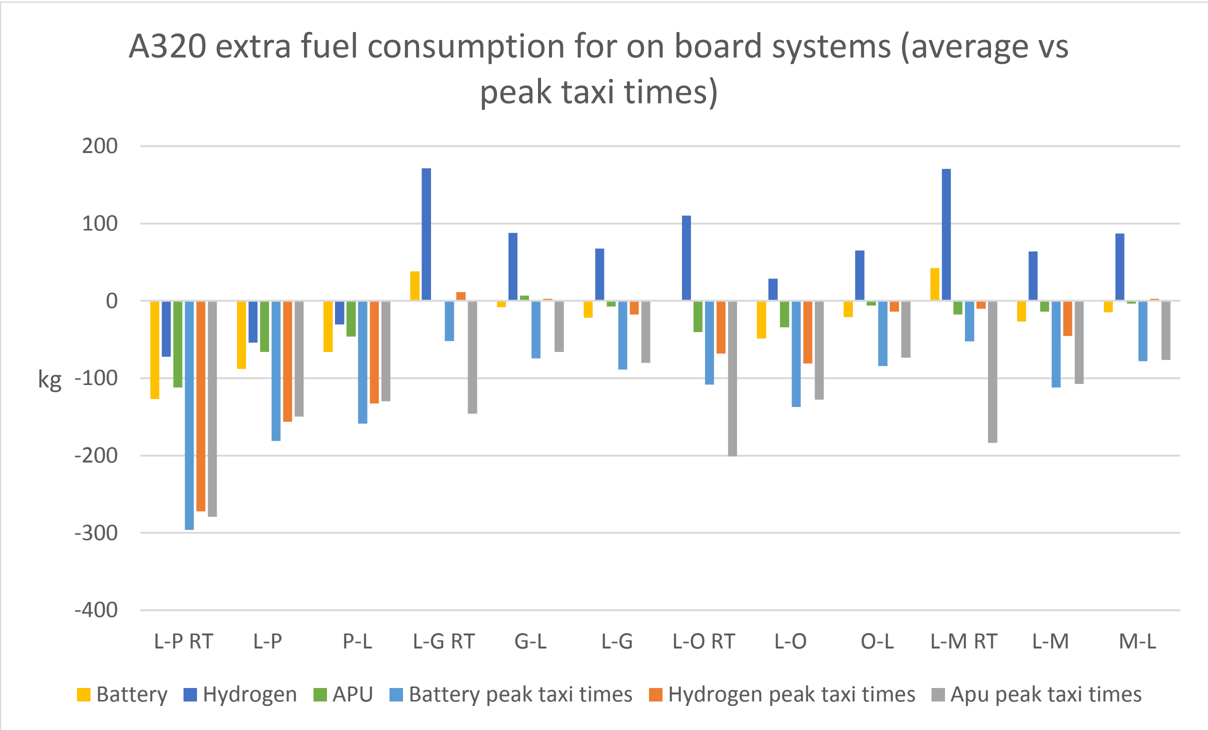

Figure 4. 21-A320 extra fuel consumption due to on board systems weight for each system and route/ round trip (average and peak taxi times)

In average operations, the shorter route (Lisbon - Porto) shows greater fuel savings, and for other routes it depends on the weight of the system (figures 4.20 and 4.21). Except for some routes and considering APU option, both aircraft in case of average taxi times have higher consumption or have almost no difference in the case of longer routes. The comparison when considering longer taxiing times shows important fuel savings for short flights and a smaller consumption reduction for longer flights. Also, there is a better improvement for fuel cell systems and APU, due to the smaller variable weight of the first system and the absence of variation in weight when considering APU as the power source for the electric actuator. Direct routes show less consumption per extra weight in the battery and fuel cell cases (figures 4.20 and 4.21). As can be seen, clear results for fuel savings are in short routes, including round trips; as long as peak taxi times (or longer taxi times) are required for the systems to be useful in longer routes, it is necessary to be certain of taxi times. As far as longer taxi times occur during certain hours, this systems could be feasible for longer flights scheduled for those hours, but in most cases this does not happen, so average times are a better reference; so short routes seem to be the one reliable option, considering that further studies could reveal more weight is required for the systems, and as seen, weight is a key factor.

4.3.3 Emissions reduction in the LTO cycle.

As mentioned before, LTO cycle is the reference in local air quality, and emissions in this part of the aircraft movement are those of more concern regarding pollutants. Figures in this section show percentages of emissions savings; negative percentages mean an increase in emissions. Results are separated in emissions per aircraft and taxi times (peak and average), and emissions of each type are displayed to compare each type between average taxi times and peak taxi times. These savings include the part of the LTO cycle that is performed in each airport for direct routes, and two LTO cycles (one for airport) in round trip cases; as mentioned before (section 3.8), LTO cycle parts that are not taxi in or taxi out are taken from standard cycles for the considered engine.

In figures 4.22 through 4.29, results of HC and CO for each case are compared; as in the whole operations, HC and CO reductions were positive (figures 4.12 to 4.15), in LTO cycle savings are higher because taxi phases represent a bigger fraction of LTO cycle. Influence of HC and CO emissions savings from taxi phases (taxi in and taxi out) is, as seen before, greater as long as taxiing times increase. Savings for LTO cycles are up to around 50% in both A319 and A320 cases for average taxi times and are over 40% in cases of less savings, and those savings increase more than 10% (almost up to 20%) in case of peak taxi times in all cases, although each case has a different value. A320 shows slightly less improvement, but engines considered for each aircraft have different emission indices. Considering that CO and HC emissions during LTO cycle are a big portion of the total (figure 1.10), these are results to take into account.

Figures 4.30 through 4.37 show NO_x and CO_2 emissions reductions or increase due to on board systems usage.

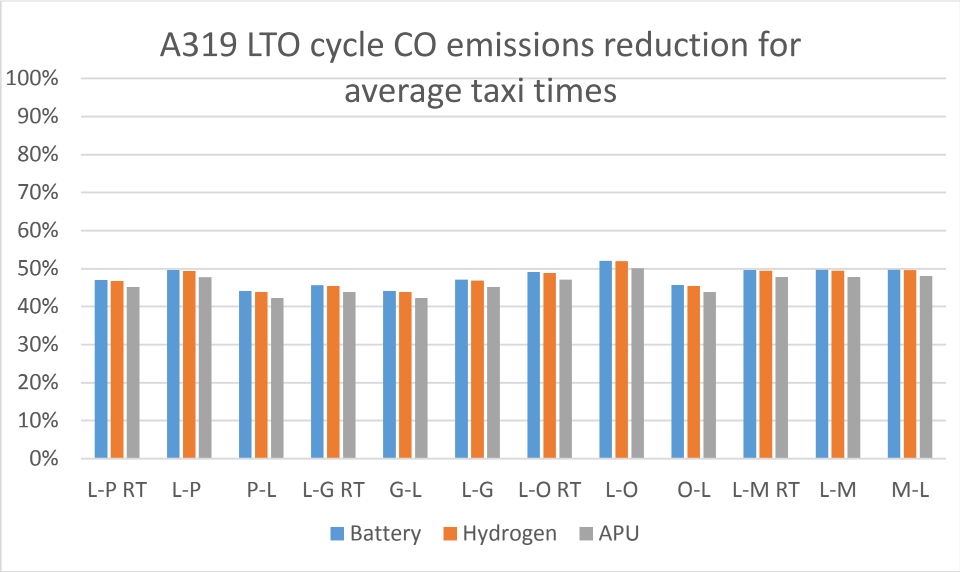

Figure 4. 22-A319 LTO cycle CO emissions reduction for average taxi times

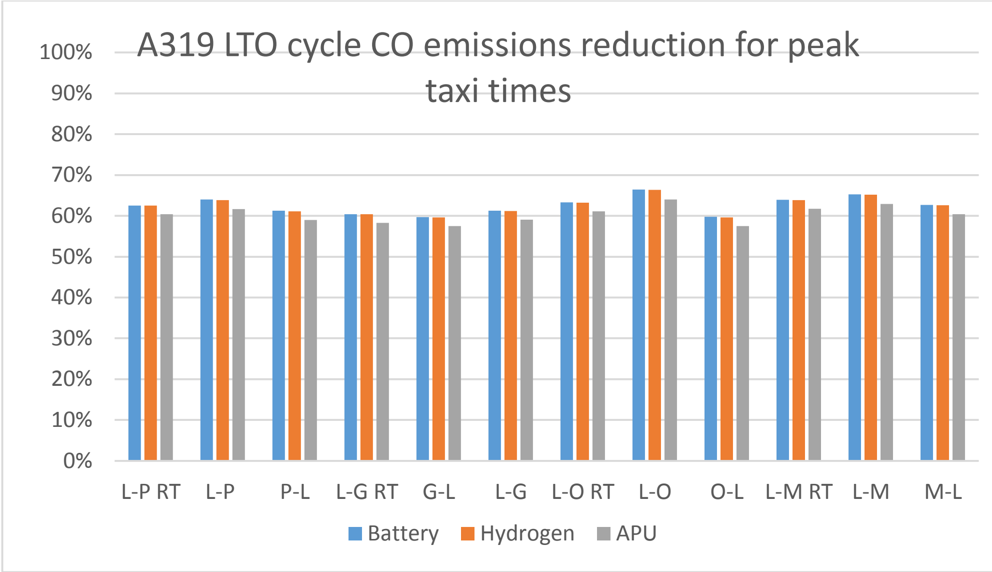

Figure 4. 24-A319 LTO cycle CO emissions reduction for peak taxi times

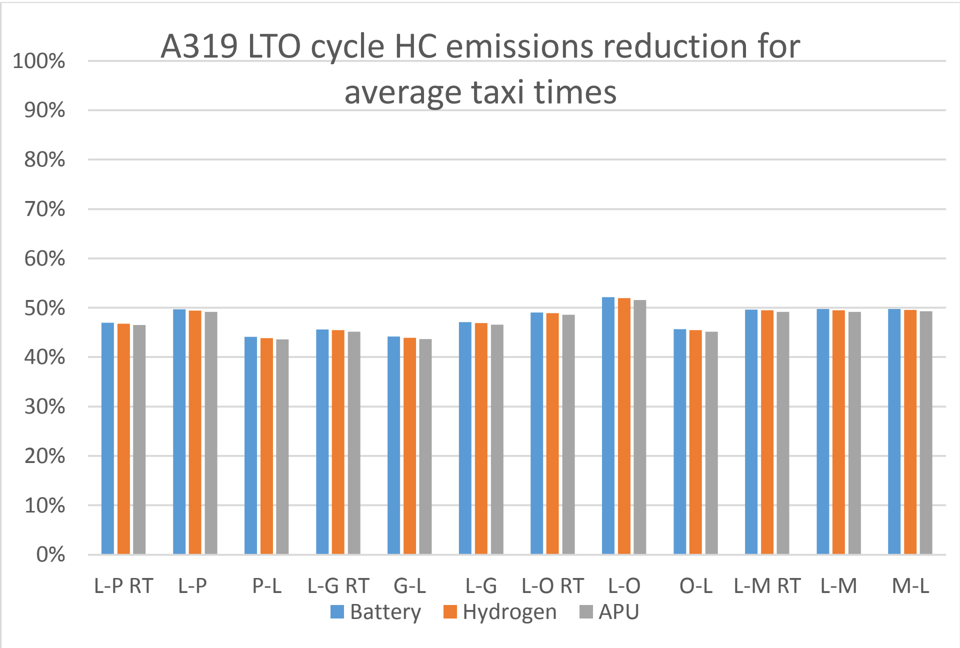

Figure 4. 23-A319 LTO cycle HC emissions reduction for average taxi times

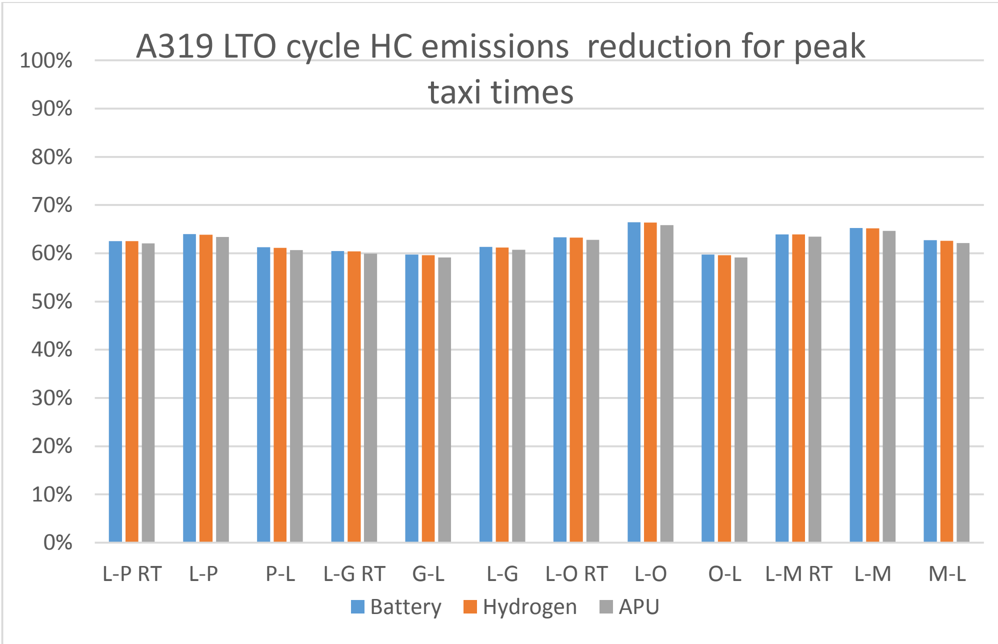

Figure 4. 25-A319 LTO cycle HC emissions reduction for peak taxi times

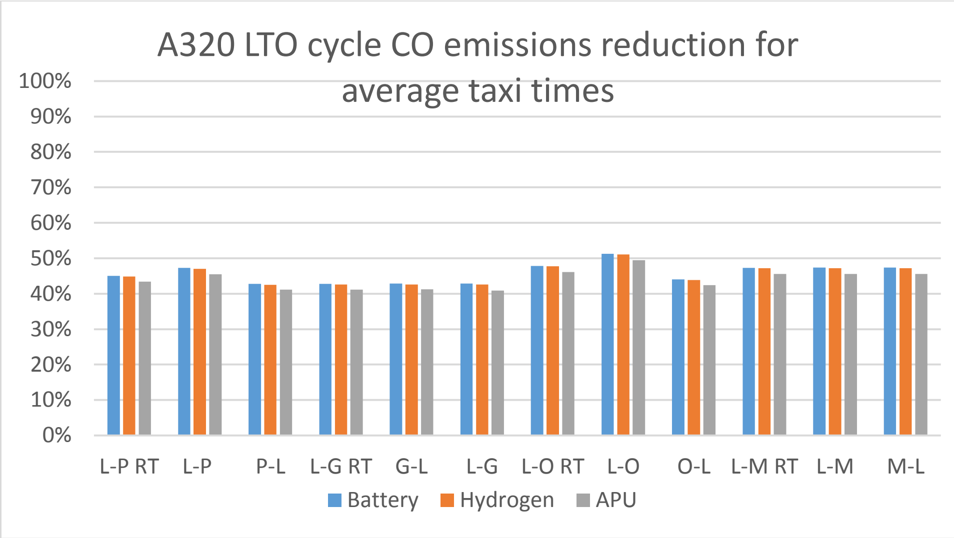

Figure 4. 26-A320 LTO cycle CO emissions reduction for average taxi times

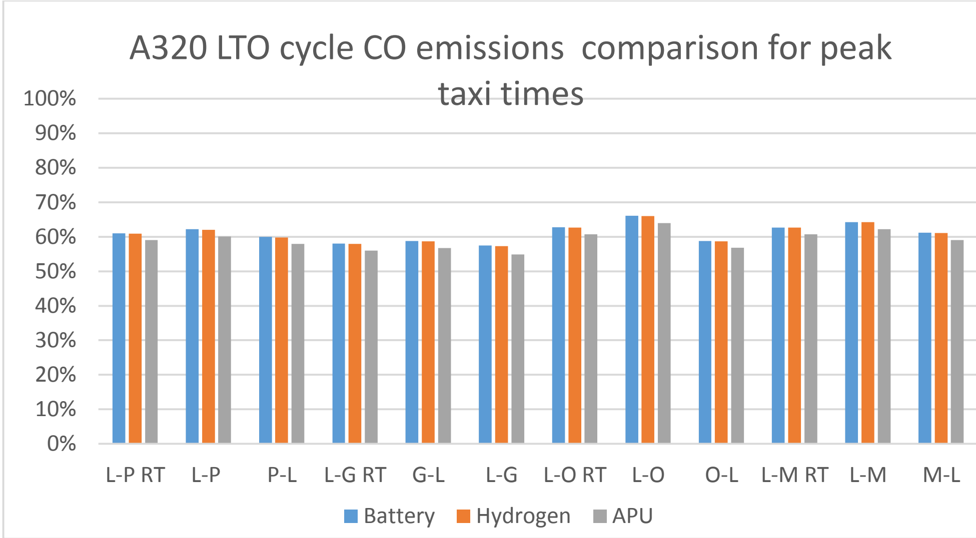

Figure 4. 28-A320 LTO cycle CO emissions reduction for peak taxi times

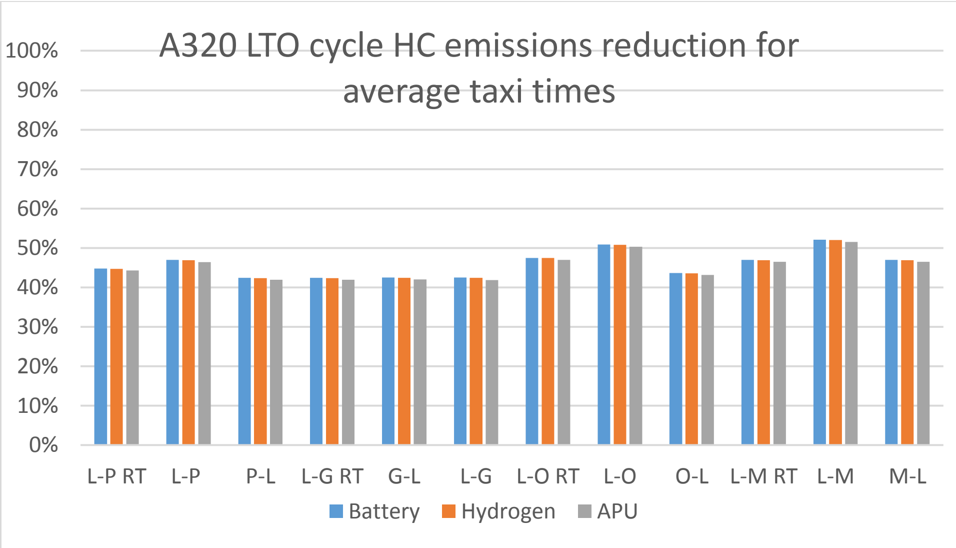

Figure 4. 27-A320 LTO cycle HC emissions reduction for average taxi times

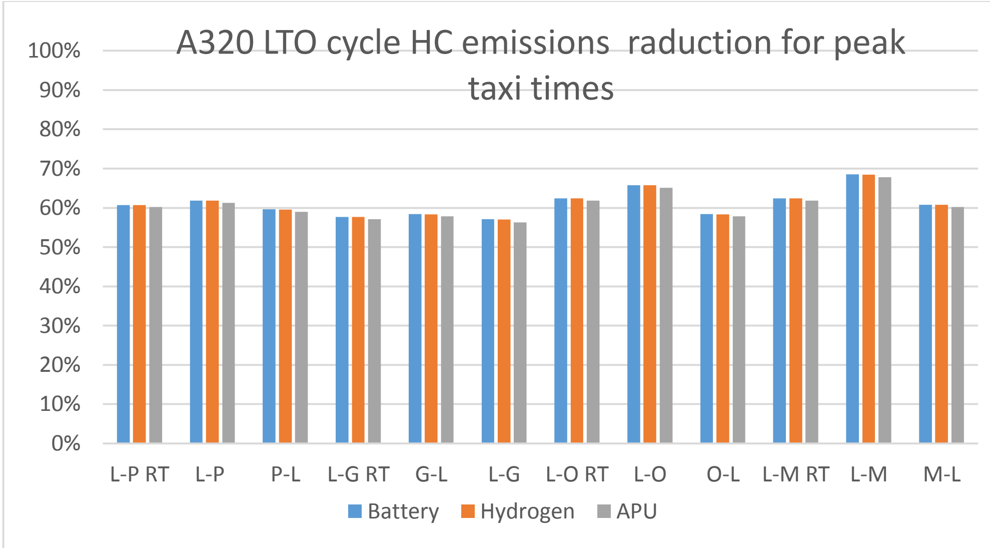

Figure 4. 29-A320 LTO cycle HC emissions reduction for peak taxi times

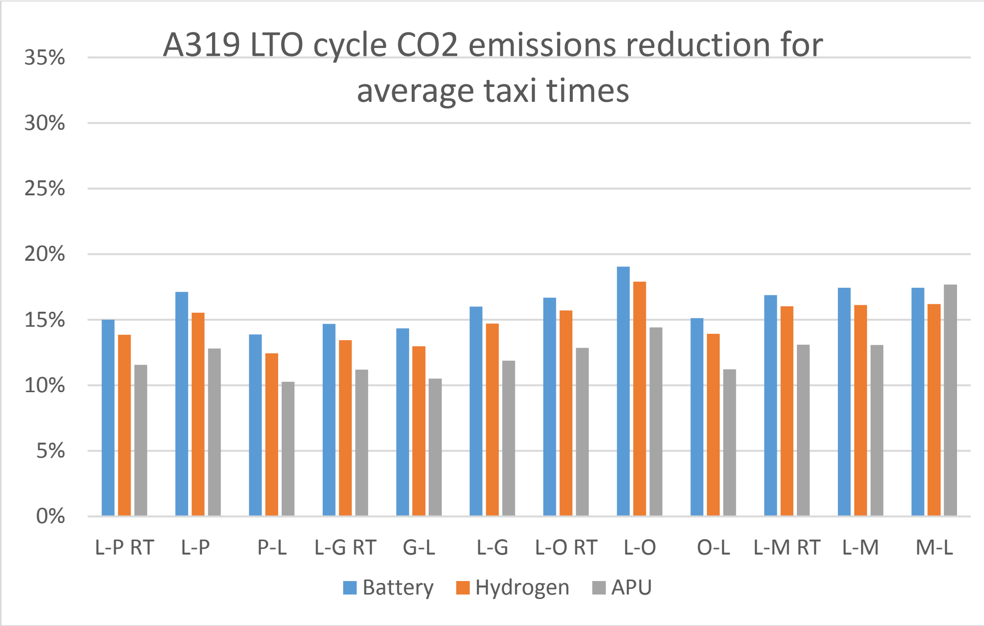

Figure 4. 30-A319 LTO cycle CO_2 emissions reduction for average taxi times

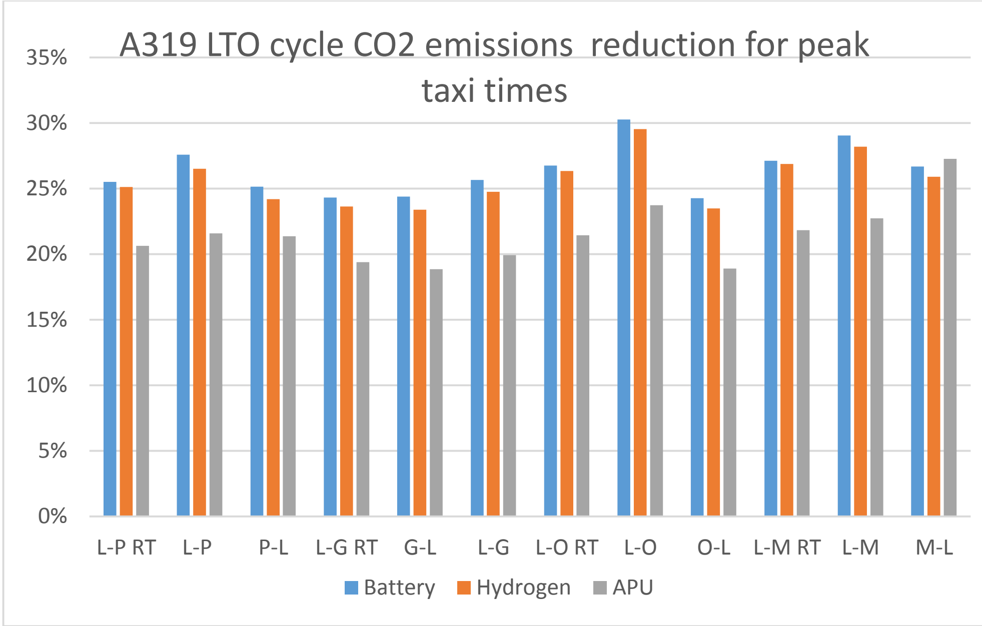

Figure 4. 32-A319 LTO cycle CO_2 emissions reduction for peak taxi times

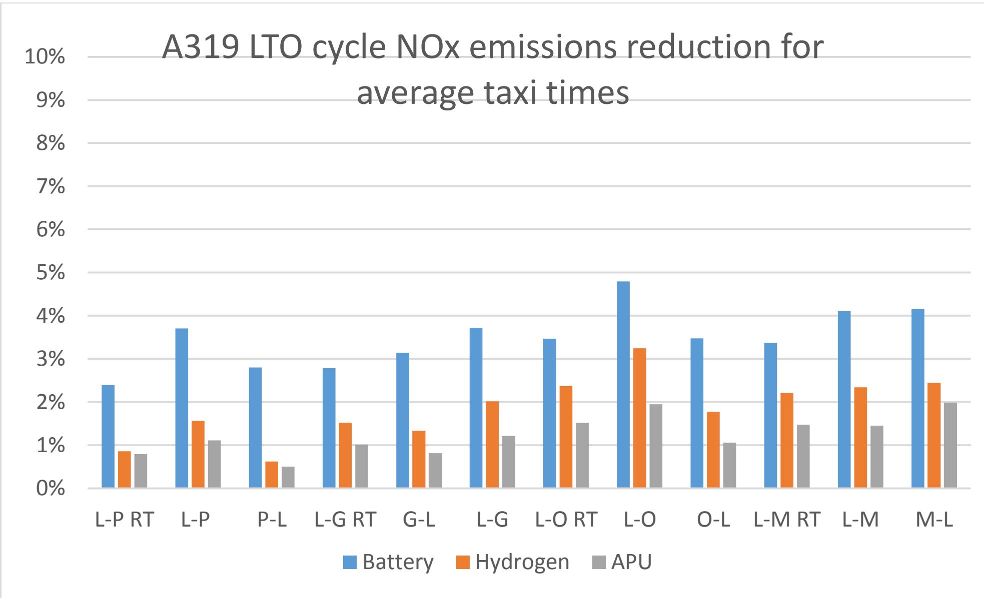

Figure 4. 31-A319 LTO cycle NO_x emissions reduction for average taxi times

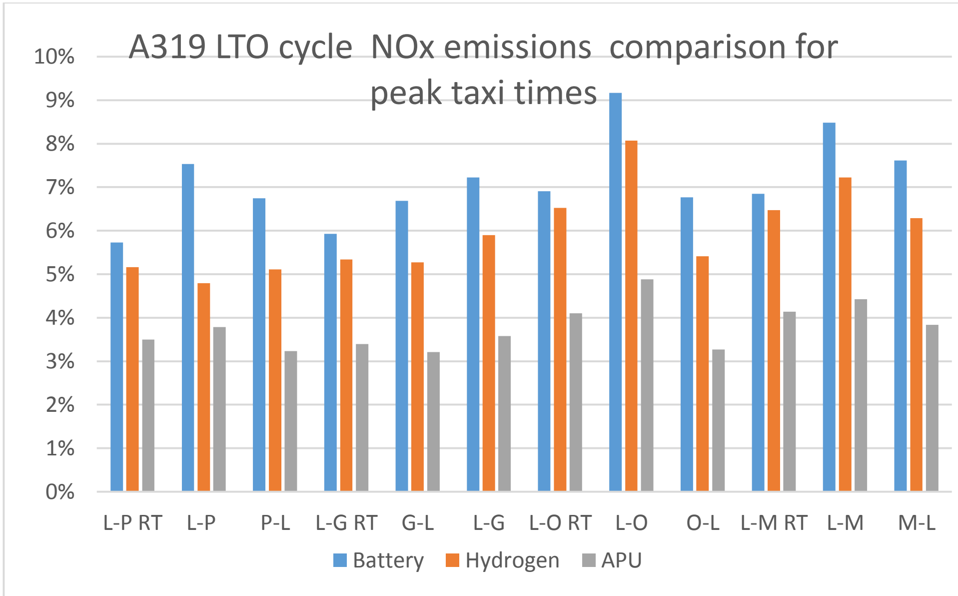

Figure 4. 33-A319 LTO cycle NO_x emissions reduction for peak taxi times

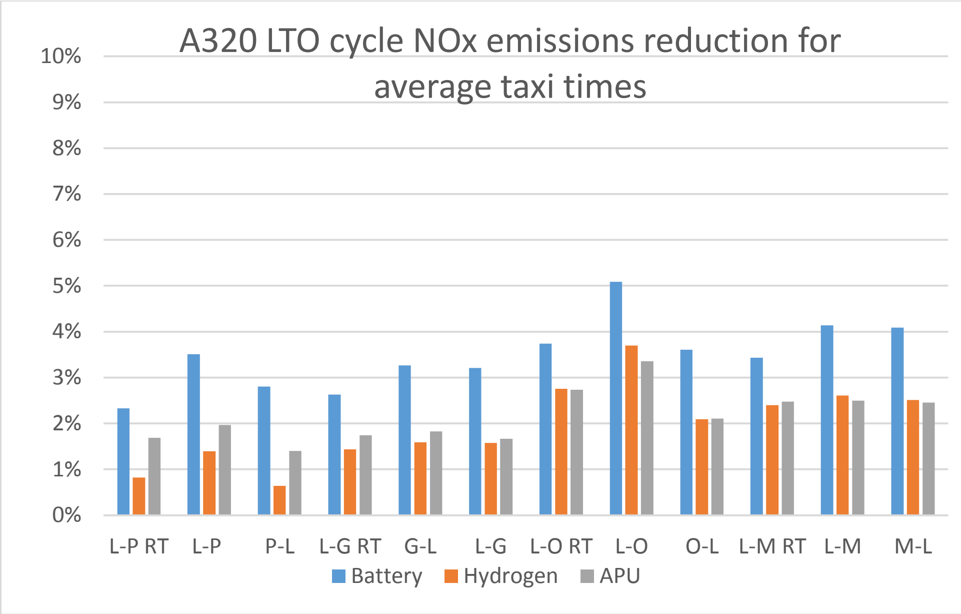

Figure 4. 34-A320 LTO cycle NO_x emissions reduction for average taxi times

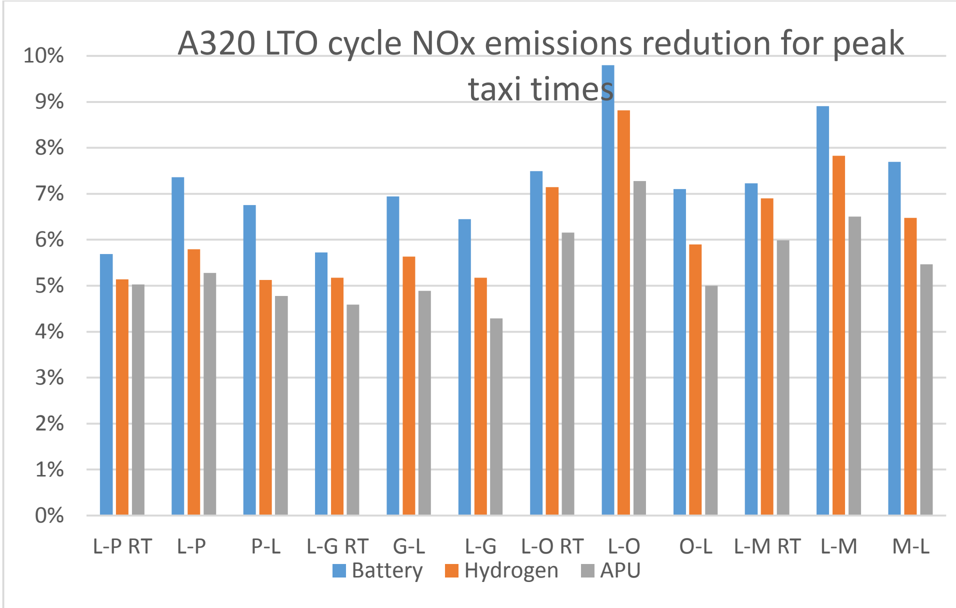

Figure 4. 36-A320 LTO cycle NO_x emissions reduction for peak taxi times

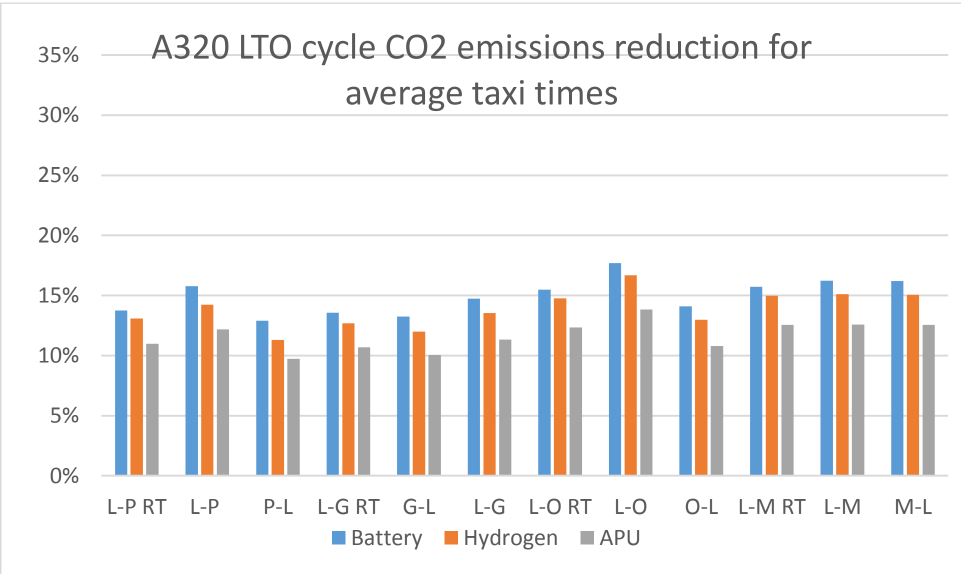

Figure 4. 35-A320 LTO cycle CO_2 emissions reduction for average taxi times

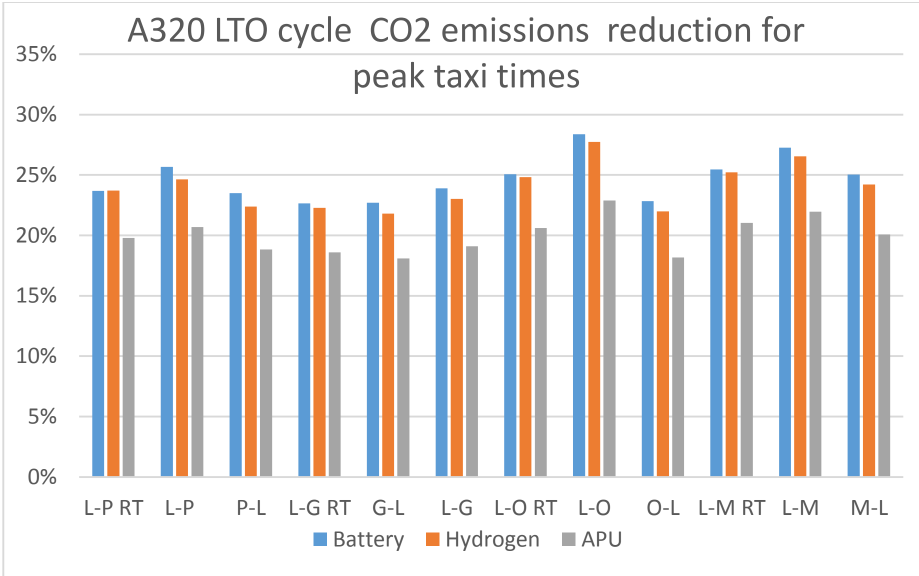

Figure 4. 37-A320 LTO cycle CO_2 emissions reduction for peak taxi times

As can be seen, LTO cycle emissions reduction are much more sensitive to changes in taxi times, as taxi out and taxi in represent a bigger portion of the LTO cycle. Savings in emissions during LTO for NO_x and CO_2 have lower values in percentage than those for HC and CO, and in LTO cycle weight of the system, load factor of the route and taxiing times influence clearly the results, as in longer taxi phases savings are higher and the extra weight reduces them. In whole operations, extra weight added is clearly more relevant in terms of extra emissions, worse for long routes, but when comparing each operation with its average LTO cycle, the load factor (higher for longer routes, but not directly linked to flight lengths, see annex 4) is key as fuel consumption and emissions are lower per extra weight added per km.

CO_2 results variation percentages are reduced compared to those of CO and HC. Considering average taxi times, highest reductions are between 15 and 20% difference for both aircraft (figures 4.30 and 4.32 for A319, 4.35 and 4.37 for A320), and showing less uniformity that CO and HC, due to the higher fuel consumption rate in the rest of the LTO cycle and the higher CO_2 emissions related. Savings are slightly higher for the A319, and results for peak taxi times show increase of carbon dioxide reductions up to more than 10%.

Regarding NO_x (figures 4.31 and 4.33 for A319, 4.34 and 4.36 for A320) reductions in emissions are positive, and this means that savings in taxi phase compensate the extra emissions related to system weight. These results are related to the complete LTO cycle, so these percentages represent smaller raw amounts of emissions than in whole operations. For average taxi times, regarding both aircraft, savings and increases have small percentages, and there is a clear difference between on board systems options, which means that a change in the weight of the on board system can make a difference, especially when load factor is lower (e.g. comparison between Lisbon Porto and Lisbon Orly in figure 4.34); in the case of APU option, reductions are affected by its own emissions. Pollutant values for an average LTO (ICAO times, considered aircraft engines) cycle for both aircraft considered are in annex 7.

Analysis of the results (NO_x) for each system and aircraft show:

-Fuel cell option is the worst for average taxi times for A320. However, in case of peak taxi times, this system shows improvements to overcome APU option savings for every case (with average times is better only in some cases, see figures 4.34 and 4.36), as its weight increase is not so high.

-Battery option shows savings for both aircraft. Round trip cases show worse results, and increase of taxi time shows improvement in both aircraft. A320 shows more reduction, and both aircraft have the best reduction of NO_x emissions with batteries and peak taxi times (up to 9% in A310 and almost 10% in A320, comparing figures 4.31 and 4.33, 4.34 and 4.36).

-As for APU option, due to its emissions, in the A319 case is the least saving option in all cases, including peak taxi times, while shows better results for A320 (figure 4.34). For peak taxi times, APU option reduces NO_x emissions in all cases for both aircraft, but as it is still the worst option for A319, in this case, as mentioned before, fuel cell option shows better savings in this case for A320.

Even so, increase of NO_x emissions is not avoidable in the whole operation, and even though values obtained for LTO cycle show savings, these savings are mostly under 5% in the best option for average taxiing times (figures 4.31 and 4.34), so emissions could increase in cases of shorter taxi times for the LTO cycle, and due to assumption errors the extra weight or the consumption associated could be greater and these small percentages of savings would be easily turned into losses. On the other hand, improvements in system weights could mean a guarantee of success in the future.

4.3.4 Comparison of taxi out emissions between options considered.

Regarding direct comparison between dispatch towing and on board systems, comparison is made for raw emissions during taxi out (when dispatch towing is considered). In this case, battery and fuel cell powered electric actuators have zero emissions on the ground (taxi).

Figures 4.38 through 4.41 show NO_x, HC and CO_2 emissions comparison between NB option and WB option for both aircraft. Due to high emissions of CO from gasoline tractors, CO comparison is apart, in figures from 4.42 to 4.45. Results are expressed in raw data, negative values mean savings and positive values mean increases. Comparison between APU and tractors show less emissions for APU but slightly higher CO_2 emissions compared to NB options. WB options show less savings than NB (as expected from section 4.2). Figures that show savings for NO_x, CO_2 and HC emissions (4.38 through 4.41) have values for each airport, with APU and tractors emissions organised in columns or single values; these figures are separated per aircraft and type of tractor (narrow body or wide body) . HC and NO_x emissions are represented in columns, while CO_2 emissions are represented with a line which results from linking each airport's value for each system (diesel, gasoline or APU).

A320 shows better results as the assumption made is that both aircraft are moved considering the same load for tractors as well as APU loads. This case has to be further studied, but as a first approach emissions savings are important except for those cases in which, due to engine characteristics (diesel, gasoline engines emissions indices), a certain pollutant shows increase. Battery and fuel cell cases saves all emissions from taxi out (and taxi in, but dispatch towing is not considered for this option). Table 4.1 shows raw saving for these alternatives (batteries and fuel cell powered system) during taxi out. Comparison shows better results for on board systems in average, except for APU CO_2 emissions. However, here flight lengths (because of the extra weight), infrastructure constraints, logistic problems, availability and airport and airlines preferences are key factors as well.

A319	NOx (g)	CO (g)	HC(g)	Fuel consumption (kg)	CO_2(kg)
Lisbon	342.912	2707.2	559.488	90.24	284.888
Geneva	257.184	2030.4	419.616	67.68	213.666
Milan/Malpensa	342.912	2707.2	559.488	90.24	284.888
Paris/Orly	278.616	2199.6	454.584	73.32	231.471
Porto	257.184	2030.4	419.616	67.68	213.666
A320	NOx (g)	CO (g)	HC(g)	Fuel consumption (kg)	CO_2(kg)
Lisbon	429.312	2336.256	459.264	99.84	315.195
Geneva	321.984	1752.192	344.448	74.88	236.396
Milan/Malpensa	429.312	2336.256	459.264	99.84	315.195
Paris/Orly	348.816	1898.208	373.152	81.12	256.096
Porto	321.984	1752.192	344.448	74.88	236.396

Table 4. 1-Emissions and fuel consumption raw savings for batteries and fuel cell options during tax out in reference scenario.

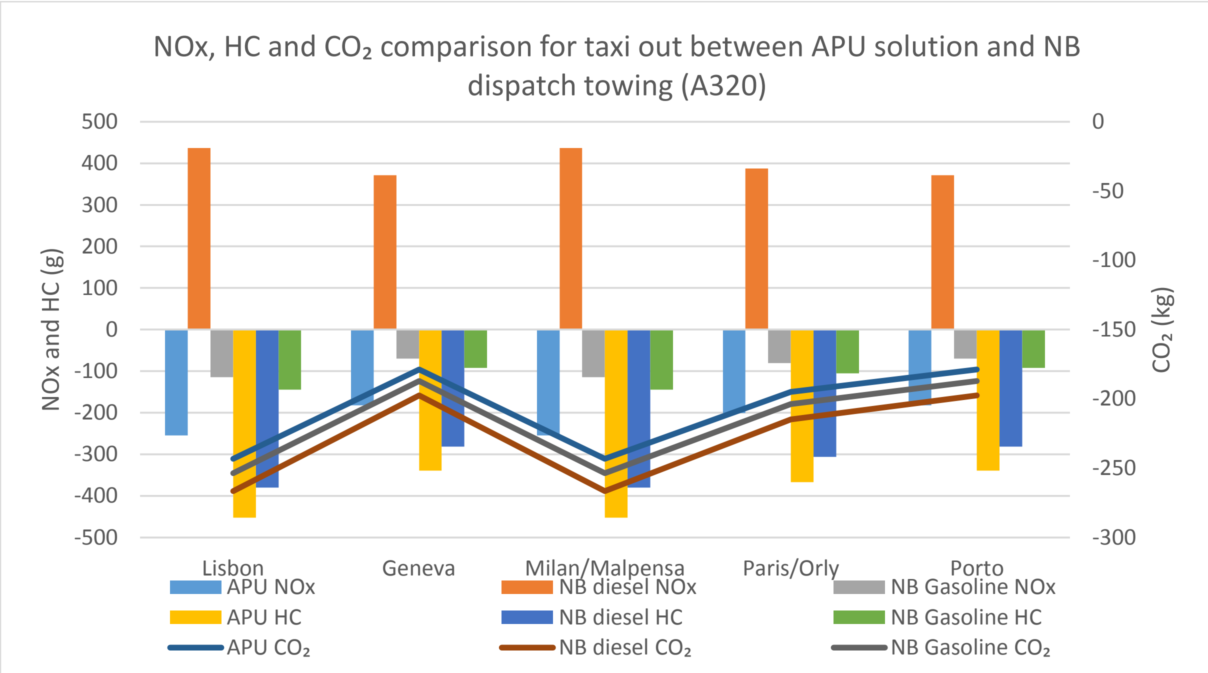

Figure 4. 38- NOx, HC and CO_2 comparison for taxi out between APU solution and NB dispatch towing (A320)

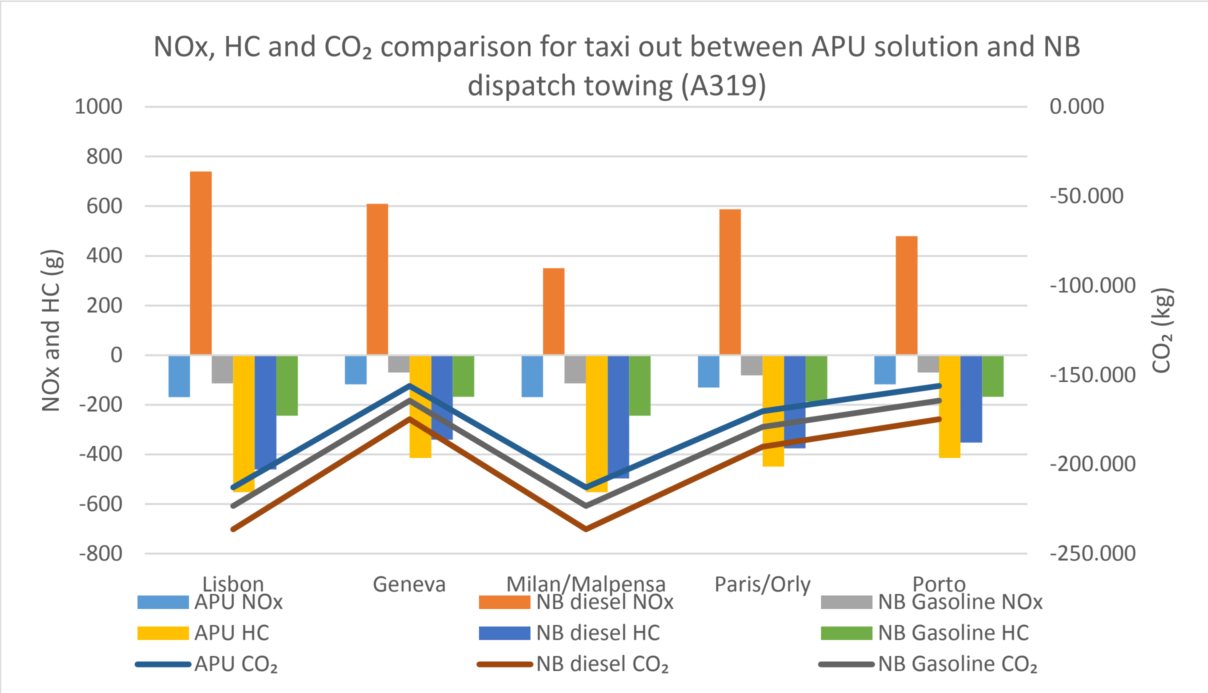

Figure 4. 39 - NOx, HC and CO_2 comparison for taxi out between APU solution and NB dispatch towing (A319)

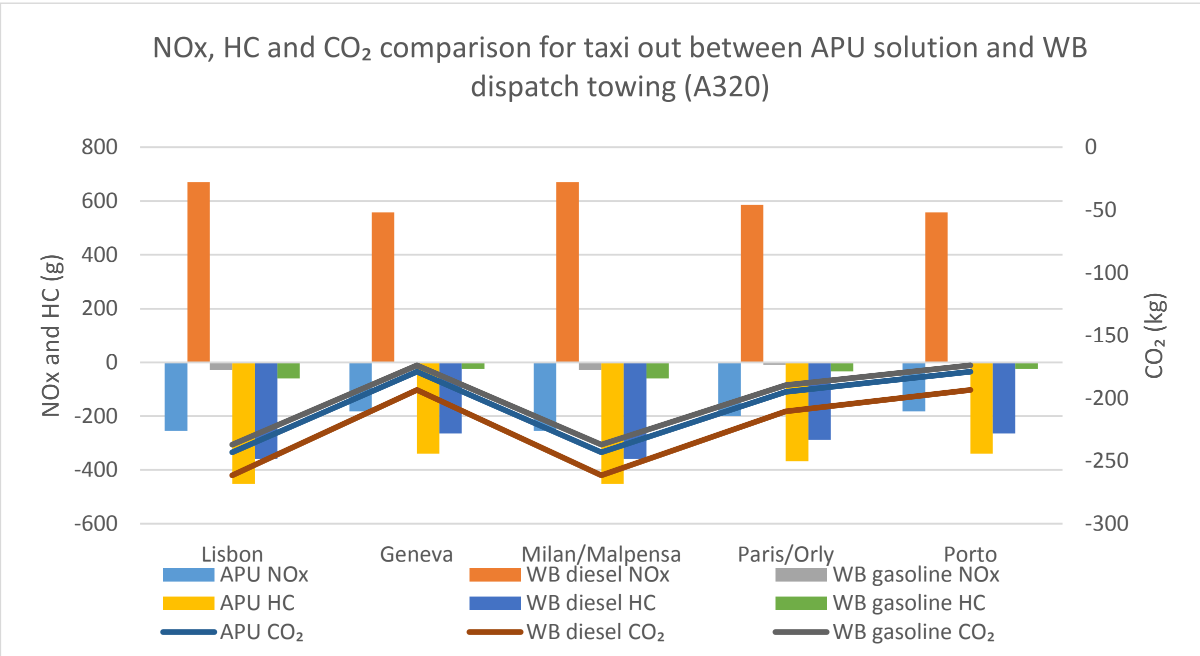

Figure 4. 40- NOx, HC and CO_2 comparison for taxi out between APU solution and WB dispatch towing (A320)

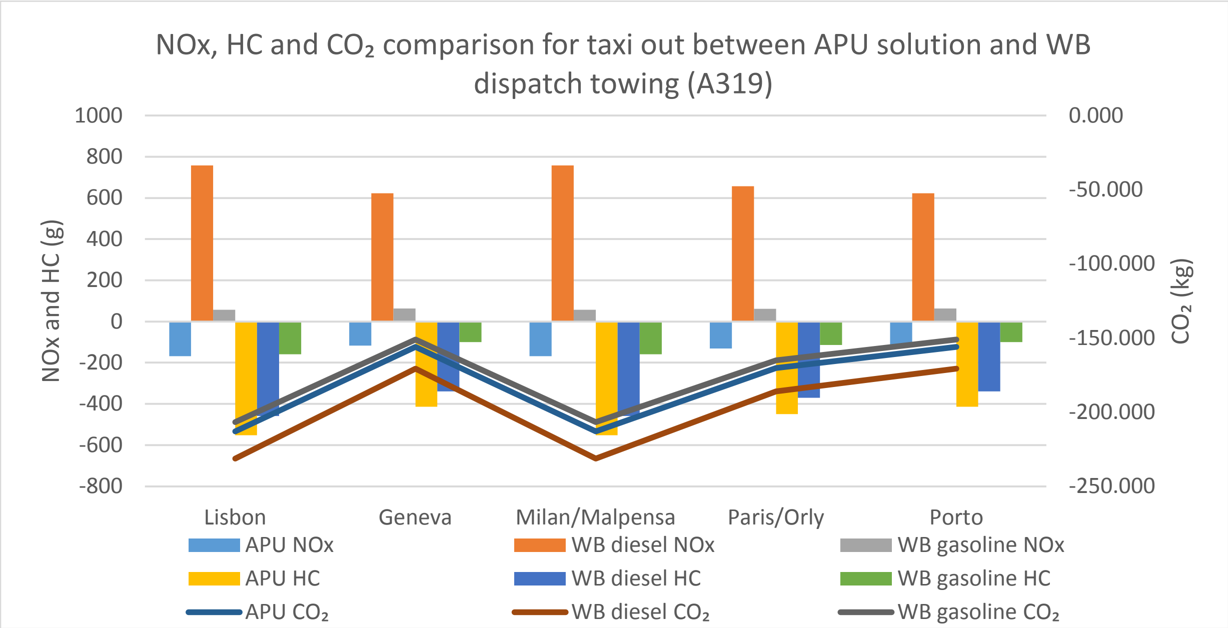

Figure 4. 41 - NOx, HC and CO_2 comparison for taxi out between APU solution and WB dispatch towing (A319)

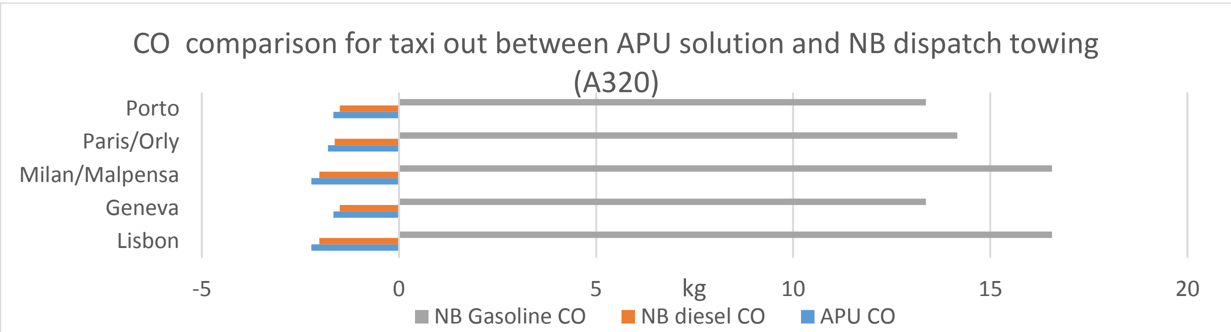

Figure 4. 42 - CO comparison for taxi out between APU solution and NB dispatch towing (A320)

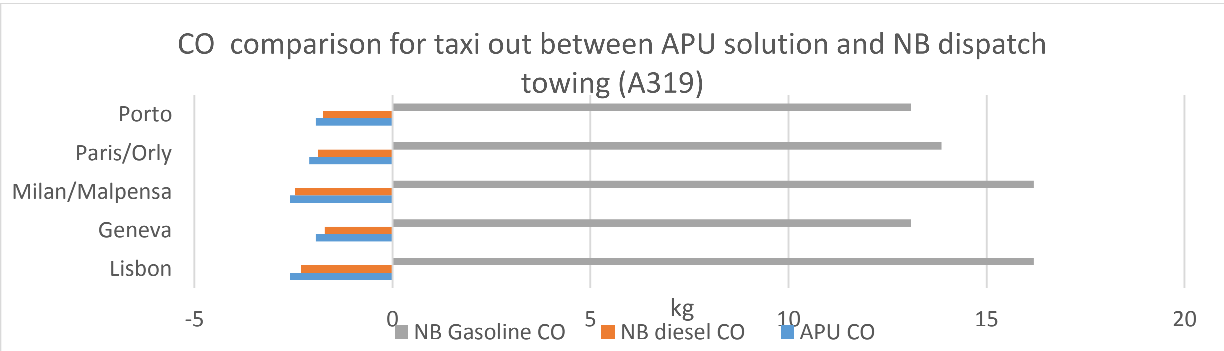

Figure 4. 43- CO comparison for taxi out between APU solution and NB dispatch towing (A319)

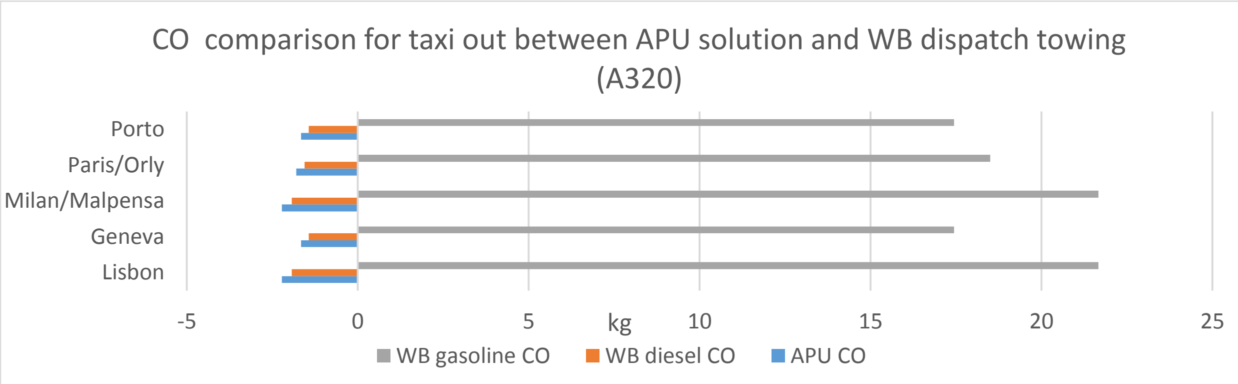

Figure 4. 44-CO comparison for taxi out between APU solution and WB dispatch towing (A320)

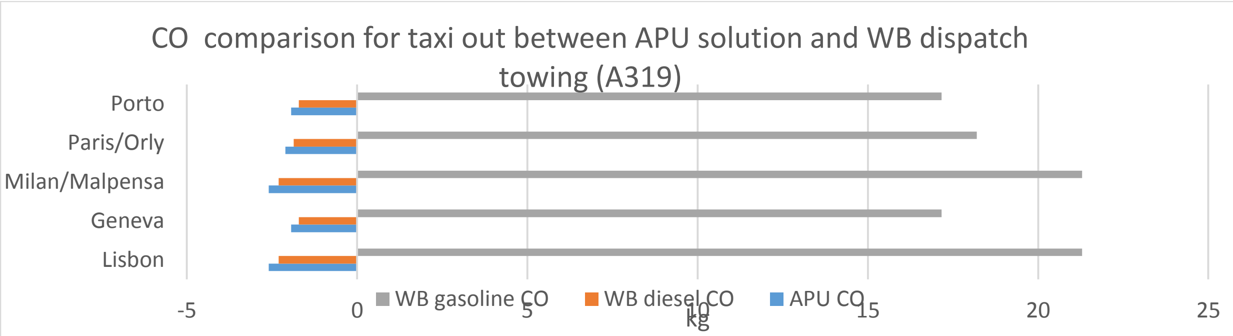

Figure 4. 45- CO comparison for taxi out between APU solution and WB dispatch towing (A319)

5 Conclusions and further considerations

On board systems show good results for short routes, reduction in LTO emissions and overall fuel consumption. NO_x emissions for overall operations show small increases for shorter routes, and even reductions in some cases. Dispatch towing with conventional tractors shows savings in fuel and some emissions but worse results. Preferences for each system will depend on availability of resources and airport needs and possibilities.

Of all the alternatives studied, main difference between them is that towing vehicles do not require to add any extra weight to the aircraft, and so there are not extra fuel consumption and emissions related during the rest of the flight, while batteries and fuel cells have zero emissions related during taxi phase and APU option has less CO, HC and NO_x emissions related than tractors, but slightly higher CO_2 emissions and fuel consumption on the ground. Regarding difficulties in infrastructure and investment, on board system powered by APU option seems to be the most suitable option since it has compatibility with airport infrastructures and procedures (as it is used currently for other purposes). Other options of on board systems show less emissions and fuel consumption related, but are likely to mean an additional cost due to lack of infrastructure and equipment. In particular, battery option shows best results for short direct routes (change of batteries at destination). Dispatch towing shows selective savings and present logistic and monetary constraints, but could be a suitable solution if one pollutant is a particular issue in the airport.

In this regard, future development of hybrid or electric tractors and improvement of batteries and fuel cells for on board systems (as well as infrastructure development) are a key factor to help alternative taxiing procedures.

Regarding dispatch towing solution, conventional tractors using internal combustion engines are the first approach to estimate the potential benefits of using a tractor to perform the taxi phase. Diesel and gasoline tractors suppose a great advantage in terms of consumption and emissions of CO_2 and some air pollutants. However, diesel tractors emissions of NO_X and gasoline tractors emissions of CO are very high, and these increments are greater for big tractors, those designed to pushback wide body aircraft and that have enough power to perform a taxi phase in the same time that aircraft do under its own power. Narrow body aircraft tractors also increase taxiing times. Besides representing a cost (for all time related costs), time is the main factor in the scheduling of the airport but it is also a tool in terms of measuring comfort of the passengers and the number of flights that the aircraft can perform, which is a vital factor in airlines activity. As said before, use of tractors will become a logistic problem in case of busy airports, where there would be required a new net of roadways for dispatch towing vehicles, as taxiways safety requirements are restrictive in terms of circulation when aircraft are taxiing. This logistic problem will not be so important in small airports where there are few departures and arrivals, and tractors would have less traffic problems in the taxiways. This does not avoid the need in any case of some centre of control for tractor movement and a connection system between aircraft and tractor, as the breaking should be made without compromising the nose gear (section 2.2.3) . As considered before, taxi out seems the only phase suitable for this alternative as the taxi in requires some kind of area where the aircraft would have to stop and be attached to the tractor.

Dispatch towing vehicles then seem suitable for less busy airports or airports with an extra roadway system, for long or short taxi phases (only taxi out), and in cases where some pollutant reduction or fuel consumption are priorities, and it is allowed to increase emissions of other kind. The availability of tractors and its price is also a constraint for this solution; however, hybrid and electric vehicle development are key factors in this field, as one hybrid solution is already available (TaxiBot) and all electric pushback tractors are currently in service, although its performance is not good enough to perform dispatch towing. These solutions reduce emission of pollutants, making dispatch towing a more attractive alternative.

As for the on board systems for full taxi phases, shorter flights with long taxi phases seem to be the most promising application for the moment. However, in some cases longer flights also show benefits in the usage of these alternative when taxi times are long enough. First condition for these systems to be useful is the fuel consumption; if considering the whole operation fuel consumption is higher than in the same operation with conventional taxi. This is why short routes are more attractive, because any extra weight added will have associated a fuel consumption that will be greater if distance increases. In other regard, NO_x emissions depend more on flight length and added weight, while main sources of CO and HC are taxi phases.

Regarding fuel consumption, short distance flights, as extra weight is added (section 4.3.2), short flight distances are the objective. APU appears to be the best option in round trip cases, while batteries reduce more fuel consumption for single trips, when they can be changed in the destination airport. For peak taxi times fuel consumption in short routes is reduced, but from the point where there are no savings, in the case of batteries consumption increase for longer taxi times (section 4.3.2). APU allows longer flight distances with fuel savings, and fuel cell alternative is suitable for sort flights and higher taxi times but it is not as good as the other two.

As for CO an HC emissions, most are generated in taxi phases, and so all alternatives reduce them, but also reductions are higher in short flights, even though there is not much difference for the cases considered in amount per operation.

NO_x emissions are higher as long as an important amount of these emissions is produced in the en-route phase, so it is more difficult to avoid these emissions in whole operations when adding extra weight. However, in this case is interesting to study LTO cycle emissions. On the ground, emissions can be totally avoided, or reduced (APU), and in LTO cycle three options show good results for total LTO cycles, and reductions in overall NO_x emissions for LTO cycle for average and peak taxi times. APU reduces less emissions on the ground, but implies less weight for the rest of the LTO cycle, meaning less pollution in average taxi times for A320, but not for the A319. This results implies a total reduction of emissions considered in the surroundings of the airport, and savings of fuel for whole operations, for short flights and long taxi phases, proving that these alternatives are a feasible solution as first approach, and a suitable tool if only ground emissions are the concern.

All systems considered show good results for both aircraft considered, but A320 shows more advantages as the systems are sized for this aircraft; a particular study of viability of less required actuators and energy sources would show better results for the A319. APU and Battery Pack plus electric actuator seem good options and more feasible for today's situation (energy distribution). NO_x emissions during en-route phase can be reduced with the improvement of engines and aircraft procedures and design, as mentioned in sections 1.2 and 2.1.2.

Selection of the alternative has to take into account the timetable of flights, as longer taxi times are preferred for these systems, and energy sources for on board systems have to be sized as accurately as possible. Direct routes are a better solution for battery option mainly, as hydrogen option is less affected for this issue and APU is not affected.

The possibility of changing batteries or recharging hydrogen in every airport supposes a great logistic challenge for a company. This would be easier considering a HUB where all could be done (case of round trips). In case batteries storage places are required to charge the batteries, as well as handling services, maintenance, and there will be added cost for the batteries and the electricity (Zhao et al. 2013)(Gerssen-Gondelach & Faaij 2012). Emissions related to direct use are zero, but this implies that emissions are produced in the place where electricity is generated. Further research on reducing life cycle emissions of electricity is required. Regarding hydrogen, in this case logistic problems are more or less similar, except for two things. Hydrogen supply is not available as the electrical supply; there is neither a great production of hydrogen nor a wide distribution reference. Also, hydrogen storage is a challenge, and could imply the use of a reformer for liquid fuels, which solves problems related to hydrogen storage but has extra costs added and less efficiency (Celikel et al. 2006) (van Vliet et al. 2010). As well, hydrogen production by electricity also has emissions related to the production of electricity. In this case the fixed weight of the fuel cell is the main constraint of the system, but it is expected future improvement in this field, as well as in batteries weight (Canada Transportaion Development Centre 2012) (Gerssen-Gondelach & Faaij 2012). As for APU, its usage at MES could reduce its life and add extra maintenance costs.

Further studies and field tests should be carried out to test the viability of these systems that appear to be feasible to check security issues, increase of total costs and better adjustment of energy sources sizes.

The main objective of this Thesis was to review the feasibility of alternatives to reduce emissions and fuel consumption in taxi phases, as well as a first approach to the potential benefits. Results achieved show that on board systems studied, as well as external systems used to compare, are useful solutions to avoid or air pollution in airports and surroundings as well as ways to save fuel, and that this advantages and its benefits will increase in the future with technology improvements (hybrid vehicles, better batteries, fuel cell development, etc.).

Annex 1

Aircraft Category	FF (kg/s)	EI CO_2 (g/kg fuel)	EI CO (g/kg fuel)	EI THC (g/kg fuel)	EI NO_x (g/kg fuel)
Narrow Body	0.038	3,155	4.94	0.29	7.64
Wide Body	0.064	3,155	0.98	0.13	11.53
Jumbo-Wide Body	0.058	3,155	0.53	0.12	11.20
Regional Jet	0.020	3,155	6.48	0.42	4.91
Turbo Prop	0.020	3,155	6.48	0.42	4.91

FF=Fuel Flow, EI= Emissions Index, CO_2= Carbon dioxide, CO=Carbon monoxide, THC=Total hydrocarbon, NO_x=Nitrogen oxides
Raw data source used to derive these weighted averages: Swedish FOI, 2009. EI CO_2 from FAA's EDMS, 2010.

Annex 1- APU emissions and fuel consumption in MES (main engine start) mode (Transportation Research Board (TRB) 2012)

Annex 2

Nº	AIRCRAFT		REGISTRATION MARKING	MSN	Passenger Maximum Capacity	CABIN VERSION	SELCAL CODE	ENGINE TYPE	MTOW (kg)	MLW (kg)	ICAO ANN.16	NOISE LEVEL (EPNdB)			ENGINE EMISSIONS (g/kN)			EASA Record Number	Acoustic Group
	TYPE	MODEL										Flyover	Side Line	Approach	HC	CO	NOx		
16	A319	111	**CS-TTA**	750	132	CY132	HR-ES	CFM56-5B5/P CFM56-5B5/3	68000	61000	CH.4	84,1	91,5	93,4	10,0	48,3	38,2	A2243	5a
	A319	111	**CS-TTB**	755	132	CY132	HS-GR	CFM56-5B5P	68000	61000	CH.4	84,1	91,5	93,4	10,0	48,3	38,2	A2243	5a
	A319	111	**CS-TTC**	763	132	CY132	LP-AB	CFM56-5B5P	68000	61000	CH.4	84,1	91,5	93,4	10,0	48,3	38,2	A2243	5a
	A319	111	**CS-TTD**	790	132	CY132	FH-PS	CFM56-5B5P	68000	61000	CH.4	84,1	91,5	93,4	10,0	48,3	38,2	A2243	5a
	A319	111	**CS-TTE**	821	132	CY132	EP-KM	CFM56-5B5P	68000	61000	CH.4	84,1	91,5	93,4	10,0	48,3	38,2	A2243	5a
	A319	111	**CS-TTF**	837	132	CY132	QR-EP	CFM56-5B5/P CFM56-5B5/3	68000	61000	CH.4	84,1	91,5	93,4	10,0	48,3	38,2	A2243	5a
	A319	111	**CS-TTG**	906	132	CY132	BQ-PS	CFM56-5B5P	68000	61000	CH.4	84,1	91,5	93,4	10,0	48,3	38,2	A2243	5a
	A319	111	**CS-TTH**	917	132	CY132	FQ-LR	CFM56-5B5P	68000	61000	CH.4	84,1	91,5	93,4	10,0	48,3	38,2	A2243	5a
	A319	111	**CS-TTI**	933	132	CY132	FQ-MP	CFM56-5B5P	68000	61000	CH.4	83,5	90,1	93,2	10,0	48,3	38,2	A343	5a
	A319	111	**CS-TTJ**	979	132	CY132	QS-EP	CFM56-5B5P	68000	61000	CH.4	83,5	90,1	93,2	10,0	48,3	38,2	A343	5a
	A319	111	**CS-TTK**	1034	132	CY132	QS-GJ	CFM56-5B5P	68000	61000	CH.4	83,5	90,1	93,2	10,0	48,3	38,2	A343	5a
	A319	111	**CS-TTL**	1100	132	CY132	AL-EJ	CFM56-5B5P	68000	61000	CH.4	83,5	90,1	93,2	10,0	48,3	38,2	A343	5a
	A319	111	**CS-TTM**	1106	132	CY132	BL-MR	CFM56-5B5P	68000	61000	CH.4	83,5	90,1	93,2	10,0	48,3	38,2	A343	5a
	A319	111	**CS- TTN**	1120	132	CY132	BL-MS	CFM56-5B5P	68000	61000	CH.4	83,5	90,1	93,2	10,0	48,3	38,2	A343	5a
	A319	111	**CS- TTO**	1127	132	CY132	AR-GH	CFM56-5B5P	68000	61000	CH.4	83,5	90,1	93,2	10,0	48,3	38,2	A343	5a
	A319	111	**CS- TTP**	1165	132	CY132	EJ-LS	CFM56-5B5P	68000	61000	CH.4	83,5	90,8	93,2	10,0	48,3	38,2	A343	5a
3	A319	112	**CS-TTQ**	629	132	CY132	QS-HL	CFM56-5B6/P	70000	62500	CH.4	84,7	92,5	93,6	7,9	96,7	28,8	A372	5a
	A319	112	**CS-TTR**	1756	132	CY132	AC-JS	CFM56-5B6/P	70000	61000	CH.4	84,0	91,7	93,5	8,6	43,3	40,5	A2283	5a
	A319	112	**CS-TTS**	1765	132	CY132	AC-QR	CFM56-5B6/P CFM56-5B6/2P	70000	61000	CH.4	84,2	92,0	93,9	7,9	43,3	40,5	A2283	5a
2	A319	112	**CS-TTU**	1668	138	CY138	AG-PQ	CFM56-5B6/P	70000	61000	CH.4	84,0	91,7	93,5	8,6	43,3	40,5	A2283	5a
	A319	112	**CS-TTV**	1718	138	CY138	AL-EH	CFM56-5B6/P	70000	61000	CH.4	84,0	91,7	93,5	8,6	43,3	40,5	A2283	5a
1	A320	214	**CS-TQD**	870	162	CY162	FL-DS	CFM56-5B4/P CFM56-5B4/2P	77000	64500	CH.4	85,4	93,8	96,0	9,2	84,7	31,7	A2428	5a
16	A320	214	**CS-TNG**	945	162	CY162	QS-BG	CFM56-5B4/P CFM56-5B4/2P	73500	64500	CH.4	84,2	94,0	96,0	6,8	34,3	47,1	A5213	5a
	A320	214	**CS-TNH**	960	162	CY162	QS-CK	CFM56-5B4/P CFM56-5B4/2P	73500	64500	CH.4	84,2	94,0	96,0	6,8	34,3	47,1	A5213	5a
	A320	214	**CS-TNI**	982	162	CY162	QS-CR	CFM56-5B4P	73500	64500	CH.4	83,7	93,6	95,5	6,8	34,3	47,1	A5213	5a
	A320	214	**CS-TNJ**	1181	162	CY162	CL-HS	CFM56-5B4/P	73500	64500	CH.4	83,7	93,6	95,5	6,8	34,3	47,1	A5213	5a
	A320	214	**CS-TNK**	1206	162	CY162	CL-JR	CFM56-5B4/P CFM56-5B4/2P	73500	64500	CH.4	84,2	94,0	96,0	6,8	34,3	47,1	A5213	5a
	A320	214	**CS-TNL**	1231	162	CY162	CL-PR	CFM56-5B4/P CFM56-5B4/2P	73500	64500	CH.4	84,2	94,0	96,0	6,8	34,3	47,1	A5213	5a
	A320	214	**CS-TNM**	1799	162	CY162	HR-KL	CFM56-5B4/P	73500	64500	CH.4	83,7	93,6	95,5	6,8	34,3	47,1	A5213	5a
	A320	214	**CS-TNN**	1816	162	CY162	HS-JR	CFM56-5B4P	73500	64500	CH.4	83,7	93,6	95,5	6,8	34,3	47,1	A5213	5a
	A320	214	**CS-TMW**	1667	162	CY162	KL-EP	CFM56-5B4P	77000	66000	CH.4	85,3	93,5	95,5	6,8	34,3	47,1	A5206	5a
	A320	214	**CS-TNP**	2178	162	CY162	FH-CP	CFM56-5B4/P	77000	66000	CH.4	85,3	93,5	95,5	6,8	34,3	47,1	A5206	5a
	A320	214	**CS-TNQ**	3769	162	CY162	BG-CJ	CFM56-5B4/3	77000	64500	CH.4	85,3	93,5	95,5	2,6	44,8	37,6	A6626	5a
	A320	214	**CS-TNR**	3883	162	CY162	BG-CK	CFM56-5B4/3	77000	64500	CH.4	85,3	93,5	95,5	2,6	44,8	37,6	A6626	5a
	A320	214	**CS-TNS**	4021	162	CY162	BG-DF	CFM56-5B4/3 CFM56-5B4/P	77000	64500	CH.4	85,3	93,5	95,5	2,6	44,8	37,6	A6626	5a
	A320	214	**CS-TNT**	4095	162	CY162	BJ-AE	CFM56-5B4/3 CFM56-5B4/P	77000	64500	CH.4	85,3	93,5	95,5	2,6	44,8	37,6	A6626	5a
	A320	214	**CS-TNU**	4106	162	CY162	BK-AG	CFM56-5B4/3	77000	64500	CH.4	85,3	93,5	95,5	2,6	44,8	37,6	A6626	5a
	A320	214	**CS-TNV**	4145	162	CY162	BK-CD	CFM56-5B4/3	77000	64500	CH.4	85,3	93,5	95,5	2,6	44,8	37,6	A6626	5a
2	A320	214	**CS-TNX**	2822	168	CY168	BR-GK	CFM56-5B4/P	77000	66000	CH.4	58,3	93,5	95,5	2,6	44,8	37,6	A6626	5a
	A320	214	**CS-TNW**	2792	168	CY168	AR-CF	CFM56-5B4/P	77000	66000	CH.4	85,3	93,5	95,5	6,8	34,3	47,1	A5206	5a

Annex 2-TAP fleet data (A320 and A319). Source: TAP

Annex 3

NM	125				
	Sum of BurntFuel	Sum of NOX_kg	Sum of CO2_kg	Sum of CO_kg	Sum of HC_kg
A319 without taxi	1470.1233	28.734739	4630.892	4.9066296	1.0176845
LTO without taxi	395.532	6.34878	1245.926	0.6875676	0.1415064
a. Taxi out	214.32	0.814416	675.108	6.4296	1.32878
f. Taxi in	78.96	0.300048	248.724	2.3688	0.489552
A320 without taxi	1554.0993	33.287625	3355.376	2.561883	0.2035516
LTO without taxi	491.52	9.886736	8.246	0.653168	0.143392
a. Taxi out	237.12	1.019616	919.296	5.548608	1.090752
f. Taxi in	87.36	0.375648	338.688	2.044224	0.401856
NM	250				
	Sum of BurntFuel	Sum of NOX_kg	Sum of CO2_kg	Sum of CO_kg	Sum of HC_kg
A319 without taxi	2207.764	39.668289	6954.45	6.4392276	1.3384164
LTO without taxi	395.532	6.34878	1245.926	0.6875676	0.1415064
a. Taxi out	214.32	0.814416	675.108	6.4296	1.32878
f. Taxi in	78.96	0.300048	248.724	2.3688	0.489552
A320 without taxi	2322.6346	45.130697	5776.256	3.546768	0.2525161
LTO without taxi	491.52	9.886736	8.246	0.653168	0.143392
a. Taxi out	237.12	1.019616	919.296	5.548608	1.090752
f. Taxi in	87.36	0.375648	338.688	2.044224	0.401856

NM	500				
	Sum of BurntFuel	Sum of NOX_kg	Sum of CO2_kg	Sum of CO_kg	Sum of HC_kg
A319 without taxi	3215.377	51.145401	10128.444	9.2519976	1.9271694
LTO without taxi	395.532	6.34878	1245.926	0.6875676	0.1415064
a. Taxi out	214.32	0.814416	675.108	6.4296	1.32878
f. Taxi in	78.96	0.300048	248.724	2.3688	0.489552
A320 without taxi	3440.848	58.672656	9298.624	5.714338	0.3528242
LTO without taxi	491.52	9.886736	8.246	0.653168	0.143392
a. Taxi out	237.12	1.019616	919.296	5.548608	1.090752
f. Taxi in	87.36	0.375648	338.688	2.044224	0.401856
NM	750				
	Sum of BurntFuel	Sum of NOX_kg	Sum of CO2_kg	Sum of CO_kg	Sum of HC_kg
A319 without taxi	4300.91	63.685451	13547.87	11.5238676	2.4049514
LTO without taxi	395.532	6.34878	1245.926	0.6875676	0.1415064
a. Taxi out	214.32	0.814416	675.108	6.4296	1.32878
f. Taxi in	78.96	0.300048	248.724	2.3688	0.489552
A320 without taxi	4691.907	73.886403	13239.448	7.719568	0.51784527
LTO without taxi	491.52	9.886736	8.246	0.653168	0.143392
a. Taxi out	237.12	1.019616	919.296	5.548608	1.090752
f. Taxi in	87.36	0.375648	338.688	2.044224	0.401856

NM	1000				
	Sum of BurntFuel	Sum of NOX_kg	Sum of CO2_kg	Sum of CO_kg	Sum of HC_kg
A319 without taxi	5409.311	76.589528	17039.358	13.5961276	2.8412144
LTO without taxi	395.532	6.34878	1245.926	0.6875676	0.1415064
a. Taxi out	214.32	0.814416	675.108	6.4296	1.32878
f. Taxi in	78.96	0.300048	248.724	2.3688	0.489552
A320 without taxi	5930.534	89.020208	17141.185	9.668398	0.5528165
LTO without taxi	491.52	9.886736	8.246	0.653168	0.143392
a. Taxi out	237.12	1.019616	919.296	5.548608	1.090752
f. Taxi in	87.36	0.375648	338.688	2.044224	0.401856
NM	1500				
	Sum of BurntFuel	Sum of NOX_kg	Sum of CO2_kg	Sum of CO_kg	Sum of HC_kg
A319 without taxi	7690.209	103.058978	24224.13	18.0039176	3.7682194
LTO without taxi	395.532	6.34878	1245.926	0.6875676	0.1415064
a. Taxi out	214.32	0.814416	675.108	6.4296	1.32878
f. Taxi in	78.96	0.300048	248.724	2.3688	0.489552
A320 without taxi	8486.35	120.132348	25191.943	13.774408	0.7570582
LTO without taxi	491.52	9.886736	8.246	0.653168	0.143392
a. Taxi out	237.12	1.37165	919.296	3.62748	0.0306432
f. Taxi in	87.36	0.505344	338.688	1.33644	0.0112896

Annex 3- EMEP guidebook data modified for A319 and A320

Annex 4

Distance	**Airway Distance - NM - Avg**	**Air Distance - NM - Avg**
MAINLAND	**190.01**	**190.33**
LIS OPO	190.04	190.42
OPO LIS	189.99	190.24
SWITZERLAND	**869.94**	**872.74**
GVA LIS	855.71	878.86
LIS GVA	884.17	866.63
FRANCE	**851.22**	**851.8**
LIS ORY	850.99	837.8
ORY LIS	851.46	865.81
ITALY & CROATIA	**974.08**	**974.58**
LIS MXP	960.33	940.71
MXP LIS	987.83	1,008.44

LOAD FACTOR	**319**	**320**
MAINLAND	58%	51%
LIS OPO	57%	50%
OPO LIS	60%	52%
SWITZERLAND	73%	67%

GVA LIS	72%	67%
LIS GVA	74%	67%
FRANCE	76%	73%
LIS ORY	76%	73%
ORY LIS	75%	73%
ITALY & CROATIA	70%	68%
LIS MXP	69%	69%
MXP LIS	71%	67%

Number of movements	**319**	**320**
MAINLAND	**2,120**	**1,179**
LIS OPO	1,049	596
OPO LIS	1,071	583
SWITZERLAND	**984**	**698**
GVA LIS	492	349
LIS GVA	492	349
FRANCE	**1,966**	**2,133**
LIS ORY	991	1,058
ORY LIS	975	1,075
ITALY & CROATIA	**394**	**896**
LIS MXP	197	448
MXP LIS	197	448

Fuel burned (avg) (kg)	**319**	**320**
MAINLAND	**1,590**	**1,657**
LIS OPO	1,589	1,649
OPO LIS	1,591	1,665
SWITZERLAND	**5,214**	**5,440**
GVA LIS	5,394	5,560
LIS GVA	5,037	5,323
FRANCE	**5,147**	**5,429**
LIS ORY	5,084	5,337
ORY LIS	5,210	5,520
ITALY & CROATIA	**5,674**	**5,987**
LIS MXP	5,378	5,733
MXP LIS	5,977	6,242

Annex 4-TAP operational data for routes selected.

Annex 5

			g/kg fuel		
CFM Internationa	Maximum rated aoutput (kN)	HC at idle	CO at idle	Nox at idle	Fuel flow (kg /sec) at idle
CFM56-5B5/P	97.89	6.20	30.00	3.80	0.094
CFM56-5B6/2P	104.5	4.6	44.8	3.6	0.11
CFM56-5B6/P	104.53	5.50	27.70	4.00	0.097
CFM56-5B5/3	97.9	3.55	41.77	3.81	0.092
CFM56-5B4/P	120.11	4.60	23.40	4.30	0.104
CFM56-5B4/2P	120.1	3.6	40.1	3.9	0.12
CFM56-5B4/3	120.1	1.92	32.07	4.22	0.102

Annex 5-Engines from TAP fleet idle characteristics (ICAO 2015a)

Annex 6

ICAO	IATA	Airport Name	Mean TXO (mins)	Standard Deviation	10th Pctl	Median	90th Pctl
LSGG	GVA	Geneva	11	4	7	10	16
LPPT	LIS	Lisbon	13	5	8	12	19
LIMC	MXP	Milan/Malpensa	13	4	8	12	18
LFPO	ORY	Paris/Orly	11	4	8	11	16
LPPR	OPO	Porto	11	4	7	10	17

ICAO	IATA	Airport Name	Mean TXI (Mins)	Standard Deviation	10th Pctl	Median	90th Pctl
LSGG	GVA	Geneva	4	2	2	3	5
LPPT	LIS	Lisbon	5	2	4	5	7
LIMC	MXP	Milan/Malpensa	5	2	3	5	8
LFPO	ORY	Paris/Orly	6	3	3	5	9
LPPR	OPO	Porto	5	2	3	5	7

Annex 6- Taxiing times for airports considered(EUROCONTROL 2015)

Annex 7

Engine Identification	**LTO HC (g)**	**LTO CO (g)**	**LTO NOx (g)**	**LTO cycle Fuel (kg)**
CFM56-5B6/2	630	10842	3158	400
CFM56-5B5/P	980	4743	3732	344
CFM56-5B6/2P	849	10205	3020	394
CFM56-5B5/3	520	6343	3047	343
CFM56-5B4/P	818	4123	5641	408
CFM56-5B4/2P	1136	10400	3847	442
CFM56-5B4/3	314	5386	4511	407

Annex 7-Engines from TAP fleet LTO cycle standard emissions

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