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MEASURES FOR IMPROVING FUEL EFFICIENCY BY IMPLEMENTING ELECTRIC TAXI SYSTEM

GRADUATE THESIS

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Assignment description:

In the first part of the thesis give the overview of various means of efficient fuel use. Present the importance of sustainable development and fuel efficiency programmes for air carriers and describe the fuel efficiency measures currently used in the aviation industry. In the main part of the thesis explore the possibilities of electric taxi systems and analyse the effect of electric taxi implementation on landing gear structure, maintenance procedures, centre of gravity position, main engine performance and air carrier operational procedures. Develop a mathematical model for the analysis of the effect of electric taxi implementation on fuel consumption and aircraft gas emissions. In the final part make a conclusion and a suggestion for future research.

Assignment presented to applicant on:
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GRADUATE THESIS

MEASURES FOR IMPROVING FUEL EFFICIENCY BY IMPLEMENTING ELECTRIC TAXI SYSTEM

MJERE ZA POBOLJŠANJE PROGRAMA UČINKOVITOG TROŠENJA GORIVA PRIMJENOM SUSTAVA ELEKTRIČNOG VOŽENJA

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MEASURES FOR IMPROVING FUEL EFFICIENCY BY IMPLEMENTING ELECTRIC TAXI SYSTEM

SUMMARY:

Aircraft gas emissions directly affect the Earth's ecosystem and human health. Environmental concerns have caused international treaties to be signed with the purpose of reducing gas emissions. Aircraft gas emissions are a direct result of fuel consumption. In order to comply with regulations, air carriers have developed and implemented fuel efficiency programmes which contain methods to reduce fuel consumption, thus gas emissions as well. Electric taxi is a new technology that can improve fuel efficiency and reduce gas emissions on the ground. There are currently two electric taxi systems in existence, but none of them has been granted certification for commercial use yet. A model was developed in the thesis to analyse the effect of electric taxi on fuel consumption and aircraft gas emissions. Using fuel consumption and taxi time data provided by Croatia Airlines it was found that electric taxi could save about 60% of fuel during taxi operations, and could reduce gas emissions by approximately the same amount, when compared to all-engine taxi.

KEYWORDS: electric taxi; fuel efficiency; fuel consumption; aircraft gas emissions

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MJERE ZA POBOLJŠANJE PROGRAMA UČINKOVITOG TROŠENJA GORIVA PRIMJENOM SUSTAVA ELEKTRIČNOG VOŽENJA

SAŽETAK:

Emisije plinova zrakoplova izravno utječu na Zemljin ekosustav i zdravlje ljudi. Ekološka pitanja uzrokovala su donošenje međunarodnih ugovora koji za svrhu imaju smanjenje emisija plinova. Emisije plinova zrakoplova izravna su posljedica potrošnje goriva. Kako bi udovoljili propisima, zrakoplovni prijevoznici razvili su i uveli programe učinkovitog trošenja goriva koji sadrže mjere za smanjenje potrošnje goriva i posljedično emisija plinova. Električno voženje je nova tehnologija koja može poboljšati učinkovitost trošenja goriva i smanjiti emisije plinova zrakoplova na zemlji. Trenutno postoje dva sustava električnog voženja, no nijedan od njih još nije certificiran za komercijalnu uporabu. U ovom je diplomskom radu razvijen model za analizu utjecaja električnog voženja na potrošnju goriva i emisije plinova zrakoplova. Koristeći podatke o potrošnji goriva i vremenima voženja koje je pružila Croatia Airlines utvrđeno je da bi električno voženje moglo uštedjeti oko 60% goriva tijekom voženja te bi moglo smanjiti emisije plinova zrakoplova za otprilike isti iznos, u usporedbi sa standardnim voženjem pomoću glavnih motora zrakoplova.

KLJUČNE RIJEČI: električno voženje; učinkovito trošenje goriva; potrošnja goriva; emisije plinova zrakoplova

CONTENTS

1. INTRODUCTION

Increasing awareness about the impact of aircraft emissions on the global ecosystem has caused the development of appropriate aviation regulations such as Volume II of the International Civil Aviation Organization (ICAO) Annex 16 – the main document that defines the requirements for aircraft engine emissions. The basic means of reduction of jet aircraft emissions, mainly carbon dioxide but also nitrogen and sulphur oxides and water vapour as well, is the reduction of fuel consumption.

Air carriers have recognized the fact that aircraft emissions are directly related to fuel consumption which is why most of them independently developed and implemented their own fuel efficiency programmes. The purpose of such programmes is not only to reduce fuel consumption but also to find different means for better and more efficient fuel use in aircraft operations. Fuel efficiency is loosely associated with the concept of sustainable development. Sustainable development implies efficiency and cost-effectiveness of a particular process or system, in this case air transport, without the harmful effects on public health and ecosystem.

This graduate thesis describes the concept of sustainable development and fuel efficiency in more detail, and provides an overview of the measures of fuel consumption reduction used by air carriers. The focus of the thesis is on a new category of savings – electric taxi – which is not yet used in commercial operations but could provide significant savings according to current indications. Electric taxi is a means of aircraft movement on the ground without the use of main engines. It uses landing gear mounted electric motors powered by the Auxiliary Power Unit (APU) for operation. The effect of electric taxi implementation on landing gear structure, maintenance procedures, centre of gravity position, main engine performance and air carrier operational procedures is described. The main goal was to analyse the effect of the implementation of electric taxi on fuel consumption and aircraft gas emissions.

In current practice, aircraft are being moved on the ground by tugs into positions for engine start, and afterwards they taxi using the power of their main engines. Multi-engine aircraft are able to taxi without thrust on one (for two-engine aircraft) or two engines (for four-engine aircraft). In that case, the engines that are not producing thrust are either set on idle thrust setting or are completely shut down. These procedures can provide reasonable fuel savings and emission reduction as was proven by V. Kumar,

L. Sherry and T. Thompson in their research *Analysis of Emissions Inventory for "Single-Engine Taxi-Out" Operations* conducted at George Mason University in Fairfax, Virginia, United States of America (USA). It is logical to conclude that electric taxi should provide even greater fuel savings considering the fact that the main engines are shut down during its operation.

The fact that not a single aircraft electric taxi system has been certified yet by either European Aviation Safety Agency (EASA) or the Federal Aviation Administration (FAA) proves that electric taxi is a relatively new concept. Research in this area is mostly limited to research conducted by manufacturers of these systems and their partners. An independent research conducted at the University of Delft in the Netherlands – *Aircraft Taxiing Strategy Optimization* by M.I. Ithnan, T. Selderbeek, W.W.A. Beelaerts van Blokland and G. Lodewijks – shows that aircraft electric taxi systems provide the greatest fuel savings and emission reduction in comparison with other methods of taxiing. On the 3rd and 4th of February 2015, in Miami, USA, more than 100 participants attended the world's first International Air Transport Association (IATA) Aircraft Taxiing Systems Conference, the subject of which were methods of alternative taxi.

The research on the possible effect of electric taxi implementation on fuel consumption and aircraft gas emissions was done in cooperation with Croatian national air carrier, Croatia Airlines, and with a manufacturer of one of the aircraft electric taxi systems, WheelTug plc, both of which provided the data necessary for the analysis.

The thesis is composed of seven chapters:

1. Introduction
2. Environmental Impact of Aviation
3. Fuel Efficiency Measures
4. Alternative Methods of Taxi
5. Model for the Analysis of the Effect of Electric Taxi Implementation on Fuel Consumption and Aircraft Gas Emissions
6. Data for the Model and Analysis of Model Results
7. Conclusion

After the introduction, the 2nd chapter presents the general environmental issues faced by today's aviation industry, and argues the importance of sustainable development and fuel efficiency programmes for air carriers and aviation industry as a whole. A historical overview of how these issues were realised to be important and the effect of aircraft gas emissions on the environment and human health is described as well.

The 3rd chapter describes the fuel efficiency measures currently used in the aviation industry in an effort to reduce fuel consumption and aircraft gas emissions. An overview of some of the alternative fuel efficiency measures, such as aviation biofuel and nanotechnology coatings which are not widely used and are still being tested, is also given.

The 4th chapter focuses on a new fuel efficiency method, alternative taxi, which includes taxiing powered by tugs and electric taxi. One of the electric taxi systems, WheelTug, is described in more detail because it is currently considered to be the closest to commercial use. General advantages of electric taxi systems are given as well.

The 5th chapter defines the mathematical model which was used to analyse the effect of electric taxi on fuel consumption and aircraft gas emissions.

Chapter 6 lists the input data provided by Croatia Airlines, which was used in the analysis. Results of the analysis are also presented in this chapter.

Finally, the last chapter gives the conclusions made according to the analysis and presents recommendations for possible future research.

2. ENVIRONMENTAL IMPACT OF AVIATION

Aviation, especially commercial passenger aviation, has been developing rapidly since the end of the Second World War. The main aspiration of the development, the bulk of which was done with little care about the environment, was to build faster and bigger aircraft that could transport more people in a shorter amount of time. Aviation is currently responsible for about 2% of global gas emissions.[1]

2.1. A HISTORICAL OVERVIEW OF ENVIRONMENTAL AWARENESS

Environmental movement in the post-war world resurfaced in the sixties, after the publication of the book *Silent Spring* by biologist Rachel Carson in 1962. The book discussed the impacts of the spraying of pesticide DDT (dichlorodiphenyltrichloroethane) and how it entered the food chain and fatty tissues of animals, including humans, and caused cancer and other genetic damage. Ultimately, the book described how by deliberately releasing chemicals into the environment without fully understanding their effects could do harm to the entire world's ecosystem.[2] The same thing is happening today. Humans are releasing huge amounts of gases into the atmosphere that have been proven to have a negative effect on the environment and human health. Although Carson's book was directed at a specific problem, it produced a significant impact on human perception of the environment. The world began to perceive environmental protection as a growing issue, especially after the first images of the Earth taken from the Moon were televised in 1969. Seeing the Earth as a *big blue marble* drifting in the vastness of space started the slow process of changing the collective consciousness of the world.[3]

In the wake of these events, the United Nations called for a Conference on Human Environment that was held in Stockholm, Sweden, in June 1972. The Conference was concluded with unprecedented principles which now form the basis of modern environmentalism. One of the principles says:

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[1] *Facts & Figures* [Internet]. 2014 [updated April 2014; cited 14 September 2015]. Available from: http://www.atag.org/facts-and-figures.html

[2] *The Story of Silent Spring* [Internet]. 2013 [updated 2013 May 12; cited 2015 September 06]. Available from: http://www.nrdc.org/health/pesticides/hcarson.asp

[3] *Environment* [Internet]. 2015 [cited 2015 September 06]. Available from: http://www.un.org/en/globalissues/environment/

"A point has been reached in history when we must shape our actions throughout the world with a more prudent care for their environmental consequences. Through ignorance or indifference we can do massive and irreversible harm to the earthly environment on which our life and wellbeing depend. Conversely, through fuller knowledge and wiser action, we can achieve for ourselves and our posterity a better life in an environment more in keeping with human needs and hopes. (...) To defend and improve the human environment for present and future generations has become an imperative goal for mankind – a goal to be pursued together with, and in harmony with, the established and fundamental goals of peace and of worldwide economic and social development."[4]

The last sentence of the principle was further elaborated after the United Nations invited doctor Gro Harlem Bruntland to establish a World Commission on Environment and Development in 1983. Bruntland and her associates published a report titled *Our Common Future* in 1987. This report featured what is now known as the most widely recognised definition of a concept known as sustainable development:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[5]

There have been many other attempts to define sustainable development more precisely. In general, sustainable development implies efficiency and cost-effectiveness of a particular process or system without the harmful effects on public health and ecosystem. Furthermore, it entails the use of renewable energy sources slower than the rate of their regeneration, and more efficient use of non-renewable energy sources.

Aviation depends on derivatives of oil which is a non-renewable source of energy. Burning oil and its derivatives produces gases which are harmful to the Earth's ecosystem and human health. This, of course, is not only constrained to aviation, but aviation is considered to be the most ineffective in terms of gas emissions per passenger, although this heavily depends on the percentage occupancy of a mode of transport.[6] The dangers

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[4] *Declaration of the United Nations Conference on Human Environment* [Internet]. 1972 June 16 [cited 2015 September 06]. Available from: http://www.unep.org/Documents.Multilingual/Default.asp?documentid=97&articleid=1503

[5] *Environment* [Internet]. 2015 [cited 2015 September 06]. Available from: http://www.un.org/en/globalissues/environment/

[6] Borken-Kleefeld J, Fuglestvedt J, Berntsen T. *Mode, Load, and Specific Climate Impact from Passenger Trips*. Environmental Science and Technology [Internet]. 2013 June 26 [cited 2015 September 06]. 47:7608–7614. Available from: http://pubs.acs.org/doi/abs/10.1021/es4003718

greenhouse gasses pose was recognised in the late 20th century. In 1997, the United Nations called for an international treaty to be signed with the purpose of reducing greenhouse gas emissions. A previous conference held in 1992 in Rio de Janeiro known as the Earth Summit concluded that greenhouse gas emissions need to be reduced but it was not legally binding. The treaty from 1997 is known as the Kyoto protocol and concludes that global warming exists and that man-made carbon dioxide emissions caused it. Countries that ratified the Protocol are obligated to develop means of reducing greenhouse gas emissions.

First global regulations that regulated aircraft engine emissions came in the form of an annex to the Convention on International Civil Aviation titled Annex 16: Environmental Protection. Particularly, Volume II of the Annex limits aircraft engine emissions and prohibits intentional venting of raw fuel to the atmosphere.[7] Putting a limit on aircraft engine emissions resulted in new technological improvements and production of more efficient aircraft engines. Technological improvements alone, however, were determined not to be enough to prevent the increase of greenhouse gases.

This is why emissions trading systems were established locally in certain regions of the world, the largest one of which is the European Union Emissions Trading System (EU ETS), also known as European Union Emissions Trading Scheme, established in 2005. The basic concept of such systems is to limit overall emissions of certain gases. In the case of EU ETS the gas is carbon dioxide. Companies operating in the European Union (EU) are under certain terms obligated to make accurate measurements of their emissions for a certain period of time, usually a year, and according to their measurements they have to buy and then surrender so-called *allowances* for carbon emissions after the period has ended. One allowance is equal to one tonne of carbon dioxide. If a company buys more allowances than the amount of their emissions they are allowed to sell their excess allowances to other companies that might need them. This is basically how companies are stimulated to reduce their emissions. If a company doesn't surrender enough allowances for their emissions then it is required to pay certain penalties. Therefore, EU ETS and similar emissions trading systems aim to stimulate companies to reduce gas emissions by financial means. Aviation has been included in the EU ETS system since 2010 but the actual trading started in 2012 and currently applies to both EU and non-EU air carriers,

[7] *Annex 16 to the Convention on International Civil Aviation: Environmental Protection*. 3rd ed. ICAO; 2008.

only to flights within the European Economic Area (EEA), which includes European Union, Iceland, Liechtenstein and Norway.

Although EU ETS has so far been successful in Europe, it is becoming apparent that a global emissions trading system is needed to slow and to eventually stop the increase of aviation carbon dioxide emissions worldwide. IATA has set up an ambitious goals to reduce carbon dioxide emissions. By 2050 they aim to reduce emissions to 50% of the 2005 levels.[8] Currently that goal seems overly ambitious and it remains to be seen how and if it will be achieved. A global emissions trading system could increase the chances of reaching the goal. After being pressured by the EU for several years, ICAO has agreed to develop a global emissions trading system to address international aviation emissions by 2016 and to have it implemented by 2020.[9] This agreement between ICAO and the EU is the reason why EU ETS currently does not apply to flights that originate in EEA or have an EEA destination, which is how the regulation was originally imagined. If no global measures for emission reduction are presented on the 2016 ICAO Assembly, EU ETS will be amended to include flights to and from the EEA.

2.2. EFFECT OF AIRCRAFT GAS EMISSIONS ON THE ENVIRONMENT AND HUMAN HEALTH

Reducing greenhouse gas emissions is important because global warming will cause extreme climate change if nothing is done to prevent it. One of the effects of global warming is sea level rise. Sea levels have already risen by an average of 7 cm globally since 1992 according to National Aeronautics and Space Administration (NASA) but the rate of sea level rise is expected to increase because the planet is constantly getting warmer and its glaciers and ice sheets are slowly melting away to the seas.[10] The sea level rise could affect up to 40% of global human population.[11]

Global warming is caused because solar energy gets trapped inside the Earth's atmosphere by so-called greenhouse gases instead of being emitted back into space and

[8] *Climate Change* [Internet]. 2015 [cited 2015 September 06]. Available from: https://www.iata.org/policy/environment/pages/climate-change.aspx
[9] *Reducing emissions from aviation* [Internet]. 2015 [updated 2015 September 03; cited 2015 September 06]. Available from: http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm
[10] Griggs MB. *NASA: Sea Level Rise is going to Get Much Worse* [Internet]. 2015 [updated 2015 August 28; cited 2015 September 06]. Available from: http://www.popsci.com/nasa-sea-level-rise-going-get-much-worse
[11] *Sea Level* [Internet]. 2015 [cited 2015 September 06]. Available from: http://www.climatehotmap.org/global-warming-effects/sea-level.html

thus heats up the planet. The most significant greenhouse gases are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Since this thesis is mainly concerned with reduction of jet aircraft engine emissions during taxi, only the effects of the gases measured in the ICAO Airport Air Quality Manual will be described. These gases are carbon dioxide (CO_2), unburned hydrocarbons (HC), mono-nitrogen oxides (NO_x), carbon monoxide (CO) and sulphur dioxide (SO_2).

Carbon dioxide is a greenhouse gas that contributes to global warming. Human exposure to low levels of carbon dioxide (less than 10%) can cause hyperventilation, high blood pressure, lung congestion, vision damage, shortness of breath, abrupt muscle contractions, central nervous system injury, dizziness, headache, sweating, fatigue, memory loss, nausea, depression, confusion, skin and eye burns, and ringing in the ears. Exposure to high levels of carbon dioxide (more than 10%) can cause death, unconsciousness, convulsions and damage to developing foetus.[12]

Hydrocarbons include a wide range of chemical compounds, including methane which is a greenhouse gas. Hydrocarbons can react with nitrogen oxides in presence of sunlight to form ozone (O_3) which also has an adverse effect on human health and is the main ingredient in ground-level smog. Effects of hydrocarbons on human health depend on type of compound, level and length of exposure. Short-term exposure can cause irritation of eyes and respiratory tract, dizziness, headaches, visual disorders, fatigue, loss of coordination, allergic skin reactions, nausea, and memory impairment. Long-term exposure is more serious and can cause damage to the liver, kidneys, and central nervous system.[13]

Mono-nitrogen oxides react with precipitation and other substances in the atmosphere and form acid rains. Exposure to low levels of nitrogen oxides can cause irritation of eyes, nose, throat and lungs, coughing, fatigue, shortness of breath and nausea. Exposure to high levels can cause serious respiratory problems, damage to lung tissue and reduction in lung function.[14]

Carbon monoxide is not a greenhouse gas but its presence affects the concentration of other greenhouse gases. By reacting with hydroxyl radical (OH) it forms

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[12] *Carbon Dioxide* [Internet]. 2015 [updated 2015 April 21; cited 2015 September 06]. Available from: http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=6
[13] *Volatile Organic Compounds* [Internet]. 2015 [updated 2015 May 13; cited 2015 September 06]. Available from: http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=31
[14] *Nitrogen Oxides* [Internet]. 2015 [updated 2015 September 08; cited 2015 September 08]. Available from: http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=19

carbon dioxide. This process also increases the amount of methane because methane is removed from the atmosphere by reactions with OH.[15] Carbon monoxide therefore has an important indirect effect on the environment. In humans, exposure to very high levels can cause convulsions, coma and death. Exposure to high levels causes impaired vision and coordination, dizziness, headaches, confusion and nausea. Pregnant women are also susceptible to miscarriage or have an increased risk of damage to foetus. Exposure to low levels can cause heart disease and damage to nervous system.[16]

Sulphur dioxide also reacts with precipitation and other atmospheric substances to form acid rain. In humans, short term exposure can cause stomach pain, menstrual disorders, watery eyes, loss of smell, headache, nausea, fever, irritation to the nose, throat and lungs, coughing and shortness of breath. Long term exposure can cause chronic bronchitis, emphysema and respiratory illnesses.[17]

2.3. SUSTAINABLE DEVELOPMENT AND FUEL EFFICIENCY

Previous subchapters described the problems arising from gas emissions and means to combat them on a global level. Definitions of sustainable development are also applicable on a more local level. Many air carriers define and implement their own sustainable development policies. Sustainable development does not only mean caring about the impact of air carrier's operations on the environment. A general goal for an air carrier would be to achieve economic sustainability and increase passenger satisfaction while caring responsibly about the environment.

The hardest part of it all is to reduce the environmental impact caused by burning jet fuel because it is the only source of energy that aviation depends on. For this purpose, air carriers have developed fuel efficiency programmes. The premise of such programmes is that through implementation of certain measures the environmental impact of burning jet fuel could be lowered. The following chapter deals entirely with existing fuel efficiency measures and describes how they could be implemented to decrease fuel consumption

[15] *Carbon Monoxide: Its Environmental Impact* [Internet]. 2010 [updated 2010 October 23; cited 2015 September 06]. Available from: http://esseacourses.strategies.org/module.php?module_id=170
[16] *Carbon Monoxide* [Internet]. 2015 [updated 2015 April 21; cited 2015 September 06]. Available from: http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=7
[17] *Sulphur Dioxide* [Internet]. 2015 [updated 2015 September 08; cited 2015 September 08]. Available from: http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=29

and consequently gas emissions i.e. environmental impact. To avoid repeating, whenever the term fuel consumption is used, it implies gas emissions as well. For example, a high fuel consumption implies an increase of gas emissions, while lower fuel consumption implies lower gas emissions as well.

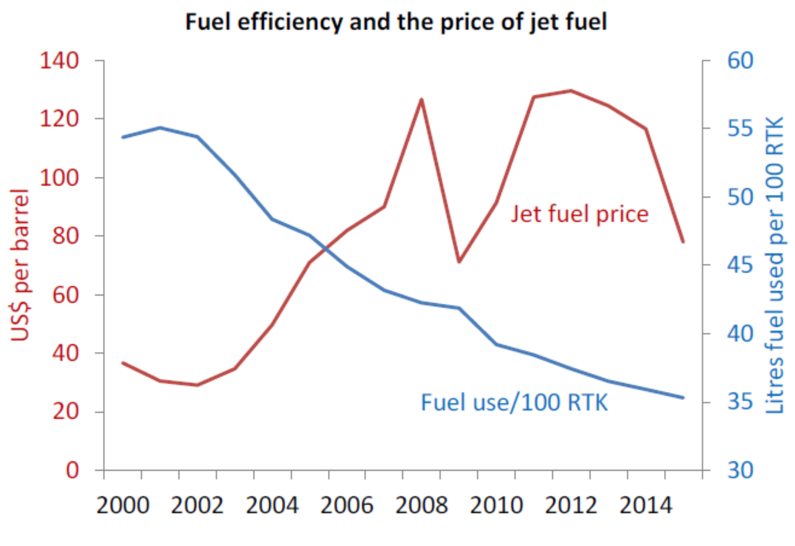
3. FUEL EFFICIENCY MEASURES

This chapter describes fuel efficiency measures, some of which are widely used across the aviation industry. The main purpose of these measures is to reduce fuel consumption, which is beneficial both in the financial aspect for air carriers and overall for the environment. Before proceeding with a description of the existing measures for fuel efficiency, a brief overview of how jet fuel prices might affect fuel efficiency is given.

3.1. CONNECTION BETWEEN JET FUEL PRICES AND FUEL EFFICIENCY

Fuel alone is the largest operating cost for air carriers and it therefore provides the greatest saving possibilities. According to IATA, fuel costs made up 28.1% of operating costs in June 2015. This is a slight decrease compared to previous years in which fuel was making up about 33% of operating costs. This decrease is due to a significant fall in jet fuel prices. IATA's report was based on oil price of 78 United States (US) dollars per barrel, which is 33.1% lower than the 2014 price.[18]

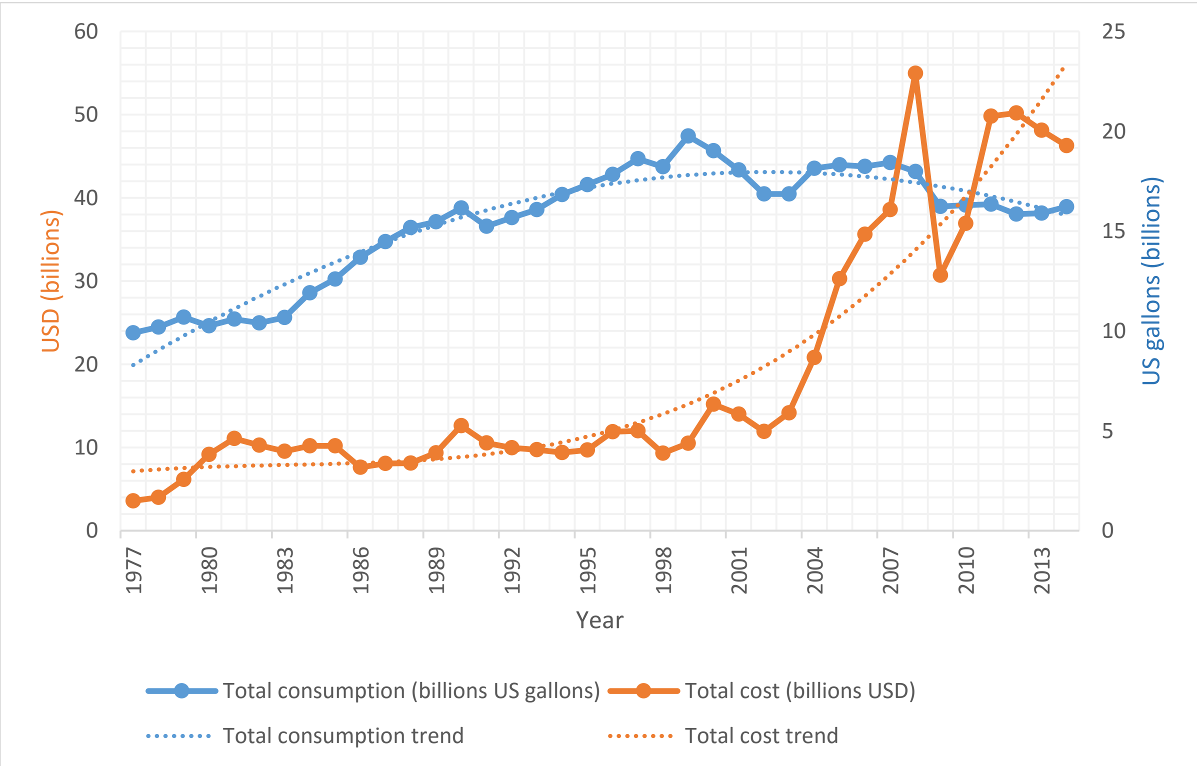
IATA's report also indicates an interesting trend regarding fuel efficiency. As shown in Graph 1, it can be observed that air carrier fuel use tends to fall during periods of high fuel prices, while it tends to be high during periods of low fuel prices.



Graph 1. Fuel use compared to jet fuel price[19]

[18] IATA. Economic Performance of the Airline Industry. IATA; 2015 June 05. p. 4
[19] Ibid. Graph from original source, *Fuel efficiency and the price of jet fuel*. p. 4

In order to support this claim, data from the United States Department of Transportation was obtained to construct a similar graph over a larger period of time. Although the same variables as used in the IATA graph were not obtainable, total consumption expressed in US gallons was used instead of fuel use per 100 revenue ton kilometres, and total fuel cost expressed in US dollars instead of jet fuel price. Graph 2 shows the new graph and it can clearly be seen that the data is relatable to the data used by IATA in Graph 1. Graph 2 represents total fuel consumption and total fuel cost for all US air carriers from 1977 to 2014. This graph was previously published in an article by the author of this thesis, Dino Švragulja, and Anita Domitrović, titled *Review of Aircraft Fuel Efficiency Measures,* and submitted to the 13th Scientific Conference Science and Transport Development – ZIRP 2015. Although data for mid-2015 is available it was excluded in this analysis because it is incomplete compared to other years.



Graph 2. Total fuel consumption and total fuel expenses of all US air carriers[20]

[20] Švragulja D, Domitrović A. *Review of Aircraft Fuel Efficiency Measures*. In: Ščukanec A, Babić D, editors. Science and Transport Development; 2015 May 12; Zagreb. Zagreb: Faculty of Transport and Traffic Sciences; 2015. Graph from original source, Total fuel consumption and total fuel expenses of all US airlines. p. 217

Differences between total fuel consumption in Graph 2 and fuel use per 100 revenue ton kilometres are firstly because of the differences in the very definition of the variables, and secondly because of the different source of data. Since only ten United States air carriers are members of IATA, Graph 2 shows that the aforementioned claim, that fuel efficiency increases during periods of high fuel prices and vice versa, is valid. In the graph, a steady rise in fuel consumption can be observed from the 1970s until the peak in 1999. During that period, jet fuel prices were relatively low and stable. On a micro scale, certain jumps in fuel prices, such as in year 1990, caused a drop in fuel consumption the next year. Other periods confirm this as well, for example a rise in prices from 1979 until 1981 caused a stagnation in fuel consumption. However, Graph 2 also shows two anomalies that do not support the claim. The two anomalies can be observed in years 2002 and 2009. Fuel prices dropped in 2002 compared to previous years but fuel consumption continued falling as well. This can be attributed to the decrease in air travel following the terrorist attacks on New York and Washington D.C. in 2001. During 2008 the fuel prices peaked and subsequently plummeted significantly by late 2008. From 2009 the prices began rising again. Graph 2 shows a drop in fuel consumption during that time which can be explained with the inability of the industry to quickly adapt to the new prices and the fact that higher fuel prices in the coming years were probably already predicted. Moreover, air carriers, especially the large ones, often practice fuel hedging. Fuel hedging is a strategy in which air carriers take up a financial position on how much they are willing to pay for fuel based on predictions, thus effectively protecting themselves if the prices rise above the hedged price. The sudden fuel price drop of 2008 caught many by surprise. Ryanair, for example, lost 169 million euros because it had to pay a hedged price of 124 US dollars per barrel while the actual prices were as low as 32 US dollars per barrel.[21] This is probably one of the reasons why fuel consumption was low during the period of low prices.

Total fuel consumption might not be the best indicator for fuel efficiency because it is expected to increase over time with the increase of overall air traffic, but its indications are nonetheless valuable. It shows that even with the increase in air traffic since the beginning of the 21st century, fuel consumption is slowly decreasing, meaning

[21] Rowling R. *European Airlines Cut Jet Fuel Hedging as Prices Fall* [Internet]. 2014 [updated 2014 August 14; cited 2015 June 20]. Available from: http://www.bloomberg.com/news/articles/2014-08-13/european-airlines-cut-jet-fuel-hedging-as-prices-fall

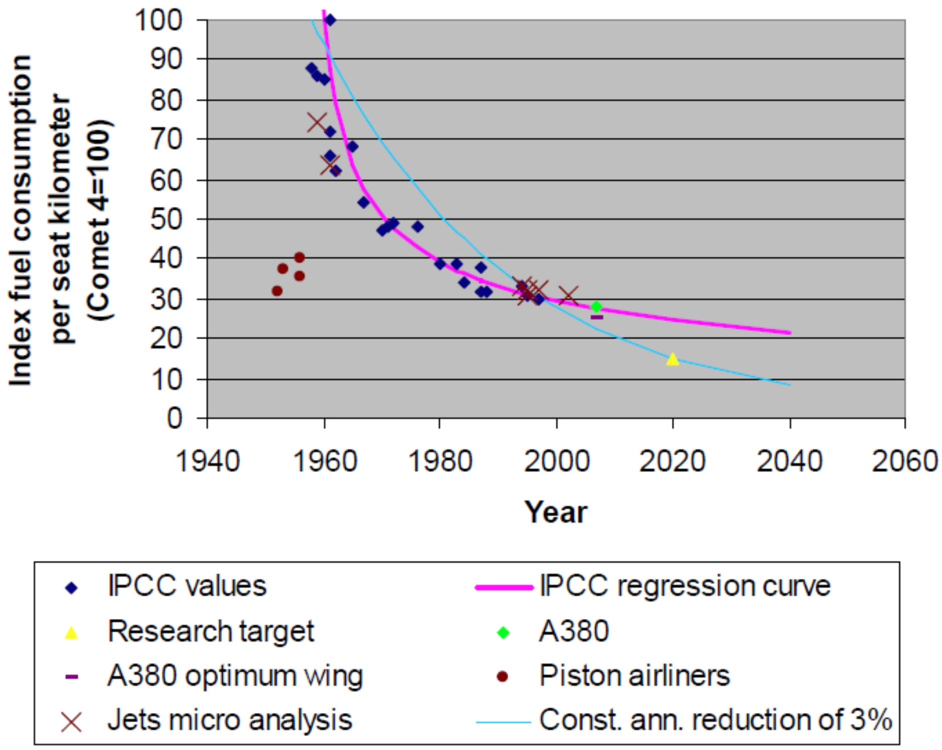
the overall fuel efficiency has increased during that time. The fact that fuel prices seem to be the main incentive for this trend is somewhat disappointing. Although the financial aspect can't be ignored, the main reason for improving fuel efficiency should be sustainable development of air carriers, because with the increasing fuel prices and new environmental protection laws, only those air carriers that can adapt to the new situation will be able to survive. Currently, the ecological compensations and penalties in the European Union's ETS are still somewhat low and acceptable. Higher costs could be an incentive for air carriers to work harder to achieve sustainable development, and consequently better fuel efficiency. The fact that EU ETS currently applies only to flights within the EEA remains to be a problem.

3.2. EXISTING FUEL EFFICIENCY MEASURES

While some might argue that reducing fuel consumption can best be done by simply reducing the number of destinations an air carrier flies to, this is not the goal of fuel efficiency programmes. The goal is to efficiently spend fuel which means that an air carrier should offer the same amount of destinations and services but at the same time have a reduced overall fuel consumption. Aviation industry has developed fuel efficiency measures extensively since the dawn of commercial jet aviation in the 1950s. According to Peeters et al., overall energy consumption per available seat kilometre fell by 43% in the period between 1960 and 2000.[22] An interesting thing to note is that this improvement is valid only when comparing jet aircraft fuel efficiency. One of the conclusions by Peeters et al. was that the last piston-engine aircraft used for commercial air transport in the 1950s have almost the same fuel efficiency as typical jet aircraft used today. This means that the fuel efficiency in general suffered a major setback in transition from piston to jet-powered aircraft and only since the late 20th century have the same levels of fuel efficiency as those of piston-powered aircraft in the mid-1950s been reached. Graph 3 shows the fuel efficiency of jet aircraft since the 1960s. Blue dots represent fuel efficiency of specific aircraft as calculated by the Intergovernmental Panel on Climate Change (IPCC). Fuel efficiency of piston-powered aircraft is represented by brown dots. The Graph clearly shows that modern aircraft, such as the Airbus A380, represented by a

[22] Peeters PM, Middel J, Hoolhorst A. *Fuel Efficiency of Commercial Aircraft*. National Aerospace Laboratory NLR; 2005 November. p. 25

green dot, have only marginally improved fuel efficiency compared to piston-powered aircraft of the mid-1950s.



Graph 3. Fuel efficiency of jet aircraft, compared to piston-powered aircraft of the 1950s[23]

Peeters et al. did not consider the Airbus A350 and Boeing B787 aircraft in their research because at the time these aircraft were still in development phase. It is believed, however, that these aircraft are the most fuel efficient jet aircraft of today.

Considerations presented in the previous paragraph show the importance of improving fuel efficiency. This subchapter describes some of the most common fuel efficiency measures used today. Generally, the measures can be divided into five areas:

- Flight Planning, Dispatch and Operational Control
- Ground Operations
- Flight Operations
- Maintenance and Engineering
- In-Flight Activities

[23] Peeters PM, Middel J, Hoolhorst A. *Fuel Efficiency of Commercial Aircraft*. National Aerospace Laboratory NLR; 2005 November. Graph from original source, Fuel efficiency jet aircraft. p. 24

3.2.1. FLIGHT PLANNING, DISPATCH AND OPERATIONAL CONTROL

Flight planning, dispatch and operational control play an important role in fuel conservation. If done scrupulously, flight planning can predict almost an exact amount of fuel that will be spent for a particular flight. Of course, there will always be unpredictable deviations which are usually the consequence of changing weather conditions or current air traffic situation.

The total amount of fuel needed to carry out a flight is defined by national law, based on standards and recommended practices of the ICAO Annex 6: *Operation of Aircraft* which state that a flight shall not be commenced unless an aircraft carries sufficient fuel and oil to safely complete the flight.[24] Basically, fuel loaded onto an aircraft for a particular flight can be divided into:

- Taxi fuel
- Trip fuel
- Contingency fuel
- Alternate fuel
- Final reserve fuel
- Additional fuel
- Extra fuel

ICAO Annex 6 does not designate amounts of fuel in this way, but rather defines them in a more legal manner. For simplification the regulation is explained in terms of fuel amounts listed above.

Possible savings regarding taxi fuel, which is fuel necessary to manoeuvre the aircraft on the ground of the departure airport from its stand to the take-off runway[25], will be discussed later in more detail. Planned taxi fuel therefore refers only to taxi-out procedure – moving the aircraft from its stand to the take-off runway on departure. Taxi-in procedure is the opposite – moving the aircraft from the landing runway to the stand on arrival. In general, a flight planning office could allocate less fuel for taxi if it is known in advance that the crew will be using a single-engine taxi procedure or an alternative way of taxiing. This is, however, very difficult to predict as it often depends on

[24] *Annex 6 to the Convention on International Civil Aviation: Operation of Aircraft*. 9th ed. ICAO; 2010.
[25] *Flight Planning*. 6th ed. Nordian AS; 2010. Ch. 3. p. 1

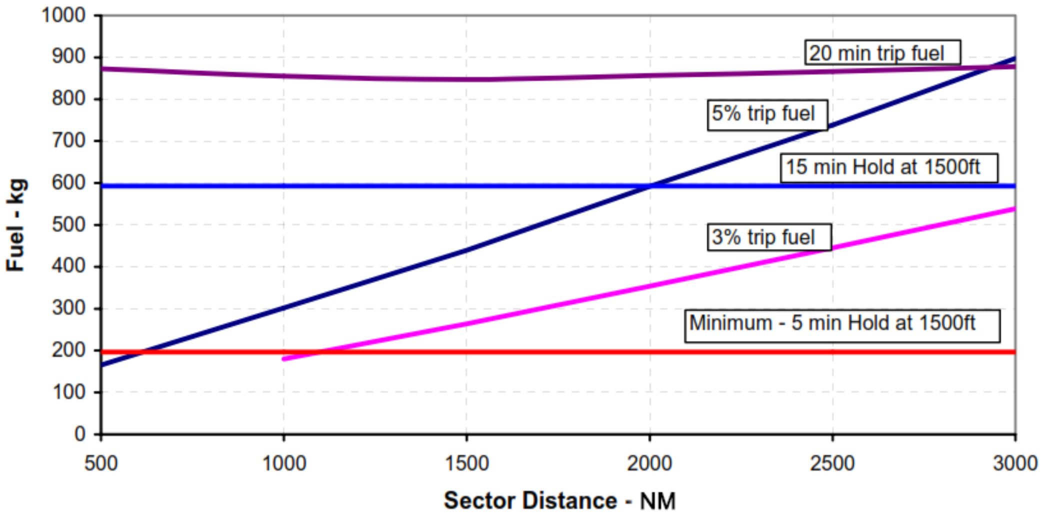
the current situation in which an aircraft is and the decisions of the crew, because single-engine taxi procedures are usually only recommended, and not mandatory.

Trip fuel is the amount of fuel required for all phases of flight from take-off at the airport of departure, to landing at a destination airport. By taking into consideration all of the possible conditions a flight will be in, fuel necessary for the flight could be planned in great detail. This means that an air carrier should be able to obtain data about weather and air traffic conditions, to account, for example, for expected re-routings. Modern flight planning systems make that possible. Another thing that can greatly improve flight planning is aircraft performance monitoring. Other than the fact that it can help air carriers to self-diagnose problems on board their aircraft, it also provides data which allows for more precise flight planning. This could have an effect on crews, more particularly, on the commander of the aircraft, who makes the decision about whether or not to carry extra fuel and exactly how much of it to carry, as explained in the next paragraph.

Planned fuel for each flight should have additions due to possible deviations because of reasons such as adverse weather or air traffic delays. If the commander thinks that the planned fuel might not be enough to conduct a particular flight, he or she can decide to load extra fuel onto the aircraft. Commanders usually make their decisions based on previous experience. This would mean that fuel necessary for a flight had been predicted imprecisely many times in the past. Having a flight planning office that can predict necessary fuel very precisely could restore the crews' trust in flight planning. This could influence the commander's decision on extra fuel in a way that less or absolutely no extra fuel is carried. The decision to carry less or no extra fuel should not be forced onto the crews, but it should rather come as a natural decision, as trust in flight planning is gradually restored.

Some might argue that extra fuel, along with some other fuel amounts such as contingency, alternate, final reserve and additional fuel, are not actually used during normal operations and therefore do not influence fuel consumption. While the first part of that statement is correct, the second one is wrong. Fuel consumption is affected by the mass of the aircraft. An aircraft with a higher mass burns fuel at a higher rate than an aircraft with a lower mass, and in this process it also produces more gas emissions.[26] Therefore, simply having unnecessary mass on board the aircraft has a negative effect on fuel consumption. This presents a very important consideration in fuel efficiency programmes and flight planning.

Contingency fuel is the greater of two of the following quantities: 5% of planned trip fuel, or fuel required for a 5 minute holding at holding speed at 1500 feet above the destination aerodrome. These two are the main definitions of contingency fuel for all aircraft but there are others that can be used instead of the former one. The 5% trip fuel requirement can be replaced by either 3% trip fuel requirement, fuel required for 20 minutes flying time based on planned trip fuel consumption, or fuel required for 15 minute holding at holding speed at 1500 feet above the destination aerodrome.[27] These alternative ways of defining contingency fuel require airworthiness approval and in the case of 20 minute fuel requirement also require a fuel consumption monitoring programme for individual aircraft to be implemented by the air carrier. Graph 4 shows how different definitions of contingency fuel affect the amount of it in relation to sector distance for an Airbus A320-214 aircraft.



Graph 4. Amount of contingency fuel needed for a particular flight in relation to sector length and different contingency fuel definitions[28]

[26] Švragulja D, Domitrović A. *Review of Aircraft Fuel Efficiency Measures*. In: Ščukanec A, Babić D, editors. Science and Transport Development; 2015 May 12; Zagreb. Zagreb: Faculty of Transport and Traffic Sciences; 2015. p. 213

[27] *Flight Planning*. 6th ed. Nordian AS; 2010. Ch. 3. p. 2,3

[28] *Getting to Grips with Fuel Economy*. 4th ed. Airbus; 2004 October. p. 15

Take for example an aircraft flying a 1500 nautical mile (NM) sector distance. According to the graph, the greater amount of the main two definitions of contingency fuel is the 5% trip fuel. If this condition is used for flight planning, approximately 430 kg of contingency fuel are required for this flight. But if an air carrier can obtain airworthiness approval to define the contingency fuel as 3% of trip fuel only 270 kg will be necessary. This means that the air carrier is able to carry 160 kg of fuel less per flight just by defining the contingency fuel differently. In addition to these basic savings, the fact that the aircraft has a lower mass causes a decrease in total fuel consumption. As mentioned earlier, a higher mass increases fuel consumption, while a lower one decreases it. Exactly how much fuel consumption is affected by mass is shown by a factor known as *cost of weight.* The term *weight* here is equivalent to *mass*. Historically, the value of cost of weight in the aviation industry has been about 4%. That means, for example, that an increase of 500 kg in aircraft landing mass burns an extra 20 kg of fuel per flight hour.[29] On a yearly basis this increase becomes significant. If a one-hour flight that's carrying an additional 500 kg of payload is conducted 4 times a day and 4 times a week, after one year it will have burned additional 16 640 kg of fuel as compared to a flight that's not carrying the additional payload. The savings can therefore be significant but it is hard to predict the exact values because it is not always possible to precisely calculate the mass of an aircraft.

Alternate fuel is the amount of fuel which should be sufficient to perform a successful missed approach at destination airport, then to climb to alternate cruising altitude and to cruise until the top of descent for an alternate airport, then to descend and execute an approach and landing at the alternate airport.[30] Alternate fuel could be minimized by choosing alternate airports which are nearer to the destination airport. This, however, might not always be possible due to primarily safety reasons, but financial and logistical reasons as well. The cheapest alternate from a fuel perspective might not always be the cheapest from a logistical and other operating costs perspective. Because of that, savings in this area are limited.

Final reserve fuel for jet aircraft is the fuel required to fly for 30 minutes at holding speed at 1500 feet above airport elevation in standard conditions and is calculated according to the estimated mass on arrival at the airport.[31] Some air carriers also define a

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[29] Denuwelaere S. *A New Approach to Cost of Weight*. Aircraft IT Operations. 2012; 5:18-21.
[30] *Flight Planning*. 6th ed. Nordian AS; 2010. Ch. 3. p. 3
[31] Ibid. Ch. 3. p. 3

specific minimum amount of final reserve fuel. The amount carried is then the larger of the two defined. From the definition it is evident that the only way to achieve savings in this area is to have a lower mass on arrival. A lower mass means reduced fuel consumption which means that the amount of final reserve fuel will be less.

Additional fuel is only required if other fuel amounts won't be sufficient to allow an aircraft to hold for 15 minutes at 1500 feet above airport elevation in standard conditions and to subsequently make a successful approach and landing.[32] The decision whether to carry it or not thus depends on other fuel amounts. In a best case scenario this amount would not be required even with all other amounts minimized. This may not be possible in all cases so another possibility would be not to minimize all the other amounts which would then be enough to avoid carrying additional fuel. Carrying additional fuel could also be avoided by so-called *tankering*. Tankering is a procedure in which additional fuel is loaded onto an aircraft to allow it to carry out another flight after landing either because no fuel is available at destination, or because the price of fuel at destination is much higher than at a departure airport. Air carriers that do tankering have to make their decision based on cheaper price of fuel at departure on one hand, and higher cost of weight on the other hand. Although tankering can be very cost-effective the method itself is not fuel efficient because it increases aircraft's mass. In the end, the decision should always be made by taking into account the safety of the aircraft and its occupants.

3.2.2. GROUND OPERATIONS

Generally, ground operations include all aircraft handling operations at airports and movement of the aircraft on the ground. Fuel savings in this area are small compared to savings that can be achieved during flight for long-haul flight operations but could be rather large in the long run, especially for short-haul and medium-haul flight operations.

Taxi procedures that can be used to reduce fuel consumption are known as engine-out taxi procedures. Depending on the type of aircraft, specifically on the number of engines it has, this procedure is done with one engine completely shut down or on idle setting for two-engine aircraft, or two engines for four-engine aircraft. For three-engine aircraft, a single engine taxi procedure is usually performed. Take an Airbus A320 for

[32] Švragulja D, Domitrović A. *Review of Aircraft Fuel Efficiency Measures*. In: Ščukanec A, Babić D, editors. Science and Transport Development; 2015 May 12; Zagreb. Zagreb: Faculty of Transport and Traffic Sciences; 2015. p. 213

example. Fuel planning for taxi fuel is based on a consumption of 11.5 kg/min.[33] For a taxi time of 14 minutes this means that the aircraft will spend 161 kg during taxi. If single engine taxi procedure is performed the aircraft will spend about 103.5 kg.[34] Notice how the amount spent during single engine taxi is not exactly half of the all-engine taxi amount. This is because an engine has to be started not less than a defined time prior to take-off in order to warm up. Also, if an aircraft stops during taxi and needs to continue moving again the crew will apply a so-called burst of thrust. Thrust is increased initially to get the aircraft to break away and start moving and then reduced to maintain speed on the ground. Bursts increase fuel consumption on the ground.

Engine warmup is necessary to extend the lifetime of the engines and to avoid possible failures in the most critical phases of flight, such as take-off. Two to five minutes are required for warm-up depending on the engine. In this short example a warm-up time of 4 minutes was used and a saving of 57.5 kg was achieved. This is a saving per one taxi operation per flight. Using the same example of a yearly aircraft operation with 3 flights per week as was done in the section about contingency fuel, this saving could theoretically amount to almost 18 tonnes of fuel per year per aircraft. A research by Ithnan et al. conducted at Amsterdam Schiphol airport and Kuala Lumpur International airport shows an average decrease of about 25% in both fuel consumption and gas emissions during taxi phase when using engine-out taxi procedures compared to all-engine taxi.[35] It is also important to take note of the effect of single-engine taxi on engine lifetime. It might be hard for air carriers to keep track of exactly which engines were used for single-engine taxi which could subsequently cause a reduction in lifetime of one of the engines which is used more often.

As was mentioned in section 3.2.1, mass of an aircraft affects fuel consumption in a way that higher mass causes higher fuel consumption and thus higher amount of gas emissions. Fuel consumption is also affected by the centre of gravity position, meaning that the distribution of the load of an aircraft plays an important role as well. Useful load, which is defined as the sum of masses of passengers, baggage, cargo and usable fuel[36], affects centre of gravity position. Ground handlers should, therefore, be aware that a more

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[33] *A318/A319/A320/A321 Performance Training Manual*. Airbus; 2005. p. 32

[34] *Getting to Grips with Fuel Economy*. 4th ed. Airbus; 2004 October. p. 18

[35] Ithnan MI, Selderbeek T, Beelaerts van Blokland WWA, Lodewijks G. *Aircraft Taxiing Strategy Optimization*. Technology University of Delft, the Netherlands; 2013.

[36] *Mass & Balance*. 6th ed. Nordian AS; 2010. Ch. 2. p. 1

forward centre of gravity position increases fuel consumption, while a more aft centre of gravity position reduces it. This is because a forward centre of gravity produces a nose-down pitching moment which is then counteracted by reduced or negative lift on the horizontal stabilizer. Because the tail lift force in this case is reduced or negative, the wings need to produce more lift. Increased lift causes an increase in induced drag which is why the fuel consumption rises.[37] Aircraft should therefore be loaded in such a way that its centre of gravity is as aft as possible without endangering safety. This is usually achieved by proper loading of baggage and cargo. Some Airbus aircraft have special systems installed that automatically manage centre of gravity position during flight by transferring fuel between different fuel tanks.[38]

Another example of ground operations that affect fuel consumption is the use of Auxiliary Power Unit. APU is a self-contained unit that enables the aircraft to be independent of external sources of energy while its engines are not running by providing electric power and *bleed air* for main engine start and air-conditioning. It is essentially a small turbine engine powered by jet fuel, however, its fuel consumption is several times lower than main engine fuel consumption, averaging at 1.8 to 2 kg/min for Airbus A320 aircraft family and Boeing 737NG. Although some fuel savings could be achieved by proper use of the APU, these will not be discussed here because the main topic of this thesis relies on the use of APU at maximum load.

3.2.3. FLIGHT OPERATIONS

Biggest fuel savings can be obtained during flight operations, especially during cruise because it is the longest of all flight phases for long-haul flights. This section will describe possible fuel savings in all the phases of a normal flight.

Configuration of the aircraft is one of the important aspects affecting fuel consumption. It regards the flaps and slats settings used during take-off and initial climb. The lowest setting is the most fuel-efficient. On an Airbus A320 the lowest take-off setting is with 18° of slats and 10° of flaps extended. Any higher configuration setting increases fuel consumption. Airbus A320 has two higher settings: 22° slats and 15° flaps extended,

[37] Švragulja D, Domitrović A. *Review of Aircraft Fuel Efficiency Measures*. In: Ščukanec A, Babić D, editors. Science and Transport Development; 2015 May 12; Zagreb. Zagreb: Faculty of Transport and Traffic Sciences; 2015. p. 214

[38] *Getting to Grips with Fuel Economy*. 4th ed. Airbus; 2004 October. p. 8

and 22° slats and 20° flaps extended.[39] Flaps and slats are high-lift devices. Their purpose is to increase the lift during critical phases of flight such as take-off and initial climb. As was stated before, increasing lift also increases induced drag which causes higher fuel consumption. Because these devices also change the geometry of the wing, parasite drag is also increased which contributes to further fuel consumption increase.

Other than configuration, fuel consumption is also affected by thrust setting. Airbus claims that a take-off and initial climb at full take-off thrust is more fuel-efficient than a take-off at a reduced thrust setting, known as *FLEX* thrust in Airbus aircraft. Although higher thrust setting means higher fuel consumption it also means that an aircraft will complete this flight phase in a shorter amount of time. Prolonged time at a lower level increases total fuel consumption even with a lower fuel consumption rate caused by the reduced thrust.[40] On a similar note, noise reduction procedures increase fuel consumption because they require thrust to be reduced earlier and configuration to be cleaned later than during normal operations.

How much fuel will an aircraft consume during the climb phase depends very much on the climb technique and type of aircraft. The standard climbing technique is to climb at 250 knots Indicated Airspeed (IAS) until reaching Flight Level (FL) 100, then to accelerate to a chosen IAS speed, commence climb at this speed and maintain it until reaching crossover altitude, and finally to climb at a constant Mach number from the crossover altitude to the requested flight level. Crossover altitude is an altitude at which an aircraft switches from constant IAS to constant Mach number climb. Airbus has chosen 300 knots IAS as the optimum climb speed for their aircraft. Table 1 shows the effect a different climb speed has on fuel consumption and time for different Airbus aircraft with 300 knots IAS used as a reference. It can be seen that the Airbus A320 aircraft family could save fuel by choosing a lower climb speed for an insignificant time penalty.

Further fuel savings could be accomplished if the aircraft were allowed to accelerate to their chosen climb speeds before FL100. This, however, depends on the air traffic control because 250 knots is the speed limit in D, E, F, and G classes of airspace for all flights.[41] Air traffic control can individually lift this limitation which would be beneficial for fuel consumption.

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[39] *A318/A319/A320/A321 Flight Crew Operating Manual*. Airbus; 2012. Ch. 1.27.50. p. 5
[40] *Getting to Grips with Fuel Economy*. 4th ed. Airbus; 2004 October. p. 26
[41] *Air Law & ATC Procedures*. 6th ed. Nordian AS; 2010. Ch. 7. p. 4

Table 1. Effect of climb speed on fuel and time for different Airbus aircraft[42]

Effect of Climb Speed on Fuel						
Aircraft	**Climb Mach number**	**Δ Fuel [kg]**				
		270 knots	**280 knots**	**300 knots**	**320 knots**	**330 knots**
A300	**0.78**	+40	+15	0	+5	+10
A310	**0.79**		+5	0	+5	+15
A318/A319/A320	**0.78**		-15	0	+30	+70
A321	**0.78**		-10	0	+25	+60
A330	**0.80**	+15	+5	0	+20	+35
A340-200	**0.78**	+45	+20	0	+10	+25
A340-300	**0.78**	+105	+50	0	-5	+20
A340-500/600	**0.82**		+135	0	-5	-10
Effect of Climb Speed on Time						
Aircraft	**Climb Mach number**	**Δ Time [min]**				
		270 knots	**280 knots**	**300 knots**	**320 knots**	**330 knots**
A300	**0.78**	+0.8	+0.5	0	-0.3	-0.4
A310	**0.79**		+0.5	0	-0.5	-0.6
A318/A319/A320	**0.78**		+0.5	0	-0.4	-0.8
A321	**0.78**		+0.8	0	-0.6	-1.0
A330	**0.80**	+0.9	+0.6	0	-0.4	-0.7
A340-200	**0.78**	+1.4	+0.8	0	-0.6	-0.8
A340-300	**0.78**	+1.5	+0.9	0	-0.6	-1.0
A340-500/600	**0.82**		+0.8	0	-0.6	-0.8

On long-haul flights the cruise phase can provide the greatest fuel savings. Two of the most important factors affecting fuel consumption during cruise are cruise speed, which can be an indicated speed or Mach number, and cruise altitude or flight level.

Each aircraft has a particular altitude at which its specific range is greatest. This altitude is known as the optimum altitude and it varies with the mass of the aircraft. Higher mass reduces specific range and reduces the optimum altitude. Specific range being the greatest at this altitude means that the aircraft is also most fuel-efficient at this altitude. Aircraft should therefore be flown at its optimum altitude whenever possible. Sometimes that's not possible, for example when the performance limitations depending on the current weather and aircraft mass cause the maximum achievable altitude to be lower than the optimum, or due to air traffic control limitations.

Since aircraft consume fuel during flight it means that their mass is progressively decreasing. This leads to continuous increase of optimum altitude during flight. On long-haul flights the optimum altitude could change for several thousands of feet. In order to be most fuel-efficient an aircraft should therefore continuously climb to maintain optimum altitude. However, air traffic control restrictions don't allow this so a procedure known as a step climb should be carried out whenever possible. Step climb is a procedure

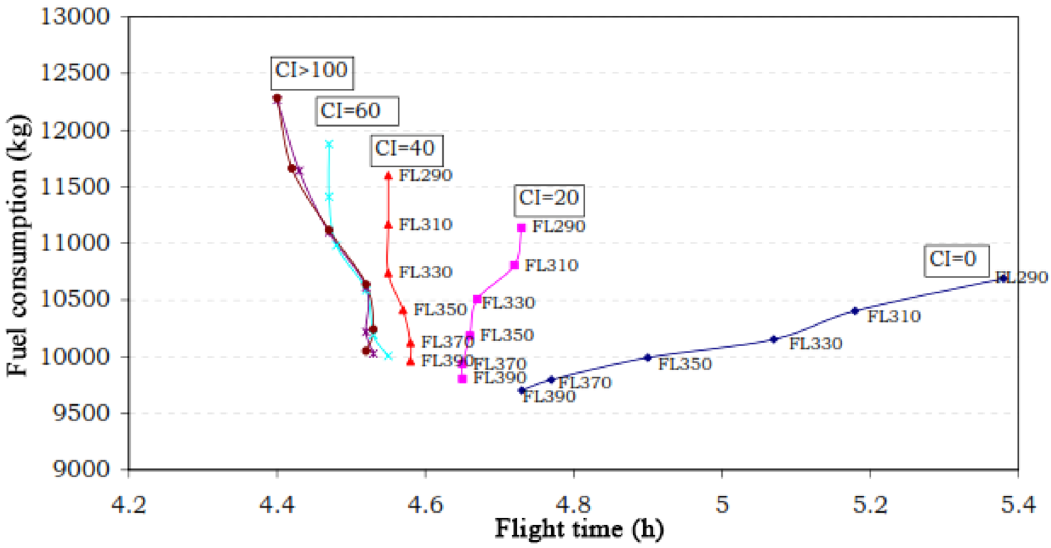
[42] *Getting to Grips with Fuel Economy*. 4th ed. Airbus; 2004 October. Table created from original source, Effect of climb speed on fuel and time. p. 34

in which an aircraft climbs to a higher altitude after flying a specified portion of flight in order to stay as close to the optimum altitude as possible.

Specific range also depends on a chosen Mach number at a particular altitude. There is a particular Mach number that corresponds to the maximum specific range and is designated as the maximum range Mach number. This Mach number is reduced progressively during flight as fuel is consumed. Because time is very important in aviation, flying at the Maximum range Mach number might not be the best option from an economic standpoint. This is why a different Mach number, called Long range cruise Mach number, was defined as a higher Mach number than Maximum range Mach number at which there is only 1% of loss in specific range. Although not the most fuel-efficient, this Mach number is often used as the optimum cruise speed because it is more economically feasible.

The most economical flight would be the one flown at the so-called Economic Mach number. This is a Mach number that's calculated by taking into account the direct operating costs and is specifically the Mach number at which the direct operating costs are minimum. It varies with the ratio of time-related cost of an aircraft operation and the cost of fuel for that operation. This ratio is known as the Cost Index (CI). A high cost index implies that the aircraft will fly faster and therefore have a higher fuel consumption, whilst a low cost index implies the aircraft will fly slower and have a lower fuel consumption.[43] Cost index is inputted into the Flight Management System (FMS) by flight crews on FMS-equipped aircraft. FMS automatically computes the optimum altitude and economic Mach number based on the cost index and other parameters that were inputted by the flight crew. This means that the computation is only as accurate as the data that was inputted into the FMS. Air carriers are the ones that determine which cost index should be used for a particular flight. The lowest possible cost index, zero, is the most fuel-efficient but it is also very time-inefficient as can be seen in Graph 5 which shows how fuel consumption and flight time change with different cost indices and for different flight levels.

[43] Švragulja D, Domitrović A. *Review of Aircraft Fuel Efficiency Measures*. In: Ščukanec A, Babić D, editors. Science and Transport Development; 2015 May 12; Zagreb. Zagreb: Faculty of Transport and Traffic Sciences; 2015. p. 215



Graph 5. Fuel consumption and flight time of an Airbus A319 in respect of cost index and flight level for a 2000 NM sector length[44]

The graph shows how drastically the flight time increases for low altitudes and low cost indices with only a small effect on fuel consumption. For instance, an aircraft flying at FL330 with a cost index of zero takes a little over 5 hours to fly a 2000 NM sector. If the cost index is increased to 20 the flight time will have reduced by almost 30 minutes for only a 300 kg increase in fuel consumption. Therefore it is very important to find a good balance between time-related costs and fuel costs in order to be efficient in both the fuel and economic aspects.

Descent phase is generally the phase with the lowest fuel consumption of all. This is because during descent engines are usually set to idle thrust while the descent speed is controlled by the aircraft's attitude. Thrust is applied if the rate of descent needs to be reduced. Logically, any use of extra thrust during descent increases fuel consumption. If the descent phase is started too early, the aircraft will have to spend unnecessary time at a lower altitude, usually far from its optimum altitude. Any deviation from the optimum altitude increases fuel consumption. Therefore, the descent should be started at the calculated Top of Descent point in order for the flight to be as fuel-efficient as possible. If the descent is continuous from the Top of Descent point to final approach then this procedure is known as a Continuous Descent Arrival. Application of this procedure reduces fuel consumption, and noise and gas emissions. Of course, this is not always

[44] *Getting to Grips with Fuel Economy*. 4th ed. Airbus; 2004 October. Graph from original source. p. 55

possible due to current air traffic or weather situation. A typical descent procedure is a step descent in which an aircraft is guided by air traffic control to progressively reduce altitude as it approaches its destination. This procedure includes periods of cruise at lower altitudes which increases fuel consumption as was explained earlier.

In case the aircraft is required to hold over a certain point, it should hold at its minimum drag speed. This is also the speed at which the lift-to-drag ratio is at maximum and is also the speed at which the endurance is highest. Being fuel-efficient during holding is not only important purely for fuel efficiency. From a safety point of view, the flight crew needs to make a decision on whether or not to divert to alternate airport if the expected holding time is too long. Aircraft could be even more fuel efficient if the flight crew is informed about the expected holding ahead of time, be it during flight planning or during flight. In certain situations the air traffic control could inform the flight crew during flight that they can expect a 20 minute holding after reaching a certain point. If the aircraft hasn’t arrived to the point yet the flight crew could reduce their cruising speed to minimum drag speed. This would mean that the aircraft will take longer to reach the designated holding point and will therefore spend less time in the actual holding pattern. This procedure is known as linear holding but is not a standard procedure and is rarely possible to be conducted due to air traffic control restrictions. Proper arrangements should be made between the flight crew and air traffic control prior to conducting it.[45]

Measures to reduce fuel consumption during final approach and landing are somewhat similar to take-off and initial climb measures and mostly depend on the aircraft’s configuration. A higher configuration setting will cause an increase in fuel consumption due to the increase of lift and consequently induced and parasite drag. Once again, the configuration refers to the flaps and slats settings used during approach and landing. Another important thing to consider is the extension of the landing gear. Extending it too early causes a significant increase in parasite drag meaning more thrust is required to maintain the glide path which is why fuel consumption rises. Final approach and landing are one of the most critical phases of flight and the flight crew might be extending the gear earlier for speed reduction during approach. If the reason for early

[45] Švragulja D, Domitrović A. *Review of Aircraft Fuel Efficiency Measures*. In: Ščukanec A, Babić D, editors. Science and Transport Development; 2015 May 12; Zagreb. Zagreb: Faculty of Transport and Traffic Sciences; 2015. p. 216

gear extension is to conduct a safe approach then fuel consumption should not be taken into consideration because safety is above all the most important aspect of every flight.

3.2.4. MAINTENANCE AND ENGINEERING

How well an aircraft is maintained can have an effect on fuel consumption. Usually it is when the aircraft is just of the production line that its fuel consumption is lowest. Over time and use its performance is slowly degraded which increases fuel consumption. Aircraft performance degradation can be divided into aerodynamic deterioration and main engine performance degradation.

Main engines are the primary consumer of fuel on an aircraft which is why they directly affect fuel consumption. As they age, fuel consumption rises. There can be many contributing factors that cause this rise. One of the most common causes of engine performance degradation is the increase in clearance between turbine blade tips and surrounding static seals.[46] In this case, comparing a specific thrust setting between a deteriorated engine and a new one, the former has to burn fuel at a higher rate in order to maintain the same setting. Because of the increased fuel burn the engine runs hotter which increases the exhaust gas temperature. Increased exhaust gas temperature is one of the main indicators of engine performance degradation. One of the other factors that contributes to its increase is dirt accumulation inside the engine. Luckily, dirt can be removed by performing a thorough water washing of the engine. This procedure is very simple and is done while the engine is still mounted on the wing. A special device is mounted on the front of the engine and is used to pump water and special cleansing additives into it.[47] The process cleans all the surfaces thoroughly and increases the efficiency of the engine which results in a lower fuel consumption and lower exhaust gas temperature. Other causes of engine performance degradation are material degradation, which is caused by extreme temperatures and causes cracks or failures in extreme cases, and foreign object damage, which is self-explanatory.

Aerodynamic deterioration is a term that describes any kind of increase in parasite drag of an aircraft. Some of these increases happen naturally as the aircraft ages but some are a result of improper maintenance. The most common examples of aerodynamic deterioration are damaged seals on control surfaces, incomplete retraction of moving

[46] Ackert S. *Engine Maintenance Concepts for Financiers*. Aircraft Monitor; 2011 September. p. 17
[47] Ibid. p. 19

surfaces, chipped paint, general skin roughness, excessive gaps between doors and fuselage, dents and other deformations due to foreign object damage and others.[48] All of these deteriorations are fixable and proper maintenance procedures should ensure that they are identified early and fixed appropriately. Some fixes that might not be directly related to aerodynamic deterioration require patches to be installed externally on the fuselage. These patches will then increase drag and thus fuel consumption as well. But it could be possible to try to make the patches as aerodynamic as possible without defeating their primary purpose, which would reduce the increase in fuel consumption. Table 2 shows the increase in fuel consumption in kilograms per sector distance for different types of Airbus aircraft. One of the simplest ways to reduce fuel consumption is to wash the aircraft fuselage. This should be done because over time and use aircraft accumulate dirt on external surfaces which makes the skin rough and causes an increase in drag. While many of these savings are relatively small compared to others described earlier it's important to remember that it is the cumulative effect of all the savings on a long-term basis that really makes the difference in both fuel consumption and gas emissions.

Table 2. Effect of aerodynamic deterioration on fuel consumption, values in kilograms[49]

Category	Condition	A300/A310	A320 family	A330/A340
Misrigging	Slat 15 mm	90	60	270
Absence of Seals	Flap (chordwise)	30	14	90
Missing Part	Access Door	50	13	150
Mismatched Surface	Forward Cargo Door 10 mm step for 1 m	20	11	80
Door seal leakage	Forward Passenger Door 5 cm	2	1	5
Skin Roughness	1 m^2	21	13	105
Skin Dents	Single	2	1	2
Butt joint gaps	Unfilled	0.2	0.1	0.6
	Overfilled	3	2	7
External Patches	1 m^2 3 mm high	6	3	16
Paint Peeling	1 m^2 leading edge slat	12	8	57
Sector Distance		**2000 NM**	**1000 NM**	**4000/6000 NM**

[48] *Getting to Grips with Fuel Economy*. 4th ed. Airbus; 2004 October. p. 23
[49] Ibid. Table created from original source. p. 23

One last example of how engineering can help reduce fuel consumption is the installation of wingtip devices. Because of their design the intensity of vortices created at the wingtips is smaller. This causes a reduction in induced drag of an aircraft by increasing the effective aspect ratio without actually increasing the wingspan. Moreover, some types of wingtip devices, such as *winglets*, are designed in a way that their lift component acts forward in the direction of flight. This creates a small thrust force which then reduces the total drag of the device, further contributing to the reduction of fuel consumption.[50]

In order to keep track of aircraft performance, air carriers should implement Aircraft Performance Monitoring (APM) programmes. The purpose of these programmes is to monitor aircraft performance in order to make an accurate assessment on the effect of aging and degradation of an aircraft to drag increase and fuel consumption. By gathering accurate data and making necessary calculations, air carriers can determine aircraft specific performance factors which can then be used by the flight planning department and can increase the accuracy of flight planning. As was mentioned in section 3.2.1, this could increase crews' trust in flight planning data which could then influence their decision on whether or not to take extra fuel on board for a particular flight.

3.2.5. IN-FLIGHT ACTIVITIES

Almost every air carrier in the world offers some kind of in-flight benefits for the passengers, for example drinks and meals during flight, an on-board duty free shop, in-flight entertainment and others. All of these activities impose additional mass which causes an increase in fuel consumption so the basic idea behind this section is to reduce unnecessary mass as much as possible.

The heavier the equipment removed, the greater the fuel saving. Some of the heaviest pieces of equipment found inside an aircraft are water heaters, coffee makers, ovens, and food and beverage carts. Most aircraft are fitted with more than one of these items so on some short-haul flights removing some or even all of them could be justified. It is important to consider the fact that this modification is not cheap and is not simple to conduct, therefore it is justifiable only as a long-term measure, when the air carrier is absolutely sure that they won't need those items in the near future. Since this measure is not justifiable for long-haul flights, aircraft that fly those could implement other measures

[50] *Principles of Flight*. 6th ed. Nordian AS; 2010. Ch. 3. p. 31

such as removal of the on-board duty free shop. Duty free shops are abundant at almost any major airport in the world so having it on board might not be necessary. Another way of reducing mass can be achieved by removing in-flight magazines that are usually offered in every seat of an aircraft, sometimes more than one. By offering less magazines per seat, or per entire row of seats, an air carrier could save on fuel. Removing paperwork has already been proven as an efficient way of reducing mass. Up until the introduction of so-called Electronic Flight Bags (EFB), which are electronic devices either integrated into aircraft cockpits or in the form of a tablet or a laptop, cockpits were usually filled with lots of heavy manuals and paperwork. Nowadays only the most critical manuals are left in the cockpit while all of them are digitised and stored on EFBs.

Even more savings could be achieved by accurately planning the amount of meals and drinks necessary for a particular flight. For example, if only 100 passengers are expected on a flight that has a capacity of 160 seats then it is not necessary to carry the amount of meals and drinks that would be needed if the aircraft were fully loaded. Moreover, most passenger aircraft are equipped with a water tank that provides potable water during flight. Some concerns have been raised recently about the quality of the water provided from the water tank[51] which is why it is mostly used in lavatories for flushing and washing hands only. This consumes very little water so the aircraft that took off with a full tank of water could land with most of it still inside. By accurately planning the amount of water in the water tank according to the expected number of passengers, fuel consumption could be lowered. Furthermore, this could save tonnes of water yearly per aircraft. Devices that remove moisture from aircraft interior could also be installed to reduce mass.

Another measure that could be implemented regards the in-flight entertainment systems. Many passenger aircraft have electronic entertainment systems installed in every passenger seat. The mass of system electronics and wiring that's necessary to connect all of them can reach up to several hundreds of kilograms. Lufthansa states that only the mass of wiring of electronic entertainment systems on an Airbus A340 sums up to about 900 kg and claims that removing it could save up to 47 tonnes of fuel per aircraft per year.[52] Their idea is to remove the wiring and have Wi-Fi based electronic systems

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[51] Goglia J. *Why Airline Crews Skip The Coffee And Tea On Board* [Internet]. 2013 [updated 2013 October 15; cited 2015 July 25]. Available from: http://www.forbes.com/sites/johngoglia/2013/10/15/why-airline-crews-skip-the-coffee-and-tea-on-board/

[52] *Fuel Efficiency at the Lufthansa Group*. Balance sustainability report. Lufthansa; 2012.

installed in every seat. Another alternative to that would be to completely remove the seat-based entertainment systems but to offer free Wi-Fi connectivity instead for all passengers. That way they could use their own personal electronic devices for entertainment or other purposes. There have been some concerns over the interference of Wi-Fi with aircraft systems. Honeywell found that it interferes with some display units they produce but that it does not pose a risk to aircraft operations.[53] Some air carriers already provide Wi-Fi on board during flight. The bigger concern with Wi-Fi is aircraft security. It is claimed that it could be used for hacking the aircraft systems and taking over the control of the aircraft from the passenger cabin.[54]

3.3. ALTERNATIVE FUEL EFFICIENCY MEASURES

Fuel efficiency measures described in the previous subchapter are widely used across the aviation industry in an effort to bring the cost of fuel down and to reduce aircraft gas emissions. The measures have been extensively optimized throughout the years so there is little improvement to be made there. Because of this, new and alternative efficiency measures are being developed. Mass and drag reduction remains as the general idea to achieve better fuel efficiency but some, more elaborate measures, attempt to influence fuel consumption directly. Three alternative measures with the greatest potential for fuel savings and gas emission reduction are aviation biofuel, nanotechnology coatings, and alternative methods of taxi. This subchapter discusses only the first two listed measures. Alternative methods of taxi are discussed separately, in the following chapter because that is the main subject of this thesis.

3.3.1. AVIATION BIOFUEL

Aviation biofuel is a term used to describe alternative fuels used for jet aircraft. It is mostly derived from sustainable oil crops such as jatropha, camelina, and algae, or from wood and waste biomass. IATA claims that these biofuels can reduce the overall carbon

[53] Hopewell L. *Wi-Fi proven to interfere with aircraft* [Internet]. 2011 [updated 2011 March 10; cited 2015 July 26]. Available from: http://www.zdnet.com/article/wi-fi-proven-to-interfere-with-aircraft/
[54] Rundle M. *In-flight Wi-Fi is 'direct link' to hackers* [Internet]. 2015 [updated 2015 April 15; cited 2015 July 26]. Available from: http://www.wired.co.uk/news/archive/2015-04/15/aeroplane-wifi-hacks-possible

footprint by about 80% during their full life cycle.[55] Their primary purpose is to reduce aviation's gas emissions because it currently represents about 2% of global emissions, and is expected to reach 3% by 2050.[56]

Biofuels are still in the development phase and will probably need a lot of time to be developed for widespread use. Despite this, they were approved for commercial use in 2011. Since then, more than 20 air carriers have been using biofuels on commercial flights. Most flights performed have used a mixture of 50% of biofuel and 50% of JET A1 jet fuel. While this doesn't provide the same emission reduction as a pure 100% biofuel would, it is still better than pure JET A1. The current goal in biofuel development is to use resources that do not affect the food supplies.

Aviation biofuel is dubbed as the single best chance for reducing greenhouse gas emissions in the short-term, meaning up to year 2050. Year 2050 is also the year IATA has selected for their emission reduction goal. They hope that by 2050 the net aviation carbon dioxide emission levels will have reduced to 50% of the 2005 levels. At present, this goal seems very ambitious and will probably be faced with difficulties. One of the biggest difficulties at present is the cost of aviation biofuel, which is currently several times more expensive than the conventional JET A1. This is because the cost to produce and deliver biofuel is much more expensive than the cost to produce and deliver jet fuel. Another important thing to consider about aviation biofuels is the way their production affects the environment. A research on a life cycle of *Jatropha curcas*, a plant that's used in biofuels, shows that a 55% reduction in greenhouse gas emissions can be expected compared to conventional JET A1 emissions. Furthermore, if the land used to produce it is a former agricultural or pastoral land results could be up to 85% better than predicted, but if natural woodland is converted in order to create land for biofuel production then an increase of 60% in greenhouse gas emissions can be expected.[57]

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[55] *Alternative Fuels* [Internet]. 2015 [cited 2015 June 20]. Available from: http://www.iata.org/whatwedo/environment/Pages/alternative-fuels.aspx

[56] Penner JE, Lister DH, Griggs, DJ, Dokken DJ, McFarland M. *Aviation and the Global Atmosphere*. Cambridge University Press; 1999. Ch. 8.3.3.1.

[57] Bailis RE, Baka JE. *Greenhouse Gas Emissions and Land Use Change from Jatropha Curcas-Based Jet Fuel in Brazil* [Internet]. 2010 Oct 26 [cited 2015 June 21]. 44(22):8684-8691. Available from: http://pubs.acs.org/doi/abs/10.1021/es1019178

3.3.2. NANOTECHNOLOGY COATINGS

Advances in nanotechnology since the beginning of the 21st century have made it possible to produce special coatings that could not only provide fuel savings, but could also improve engine service life and could help prevent aircraft icing. Nanotechnology coatings, also known as nano-coatings, are polymers that are spread across a surface thus giving it special properties.

The first specialized nano-coatings in aviation were used on the F-22 Raptor fighter jet in order to grant it additional stealth abilities. In civil aviation, nano-coatings can be used for a variety of reasons. Coatings with heat-insulting properties can be applied to engine parts which are subject to high temperatures. This can slow down the aging process of the engine and increase its service life by 300%.[58] Engines are thus able to run hotter with increased efficiency and without damage to critical parts which, as was described earlier, could cause an increase in fuel consumption.

Coatings with super-hydrophobic properties are designed to repel water. Use of these coatings could prevent accumulation of icing on board aircraft surfaces. Icing presents an increase in parasite drag of an aircraft and while there are systems in place that are used to prevent it, they all use the power of the engines to do so. Nano-coatings are a passive way of protection which could reduce fuel consumption by preventing icing and by reducing the need to use a portion of the engine power to run other anti-icing equipment. In sub-zero temperatures water freezes instantly when it comes in contact with a surface that's not treated with a nano-coating, but when it comes in contact with a treated surface it does not freeze and instead slides down the surface. A demonstration video found during research shows the nano-coating being tested at -4° C while the simulation system used for testing is able to simulate temperatures up to -29° C.[59] It is also not clarified if the coating used in the test is super-hydrophobic or if it is just a simple nano-coating. Further research will be needed to determine the applicability of these coatings to conventional aircraft that fly in temperatures much lower than these.

Simple nano-coatings without special properties can provide fuel saving benefits as well. The idea behind this is that almost every surface is a rough surface on an atomic

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[58] *Nano-Coating May Reduce Fuel Consumption of Aircraft Engines* [Internet]. 2014 [updated 2014 May 15; cited 2015 June 20]. Available from: http://www.european-coatings.com/Raw-materials-technologies/Applications/Industrial-coatings/Nano-coating-may-reduce-fuel-consumption-of-aircraft-engines

[59] *Icing Simulation System* [Internet]. 2015 [cited 2015 June 20]. Available from: http://appealingproducts.com/research-and-development/surface-icing-simulation-system/

level. Gaps, crevices and other imperfections that are invisible to the naked eye cause minute increase in local drag. The purpose of nano-coating in this case would be to fill the surface imperfections and create a seemingly perfect flat surface. This doesn't only help reduce the drag, but also prevents dirt and other debris from accumulating on the aircraft surface. Figure 1 shows a schematic comparison between an untreated (up) and treated (down) aircraft surface. One of the greatest benefits of nano-coatings is that they are very lightweight and have a negligible effect on fuel consumption due to aircraft's mass increase, even on large jet aircraft. Thus the net effect of nanotechnology coatings is the reduction of total fuel consumption and greenhouse gas emissions.

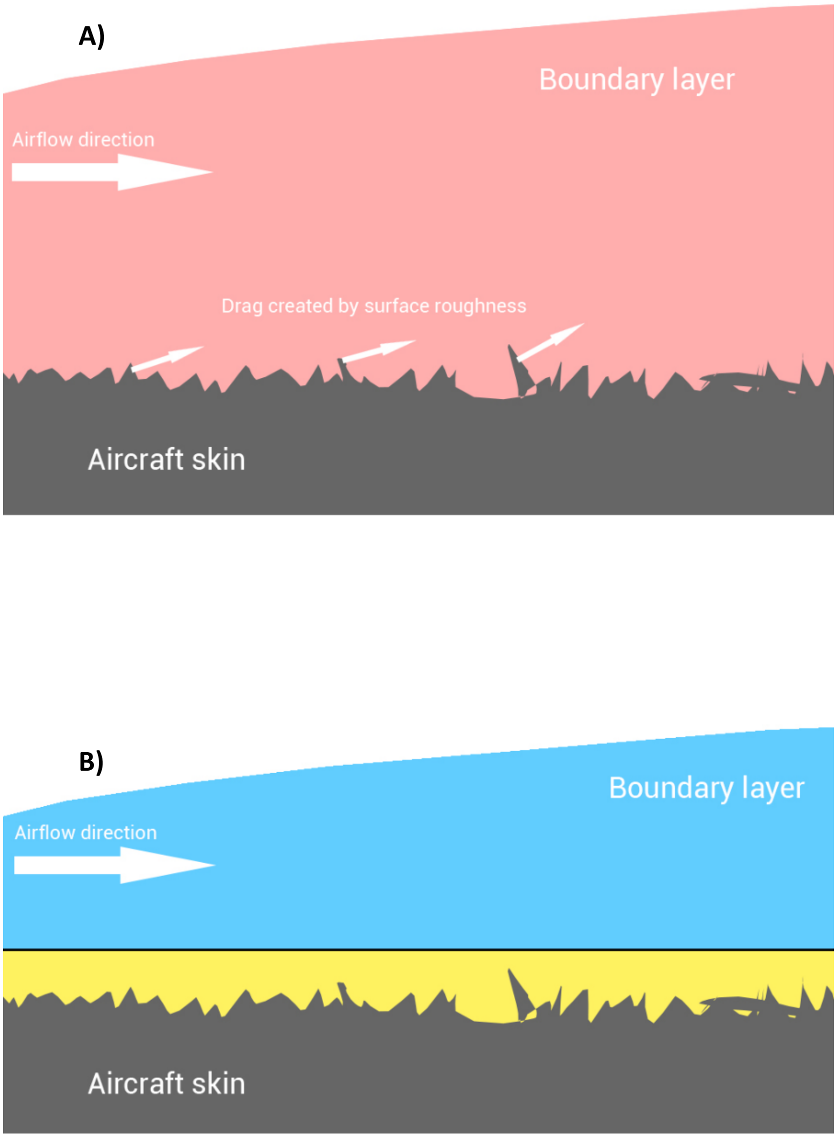

Figure 1. Effect of nanotechnology coating on aircraft surface drag.
A) Aircraft surface without the coating
B) Aircraft surface treated with a nano-coating

4. ALTERNATIVE METHODS OF TAXI

While on the ground, aircraft generally move around on the manoeuvring area of an airport by using the power of their own main engines. Needless to say, the main engines are designed for flight and are very fuel inefficient for use on the ground. Take Airbus A320 family of aircraft for example. According to its Flight Crew Operating Manual (FCOM) the fuel planning value for fuel consumption during taxi is 11.5 kg/min.[60] That's 690 kg of fuel per hour. Of course, actual fuel consumption varies and may be smaller or larger than this number. Usually, aircraft don't spend hours on the ground taxiing. Taxi time is measured in minutes.

It's important to distinguish two types of taxi times that are measured and those are taxi-out and taxi-in times. Taxi-out time can be defined as the period of time it takes an aircraft to taxi from its parking position after pushback is completed to the active runway prior to departure. Taxi-in time can be defined as the time it takes an aircraft to taxi from the active runway to its designated parking position after landing. Taxi-out times are usually longer than taxi-in times and they vary from just a few minutes on smaller airports to more than 15 minutes on larger ones. Under exceptional circumstances delays might happen that cause the taxi-out time to be more than an hour long or even longer. According to a US Department of Transportation report, average taxi-out time in the latest reported year, 2007, was 16.7 minutes while the average taxi-in time was 6.9 minutes.[61] The report also shows that the general trend is an increase in taxi times with each year. The only anomaly that deviated from the trend was that there was a reduction in taxi times following the terrorist attacks on New York and Washington D.C. in 2001. The increase in taxi times is explained by the increase in air traffic and the fact that airports cannot adapt to the increase fast enough because of infrastructure limits.

Air traffic will continue to rise over the years and the main focus of the industry will be how to reach the fuel efficiency goals with the constant increase in air traffic. The main reason behind the fuel efficiency goals is to prevent climate change that our planet is facing because of the increase in greenhouse gas emissions. Alternative taxi methods aim to reduce fuel consumption and aircraft gas emissions while the aircraft is on the

[60] *A318/A319/A320/A321 Performance Training* Manual. Airbus; 2005. p. 32
[61] Goldberg B, Chesser D. *Sitting on the Runway: Current Aircraft Taxi Times Now Exceed Pre-9/11 Experience*. US Department of Transportation; 2008 May. p. 1,2

ground. There are currently two alternative taxi methods in the world: taxiing powered by tugs, and electric taxi.

4.1. TAXIING POWERED BY TUGS

When talking about aviation, a tug is a land vehicle that's used to move aircraft on the ground. The most common use of tugs nowadays is for pushback operations at airports that require pushback. Normally, the aircraft is pushed back by the tug from its parking position onto the nearest taxiway. The tug is operated by a driver who's responsible for the pushback operation. During pushback, the flight crew starts the main aircraft engines and when pushback is complete, after the engines are started, the tug disconnects from the aircraft which then continues to taxi to the active runway on its own power.

Taxiing powered by tugs imagines a different concept in which a tug is not only used for pushback but also to taxi an aircraft to the active runway. In order to achieve this, special tugs are used that do not use tow bars for connecting the aircraft to the tug. Usually, in most operations tow bars are connected to the nose gear of an aircraft and can cause high loads on the nose gear structure, especially during braking and at high speeds. An example of a classic tug with a tow bar can be seen in Figure 2.

Figure 2. An Airbus A320 aircraft being towed by a classic tug with a tow bar[62]

[62] Obtained from Mr. Dino Kučić [private photo collection] (August 2015)

Virgin Atlantic planned to use tugs with tow bars to tow their Boeing 747 aircraft to the runway for each departure. Six trials were done at three airports in 2007 and 2008 but Boeing determined that towing an aircraft puts too much stress on the landing gear and reduces its lifetime which is why the idea was abandoned[63].

TaxiBot tug is a semi-autonomous *towbarless* vehicle powered by a hybrid Diesel-electric engine. It was developed by Israel Aerospace Industries with support and cooperation of Lufthansa LEOS. With TaxiBot, aircraft's braking system and TaxiBot itself absorb all of the kinetic energy during braking which is why the loads on the nose gear are reduced as compared to tugs with tow bars, in which the tug absorbs all of the kinetic energy but all the loads are transmitted through the nose landing gear.[64] Two versions of TaxiBot exist, one for narrow-body and the other for wide-body aircraft. The narrow-body version can be seen in Figure 3 on the next page.

The system is semi-autonomous because the pilot is in control of the tug during taxi. This is achieved through a special connection mechanism between the nose gear and the tug. The tug driver is responsible for pushback operation and for returning the tug to the apron. The system is completely external which means that no additional equipment has to be installed on an aircraft (except for a simple cable connection and a cockpit control panel on some Airbus aircraft[65]). During taxi with TaxiBot, the pilot uses the aircraft taxi controls almost just as he would during normal taxi. The connection mechanism translates the pilot's commands to the tug. The system accelerates automatically to a maximum allowed speed for a particular taxiway. Speed can then be controlled by the pilot simply by applying the main brakes. A special adaptive computer traction algorithm analyses the pilot's braking actions to determine the desired taxiing speed. Main engines are started during taxi to allow them to warm up. The tug is disconnected from the aircraft before it reaches the active runway.

[63] Webster B. *Virgin's green idea loses its pulling power* [Internet]. 2008 [updated 2008 March 10; cited 2015 August 29]. Available from: http://www.thetimes.co.uk/tto/environment/article2143692.ece
[64] TaxiBot. *TaxiBot Taxiing System* [presentation]. Miami, USA: IATA Aircraft Taxiing Systems Conference; 2015 February. sl. 12-14
[65] Ibid. sl. 11

Figure 3. Narrow-body TaxiBot tug[66]

The main advantage of TaxiBot is that it imposes no additional mass to an aircraft and no need to install new components, except as previously mentioned, while providing taxi abilities without main engine fuel consumption. This means less greenhouse gas emissions and less noise in the airport environment. The system also reduces risks of jet blast and foreign object damage. It is also the only alternative taxi system certified by EASA (narrow-body version only) and is currently pending certification by the FAA. Narrow-body TaxiBot tug is currently used in real ground operations at Frankfurt International airport while the wide-body version is in the test phase which should be completed by the end of 2015.[67]

However, the existing certification requires a safety driver to be present in the tug while the original concept was to have an autonomous vehicle which would return to the apron on its own after being used for taxi by the pilot. While all of this implies lower fuel costs, it is unknown how much it will increase ground operations costs. Another

[66] *Narrow-body TaxiBot Picture* (Lufthansa LEOS) [image on the Internet]. 2015 [updated 2015 February 20; cited 2015 August 10]. Available from: http://www.airportsinternational.com/2015/02/press-day-for-taxibot/16421

[67] *Innovative TaxiBot now used in real flight operations* [Internet] 2015 [updated 2015 February 20; cited 2015 August 10]. Available from: http://www.lufthansagroup.com/en/press/news-releases/singleview/archive/2015/february/20/article/3439.html

important thing to consider is that the system relies on tugs being available at airports in order to be utilized. Air carriers that fly to airports without TaxiBot will not benefit from the system. Furthermore, at busy airports the demand for tugs might exceed the capacity which would further hinder the benefits. It goes without saying that failures of TaxiBot during the towing operation could cause congestions at taxiways and subsequent delays.

4.2. ELECTRIC TAXI

Electric taxi is a means of moving an aircraft on the ground on its own power but without the use of its main engines. This is achieved through electric motors which are installed on the aircraft's landing gear. The electric motors draw power from the aircraft's APU unit. The system is controlled by a pilot in the cockpit using specialized controls. Currently there are two electric taxi systems in existence: Electric Green Taxiing System (EGTS), that's being developed by Honeywell Aerospace and Safran, and WheelTug, which is being developed by the company of the same name, WheelTug plc. Neither of the two systems have been granted certification for commercial use yet.

4.2.1. ELECTRIC GREEN TAXIING SYSTEM

EGTS is an electric taxi system designed for narrow-body jet aircraft, mainly Boeing 737 and Airbus A320. Its target segment are air carriers that operate on short or medium-haul flights out of busy airports.[68] Unlike the TaxiBot system, EGTS uses aircraft-mounted equipment to provide power for pushback and taxi. This means that the system is completely autonomous and does not depend on any kind of external sources of energy.

The system relies on two electric motors to move the aircraft on the ground. Each electric motor is mounted off-axis on each main landing gear leg, between the two wheels. EGTS system mounted on an Airbus A320's main landing gear can be seen in Figure 4.

[68] Honeywell, Safran. *EGTS Electric Taxiing System* [brochure]. Honeywell, Safran; 2014. p. 4

Figure 4. EGTS system mounted on an Airbus A320's main landing gear[69]

Pilots are provided with an interface unit that's used to control the aircraft on the ground via EGTS. The desired command inputted by the pilots is received by EGTS controller and forwarded to the Wheel Actuator Controller Unit which is installed in the cargo hold of the aircraft. This unit then converts electric current into instructions for the electric motor which applies the required torque to move the aircraft. The system is powered by the APU generator which has to be modified to generate additional power because of high electric loads required by EGTS[70], necessary to develop advertised speeds of up to about 20 knots, which is a typical taxiing speed.[71]

From the described operational process of the system, it can be seen that it requires installation of several pieces of new equipment as well as modification of the APU generator. The total additional mass the system will impose on aircraft is estimated to be about 880 lbs (400 kg).[72] Because of this additional mass the aircraft will have increased fuel consumption during flight but overall benefits should be a reduction in total fuel

[69] *EGTS system prototype installed on A320* [image on the Internet]. 2013 [updated 2013 June 20; cited 2015 August 12]. Available from: http://commons.wikimedia.org/wiki/File:EGTS_system_prototype_installed_on_A320_(2).jpg
[70] Honeywell, Safran. *EGTS Electric Taxiing System* [brochure]. Honeywell, Safran; 2014. p. 8
[71] Cadmus. *Deriving Benefits from Alternative Aircraft-Taxi Systems* [presentation]. Miami, USA: IATA Aircraft Taxiing Systems Conference; 2015 February. sl. 17
[72] Ibid. sl. 17

consumption as well as reduction of greenhouse gas emissions. EGTS claims a 4% reduction in total block fuel consumption for their reference scenario which is an Airbus A320 flying a 600 NM long sector with 15 minutes of taxi-out time and 8 minutes of taxi-in time.[73]

The main benefit of the system is reduced fuel consumption which implies reduced greenhouse gas emissions. It also removes the need to use airport ground equipment for pushback operations because the system allows the aircraft to move in reverse on its own. This also allows for shorter turnaround times. Just as with the TaxiBot system, the risks for jet blast and foreign object damage are reduced because the main engines are not started until 2 to 5 minutes prior to reaching the active runway, which ensures adequate engine warmup. There have been some concerns about the effect of EGTS on carbon brake cooling because of the mechanism's position on the main landing gear. The manufacturers claim that they have evaluated several options and concluded that the one in which the electric motor is off-axis and between the wheels retains the current efficiency of carbon brake cooling.[74] However, the system will most likely require brake cooling fans to be installed for aircraft flying in warmer climates. The system was demonstrated several times since 2013 but has not yet been certified for commercial use. How much it will cost the air carriers to retrofit their existing aircraft with EGTS, or how much the cost of new aircraft with pre-installed EGTS will rise is still unknown.

4.2.2. WHEELTUG

Similarly to EGTS, WheelTug is an electric taxi system designed for narrow-body jet aircraft, Boeing 737NG and Airbus A320 family of aircraft. The main difference between EGTS and WheelTug is that the former system is installed on the main landing gear, while the latter one is installed on the nose landing gear of the aforementioned aircraft. Except where indicated by a reference in the footnote, some specific information found in this section of the thesis was obtained personally by the author in consultations with Mr. Jan Vana, a director at WheelTug. Because of this, and because of the fact that WheelTug currently seems closest of the two electric taxi systems to commercial operational use, this section will describe the WheelTug system in more detail.

[73] Honeywell, Safran. *EGTS Taxiing System* [presentation]. Miami, USA: IATA Aircraft Taxiing Systems Conference; 2015 February. sl. 17
[74] Ibid. sl. 25

Unlike EGTS, which requires a modified APU, WheelTug is designed to work with the existing APUs found in Boeing 737NG and Airbus A320 family of aircraft. Because of that and because of the small size of the system, it is limited to taxiing speeds of up to 10 mph (8.69 knots) which, although more than three times faster than average human walking speed that's often used to define taxiing speed, is still slower than the taxiing speeds advertised by its competitors. The company has stated that they have designed WheelTug to be a system that can provide autonomous pushback and low-speed taxiing capability because most taxi operations on big airports involve a lot of stopping during taxi, especially during busy periods, and also because taxi-out and taxi-in times at small and medium size airports don't justify electric taxi system usage for a long taxi. Therefore, the system is designed for so-called stop-and-go taxi operations, and gate/terminal operations. In case an aircraft has a clear way to taxi from its stand to the runway continuously, the benefits of electric taxi are lost due to lower acceleration capabilities it provides, compared to acceleration by main engines. It's interesting to note that the company does not advertise fuel savings as the primary benefit of the system. According to the company the greatest benefit of their electric taxi system is time savings. One of the simplest examples of a time saving is the fact that autonomous pushback removes the need to wait for ground equipment. Not only is the turnaround time shortened, but also the cost of pushback is removed.

The company stated that the development phase of the system is over and that they are now actively working on getting the system certified. By the end of this year, 2015, the company will make a decision for which aircraft type will the Supplemental Type Certificate (STC) be developed first. At the moment it seems that an STC for Boeing 737NG is going to be first. The company plans to have the system certified for the first chosen aircraft type by FAA in 2017. Certification of the system for the second chosen aircraft type should follow a year later, 2018. EASA certification should follow shortly after that. WheelTug is a retrofit system, meaning it is removable from the aircraft. It will be offered to companies on operating lease.

4.2.2.1. Description of WheelTug System's Parts

Other than the placement of the electric motors on the nose gear, some other things that differentiate WheelTug from EGTS is that WheelTug is more than two times lighter than EGTS and it doesn't require modifying the APU. The mass of the WheelTug system is 300 lbs (136 kg). It consists of two electric motors mounted into each of the nose wheel hubs. Figure 5 shows an ordinary Boeing 737NG nose wheel on the left, and the same type of wheel with the WheelTug electric motor protected inside a metallic cover on the right. One of the problems in this design is that its size is limited by the dimensions of the nose wheel hubs, so the ability of such a small electric motor to provide adequate torque at low speeds while retaining good high speed capabilities was questioned. The problem was solved using a specially designed system in which a high phase order inverter is connected to a high phase order concentrated winding induction motor using a mesh connection.[75] Conventional inverter drive systems deliver maximum power, hence torque, only when producing full output voltage at full output current. However, the output voltage of the inverter is restricted by the terminal voltage of the motor in low speed operation which is why it cannot deliver full output power. Terminal voltage of the motor can be increased by increasing its voltage-to-frequency ratio. This can be done either mechanically, for example by increasing the number of turns or by rewiring the mesh connection, or electronically.

Figure 5. Boeing 737NG nose wheel without (left) and with WheelTug system installed (right)[76]

[75] *Chorus Motor Tutorial: Meshcon (Optimized Variable Torque) Derivation* [Internet]. 2015 [cited 2015 August 06]. p. 1. Available from http://www.chorusmotors.com/technology/MeshconDerivation.pdf
[76] Obtained from Mr. Jan Vana [courtesy: WheelTug] (August 2015)

By improving low-speed capabilities mechanically, the system loses some of its high-speed capabilities. The specially designed system used by WheelTug uses electronic means of changing voltage-to-frequency ratio during motor operation by utilising harmonic frequencies of the fundamental frequency.[77] This allows the motor to adapt to the current operational requirement in real time. During low-speed operation it is operating at high voltage-to-frequency ratio, which is subsequently reduced for higher-speed operations. WheelTug is using a proprietary motor technology called Chorus Meshcon that was developed and patented by its mother company Chorus Motors. Other, more detailed information about the electric motor is not public, but it is said that this motor is more heat-tolerant than those used in similar systems.

As previously mentioned, the electric motors draw power from the existing APU unit. Minor additional wiring has to be installed on the aircraft to connect the motors with the APU via the APU output connectors available in the avionics bay. The motors are also electrically connected with WheelTug System Controller unit that's located in the aircraft's avionics bay. The controller unit houses the electronics and the software needed to communicate pilot's commands to the electric motor. Figure 6 shows the WheelTug System Controller unit.

Figure 6. WheelTug System Controller unit[78]

The controller unit is electrically connected with the WheelTug control panel located in the cockpit. The control panel is a unit that serves as a direct interface between the pilots and the WheelTug system. Figure 7 on the next page shows the publicly available concept design of the WheelTug cockpit control panel. The panel will most

[77] *Chorus Motor Tutorial: Meshcon (Optimized Variable Torque) Derivation* [Internet]. 2015 [cited 2015 August 06]. p. 1. Available from http://www.chorusmotors.com/technology/MeshconDerivation.pdf
[78] Obtained from Mr. Jan Vana [courtesy: WheelTug] (August 2015)

probably be located on the pedestal in the cockpit where throttle and other engine controls are located. It looks very simple and easy to use. The master power switch, dubbed *PWR*, that turns the WheelTug system on or off is located on the right side of the panel and protected under a red cover. Next to it, a button dubbed *RVS* is used to control the direction of rotation of the electric motor meaning it controls whether the aircraft moves forward or backward. When the button is engaged the aircraft moves backward. On the top left side of the panel, two LED (Light-Emitting Diode) displays indicate the current system power and the temperature of the electric motor. A round wheel beneath the two displays is used to increase or decrease power to the system. Lower left part of the panel is equipped with a button used to test the operability of the WheelTug system and a system status light. The final design of the WheelTug control panel might differ from what is described here.

Figure 7. Publicly available WheelTug cockpit panel design[79]

All the described parts are standard pieces of equipment of a WheelTug system. Optionally, air carriers can choose to install a video camera system with a live feed in the cockpit to aid the pilots during autonomous pushback operations.

[79] Obtained from Mr. Jan Vana [courtesy: WheelTug] (August 2015)

4.2.2.2. Effect of WheelTug System on Nose Landing Gear

An important thing to consider is how the system affects the nose gear. As was stated, the mass of the entire system is about 136 kg. Aircraft landing gear is designed to be as light as possible while supporting the aircraft's mass on the ground during taxi, take-off and landing. The nose gear is often smaller and lighter than the main landing gear, as is the case with both Boeing 737NG and Airbus A320 family, because it is designed to withstand less load than the main landing gear. Therefore, imposing additional mass on it could increase the wear of the nose gear system. The company has stated that they have done thorough analysis on the impact of the WheelTug system on the nose landing gear and that, from a safety point of view, the system complies with all the requirements. However, some modification of the nose landing gear might be necessary.

Figure 8 on the next page shows the WheelTug pre-certification system installed on a Boeing 737NG's nose gear. Except for the obvious modification which is the WheelTug system and its appropriate wiring that has to be installed on the nose gear, modifications of some of the parts on the nose gear might have to be made. Parts that might have to be modified include some life-limited parts, nose landing gear actuators, and shimmy dampers. The nose landing gear actuators that control retraction and extension of the gear will essentially look the same as the existing ones, but will be modified to provide additional hydraulic power to compensate for the added mass on the nose gear. Shimmy dampers are devices that are used to prevent nose wheels from vibrating or shimmying. They are designed specifically for the nose wheel of each aircraft type therefore modifying the mass of the nose wheel might require a modified shimmy damper as well. Some life-limited parts on the nose gear might have to be reinforced, probably by using stronger metals such as titanium instead of aluminium or 2024 aluminium alloy in the design of such parts. The company has stated that all the modifications will be free for the operator that leases the WheelTug system from them.

Figure 8. WheelTug system installed on a Boeing 737NG's nose gear[80]

Another concern about the effectiveness of the nose-gear-mounted electric taxi system was lifting of one of the nose wheels of Airbus A320 family of aircraft in tight turns. As opposed to the Boeing 737NG, the A320 family's nose gear leg is not perpendicular to the ground, it is in fact slanted forward. Because of this, during tight turns, the outboard wheel gets lifted of the ground, as is shown in Figure 9 on the next page. The concern was that one wheel touching the ground might not provide adequate traction. This claim was dismissed by WheelTug, and the company states that they have tested the system and have found no issues that could have been caused by lifting of the nose wheel. Moreover, they state that reduced area of contact causes double load to be carried by the wheel that remains in contact with the ground. This, and the fact that taxi speeds in tight turns are low, assures that the system will perform well on Airbus A320 family of aircraft.

[80] *WheelTug wheel-hub electric motor installed on the nose gear of the 737-700 test aircraft* [image on the Internet]. 2013 [updated 2013 July 25; cited 2015 August 12]. Available from: http://www.airlinereporter.com/2013/07/rock-and-roll-more-options-for-an-electric-ground-taxi-system/

Figure 9. Airbus A320 nose wheel lifted of the ground during a tight turn[81]

4.2.2.3. Operational and Maintenance Procedures

Detailed operational and maintenance procedures that will have to be implemented by air carriers in their operating manuals are not publicly available. The following section will describe the basics behind using the system and its maintenance.

In order to be able to use the system, pilots will need to undergo only one hour of computer-based training. The company claims that no additional and no recurrent training will be necessary because the system is very simple to use. Additionally, all the training will be provided free to air carriers that lease the system from them.

Air carriers will develop and implement their own operational procedures according to the recommendations given by WheelTug. These procedures will define when to use the electric taxi system. For example, if the expected taxi time is less than 5 minutes the procedures could state not to use the system, or in special cases if it's necessary to taxi fast the procedures could state that the system should be used, but only for autonomous pushback.

[81] *A320 nose wheel in tight turn* [image on the internet]. 2011 [updated 2011 December 09; cited 2015 August 08]. Available from: http://www.flightglobal.com/news/articles/video-l-3-and-lufthansa-get-moving-with-e-taxi-demonstrator-365815/

The system in general is very user friendly. The simplicity of the control panel in the cockpit was already shown in section 4.2.2.1. Pilots will be using the WheelTug system only to move forward or backward. The existing steering control in aircraft will not be modified in any way and will be used to steer the aircraft. When the WheelTug system is engaged and when the pilot inputs the command to move forward the system will accelerate on its own until the pilot releases the command. In this case, the system will maintain the speed it has reached automatically, similarly to cruise control in cars. Maximum forward speed of the system is 10 mph (8.69 knots). The motor is designed to disengage itself automatically if forward moving speed manages to reach 20 mph (17.38 knots). On the same note, if the system detects any brake input by the pilots it automatically disengages itself in order to prevent conflicting inputs.

When moving backward, the system accelerates automatically to a maximum speed of 5 mph (4.34 knots) while the pilot is giving the command to move backward. The backward moving speed is limited to ensure that the aircraft doesn't tip over in case a sudden stop has to be made. When the pilot releases the command to move backward the system is disengaged automatically because backward movement is used only for pushback operations.

It is interesting to note that an early version of WheelTug featured an electric motor that was able to develop speeds of up to 25 mph (21.72 knots). However, this version was much bigger and heavier than the present one. The company concluded that high speed taxi is not used often and decided to design a smaller and less complicated system at the cost of lower speed. It was stated that a future version of WheelTug could offer high-speed taxi capabilities should there be enough interest for it to be developed.

Regarding maintenance procedures, the company has stated that it will provide all the necessary manuals to air carriers for free. These will be enough for air carriers to perform line maintenance and general troubleshooting on their own. This includes visual inspections of the system which will be done on every nose gear tyre and wheel change. This happens roughly each month or month and a half, or every 100 to 150 flight hours.

Generally, all scheduled maintenance will follow the same periods as existing nose gear maintenance procedures. Scheduled base maintenance will be done by WheelTug authorised Maintenance, Repair and Overhaul (MRO) companies which will be available all over the world. These companies will also be responsible for installing and removing the WheelTug system. Because installing WheelTug requires modification of some parts of the nose gear, the companies will have a certain number of modified nose gears prepared for installation already in stock. That way, when an air carrier requests installation, the unmodified nose gear will be removed completely from the aircraft and a new modified one will be installed. The companies will keep a pool of both modified and non-modified nose gears so that an air carrier can receive its unmodified nose gear back should they desire to remove the system. The installation procedure itself will take two 8-hour shifts so an aircraft won't be out of the service too long. WheelTug will be included in the Master Minimum Equipment List (MMEL), meaning aircraft will be able to fly even when the system is inoperative. The company has stated that it will cover all the installation and scheduled maintenance costs to air carriers that lease the system from them.

4.2.3. ADVANTAGES OF ELECTRIC TAXI

Some of the advantages of using alternative taxi methods were already mentioned in subchapters 4.1 and 4.2.1. Both the electric taxi and taxiing powered by tugs all share similar advantages. This also applies to the two different types of electric taxi systems currently in existence.

The most obvious advantage of using an electric taxi system is reduced fuel consumption. Fuel can make up to a third of air carrier's direct operating costs, therefore using less fuel can save a lot of money. Aircraft gas emissions are a direct product of fuel combustion i.e. fuel consumption. Since fuel consumption is decreased by the use of electric taxi systems, aircraft emissions will be decreased as well. One of the goals of this thesis is to determine how big exactly the fuel and gas emissions savings can be in terms of kilograms, because the price of fuel is constantly changing. Chapter 5 describes a general model that can be used to estimate possible fuel and emissions savings by implementing an electric taxi system, and chapter 6 includes a savings analysis for Croatia Airlines based on the model.

Other than the obvious savings, electric taxi systems also reduce turnaround times because they remove the need to use tugs and because engines can be started later and shut down earlier, during taxi. Because engines can be off during pushback and parking operations, dangers to ground crews are reduced. They can start working on the aircraft immediately after it stops and they don't have to wait for the engines to be shut down which also reduces turnaround time. Electric taxi therefore improves safety of personnel and vehicles in the airport environment. Reduced turnaround time means reduced airport costs for air carriers and it could also enable them to add a full new flight cycle per day without requiring additional staff.

The fact that engines are off reduces their wear and increases their lifetime. Foreign object damage is also reduced, and dangers due to jet blast are eliminated. This increases manoeuvrability in the airport environment because it allows ground personnel and other aircraft and vehicles to move about without worrying about jet blast. This is especially beneficial for large airports that have gates and parking positions which are packed closely together. Electric taxi therefore increases gate and taxiway throughput at airports.

Another benefit of electric taxi is reduced wearing of brakes, especially carbon brakes, because they will generally not be used during electric taxi until main engines are started. Other benefits include reduced noise in airport environment and more aircraft movements hence possibly increased airport capacity.

5. MODEL FOR THE ANALYSIS OF THE EFFECT OF ELECTRIC TAXI IMPLEMENTATION ON FUEL CONSUMPTION AND AIRCRAFT GAS EMISSIONS

In order to analyse the effect of implementing electric taxi on fuel consumption a generic model was made. The model is rather simple and straightforward. It includes basic mathematical operations to compare total fuel consumption during different kinds of taxi operations. This chapter describes that generic model which, since it is generic, can be used to estimate fuel savings for any kind of alternative taxi. During research it was found that there are many considerations that could have an impact on the final results that are presented by this model in the next chapter.

5.1. FUEL EFFICIENCY INDEX

To describe possible fuel savings that electric taxi could yield a simple equation is used:

$$FEI = \frac{FC_{ex}}{FC_{all}} \tag{1}$$

Where *FEI* stands for Fuel Efficiency Index – a ratio of total fuel consumption during electric taxi expressed in kilograms (FC_{ex}), and total fuel consumption during all-engine taxi (FC_{all}), also expressed in kilograms. This definition of Fuel Efficiency Index is unique to this thesis and it should not be confused with similar terms used elsewhere.

FEI is therefore a dimensionless quantity. A value of *FEI* equal to 1 would mean that the same quantity of fuel was spent during electric taxi as was during all-engine taxi. That would mean that electric taxi is not fuel-efficient compared to all-engine taxi. *FEI* value larger than 1 would mean that the efficiency of electric taxi is worse than that of all-engine taxi. *FEI* value smaller than one indicates that a lower quantity of fuel was spent during electric taxi than during all-engine taxi.

The goal of the thesis is to confirm the claim that electric taxi systems will decrease fuel consumption. Mathematically this is logical because the main engines will not be running during a portion of taxi operation. Fuel will still be spent because electric taxi systems use the APU unit for power, but since APU fuel consumption rate is lower than main engine fuel consumption fuel efficiency should be greater. Therefore, the desired value of *FEI* will be a value lower than 1. The lower the number, the more fuel efficient an electric taxi system is.

To correctly use the *FEI* equation (1) one must properly compare fuel consumption data. Firstly, fuel consumption data for all-engine taxi should be obtained. Number of Landing to Take-Off (LTO) cycles per destination, taxi-out and taxi-in times per destination also have to be noted. Secondly, fuel consumption data for electric taxi has to be estimated. Data is estimated solely because no electric taxi system has been granted certification for commercial use so far. All the model assumptions are described later in subchapter 5.5. After the certification, actual data could be obtained and inputted into this model to acquire actual *FEI* values, which is a recommendation for future research.

Similarly to *FEI*, another index was devised to further illustrate the fuel efficiency of electric taxi:

$$FEI_{SE} = \frac{FC_{SE}}{FC_{all}} \tag{2}$$

Where FEI_{SE} stands for Single-Engine Fuel Efficiency Index – a ratio of total fuel consumption during single-engine taxi operation expressed in kilograms (FC_{SE}), and total fuel consumption during all-engine taxi (FC_{all}).

5.2. TOTAL FUEL CONSUMPTION VARIABLES

Fuel efficiency indices described in the previous subchapter can be used to describe fuel efficiency for the entire fleet of aircraft. For variables on the right side of the *FEI* equations, both estimates and actual data can be used, however it is recommended to use actual data whenever possible. The fuel consumption variables described in this chapter relate to the entire taxi-out and taxi-in operations meaning, for example, that electric taxi fuel consumption values include engine warm-up and cool-down times during which the fuel flow is assumed to be the same as in all-engine taxi operations.

5.2.1. TOTAL FUEL CONSUMPTION DURING ALL-ENGINE TAXI

Total fuel consumption during all-engine taxi, designated as FC_{all}, represents the total quantity of jet fuel in kilograms used by aircraft or fleet of aircraft during all-engine taxi operations. Although the value of this variable can be estimated it is recommended to use actual fuel consumption data, or at least the fuel planning data for taxi-out operations and then to estimate data for taxi-in operations. The equation for total fuel consumption during all-engine taxi is:

$$FC_{all} = \sum_{i=1}^{n} N \cdot \left(FF_i + FF_{APU_i}\right) \cdot \left(t_{out_i} + t_{in_i}\right) \qquad \text{[kg]} \qquad (3)$$

Where:

- n is the number of destinations for which the analysis is being done
- N is the number of LTO cycles per destination
- FF_i is the average main engine fuel flow per destination of an aircraft during all-engine taxi
- $FF_{APU\,i}$ is the average APU fuel flow
- $t_{out\,i}$ is the average taxi-out time per destination
- $t_{in\,i}$ is the average taxi-in time per destination.

If the data used is the fuel planning data found in operational flight plans then the planned taxi fuel mass and taxi time will be available. Taxi fuel mass and taxi time in operational flight plans refer only to the taxi-out operations, therefore an estimate is needed for taxi-in operations. The fuel flow FF in this case can be estimated by dividing the available data for the taxi fuel mass m_{out} with taxi-out time t_{out}:

$$FF = \frac{m_{out}}{t_{out}} \qquad \text{[kg/min]} \qquad (4)$$

Calculating fuel flow averages per destination by hand can be very time consuming. Air carriers nowadays log fuel consumption data automatically so it would be beneficial to obtain that data for the analysis instead of using the planning data from operational flight plans.

Since taxi-in times are not planned it might prove difficult to estimate them if no actual data is available. In that case they could be omitted from the model but it should then be clearly stated that the analysis is performed for taxi-out operations only. The FC_{all} equation then becomes:

$$FC_{all} = \sum_{i=1}^{n} N \cdot \left(FF_i + FF_{APU_i}\right) \cdot t_{out_i} \quad \text{[kg]} \qquad (5)$$

5.2.2. TOTAL FUEL CONSUMPTION DURING ELECTRIC TAXI

Total fuel consumption during electric taxi, FC_{ex}, is the total quantity of jet fuel in kilograms used by aircraft, or fleet of aircraft, during electric taxi operations. Electric taxi operations in this context do not only refer to the period of taxi while electric taxi system is used to move the aircraft on the ground, but rather refer to the entire taxi-out or taxi-in operation.

It is assumed that aircraft main engines are off during the period of operation of an electric taxi system, therefore main engine fuel flow is zero. It is also assumed that during that period the APU is working on full electrical load and its fuel flow is corresponding to such conditions. With those assumptions in place, the equation for total fuel consumption during electric taxi is:

$$FC_{ex} = \sum_{i=1}^{n} N \cdot \left[FF_{APU_i} \cdot \left(t_{ex,out_i} + t_{ex,in_i}\right) + \left(FF_i + FF_{APU_i}\right) \cdot \left(t_{out_i} - t_{ex,out_i} + t_{in_i} - t_{ex,in_i}\right)\right] \quad \text{[kg]} \qquad (6)$$

Where:

- $t_{ex,out\ i}$ is the taxi-out time during the period of operation of an electric taxi system
- $t_{ex,in\ i}$ is the taxi-in time during the period of operation of an electric taxi system. Other variables are the same as described earlier.

Because no electric taxi system has so far been certified and no operational procedures for the use of such systems were developed, the model makes some assumptions as to which operations to include in the analysis. One of the most important things to consider are the engine warm-up and cool-down times.

Depending on the engine the warm-up time can range from 2 to 5 minutes.[82] Air carriers define this period in their operating manuals. During the warm-up time the engines need to be running at or near idle. The model assumes that a warm-up time of at least 3 minutes is necessary in all taxi-out operations. Taking account of the possible workload increase in the cockpit, only the taxi-out times of 5 minutes or longer are considered valid for the analysis. For example, a 5-minute taxi-out time in case of an electric taxi operation will consist of 2 minutes electric taxi and 3 minutes all-engine taxi.

Similarly to the warm-up time in taxi-out operations, engine cool-down time is necessary in taxi-in operations. For an Airbus A320, this is defined as 3 minutes and is the time during which the engines are running at or near idle setting. Considering the fact that engines are usually already running at a low or idle setting during final approach and landing, they could theoretically be shut-off as soon as the aircraft clears the active runway and the aircraft could switch to electrically powered taxi. However, using reverse thrust hinders this advantage.[83] The model assumes that a 3-minute cool-down period is necessary in all taxi-in operations. Because of possible workload increase only the operations in which taxi-in times are 4 minutes long or longer are considered valid for the analysis. For example, a 4-minute taxi-in time would consist of 3 minutes all-engine taxi and 1 minute of electric taxi.

If certain taxi times are considered as invalid for electric taxi, then the taxi-out $t_{ex,out\ i}$ and/or taxi-in $t_{ex,in\ i}$ times are considered as zero. This means that destinations at which electric taxi is not plausible are included in the calculation and decrease fuel efficiency i.e. increase the fuel efficiency index *FEI*.

[82] *Getting to Grips with Fuel Economy*. 4th ed. Airbus; 2004 October. p. 17

[83] Nicolas Y. *Taxiing aircraft with engines stopped*. FAST, Airbus technical magazine. 2013 January. p. 8. Available from: http://www.airbus.com/support/publications/

Taking account of the warm-up and cool-down times of 3 minutes, equation (6) can be simplified as follows:

$$t_{ex,out_i} = t_{out_i} - 3 \qquad [\text{min}] \qquad (7)$$

$$t_{ex,in_i} = t_{in_i} - 3 \qquad [\text{min}] \qquad (8)$$

$$FC_{ex} = \sum_{i=1}^{n} N \cdot \left[FF_{APU_i} \cdot \left(t_{out_i} + t_{in_i} - 6\right) + \left(FF_i + FF_{APU_i}\right) \cdot 6\right] \qquad [\text{kg}] \qquad (9)$$

If only taxi-out operations are considered then the equation (9) becomes:

$$FC_{ex} = \sum_{i=1}^{n} N \cdot \left[FF_{APU_i} \cdot \left(t_{out_i} - 3\right) + \left(FF_i + FF_{APU_i}\right) \cdot 3\right] \qquad [\text{kg}] \qquad (10)$$

5.2.3. TOTAL FUEL CONSUMPTION DURING SINGLE-ENGINE TAXI

The purpose of calculating FEI_{SE} index is solely to illustrate the differences in fuel efficiency between single-engine taxi and electric taxi. Single-engine taxi procedures are usually just a recommendation in most air carriers which is why it might prove difficult to predict when they are being used, and it could be difficult to obtain actual data. Because of that, the model assumes that the fuel flow during single-engine taxi is either 75% of the default flight planning value of 11.5 kg/min or 75% of the actual all-engine fuel flow value if actual data is used. The latter option requires the fuel flow data to either be obtained from automatic logs or to be extrapolated from the taxi fuel and taxi time data found in operational flight plans, as was shown in section 5.2.1. With these assumptions in place, the equation for total fuel consumption during single-engine taxi is:

$$FC_{SE} = \sum_{i=1}^{n} N \cdot \left[\left(0{,}75 \cdot FF_i + FF_{APU_i}\right) \cdot \left(t_{SE,out_i} + t_{SE,in_i}\right) + \left(FF_i + FF_{APU_i}\right) \cdot \left(t_{out_i} - t_{SE,out_i} + t_{in_i} - t_{SE,in_i}\right)\right] \qquad [\text{kg}] \qquad (11)$$

Where:

- $t_{SE,out\,i}$ is the taxi-out time during which only one engine is operating
- $t_{SE,in\,i}$ is the taxi-in time during which only one engine is operating

Assuming the same considerations for engine warm-up and cool-down times described in section 5.2.2, the model will only consider taxi-out times in excess of 5 minutes and taxi-in times in excess of 4 minutes as valid for analysis. Similarly to electric taxi, taxi times invalid for single-engine taxi are considered to be zero, and will decrease fuel efficiency index.

By taking account of engine warm-up and cool-down times of 3 minutes, equation (11) can further be simplified:

$$t_{SE,out_i} = t_{out_i} - 3 \qquad [\text{min}] \qquad (12)$$

$$t_{SE,in_i} = t_{in_i} - 3 \qquad [\text{min}] \qquad (13)$$

$$FC_{SE} = \sum_{i=1}^{n} N \cdot \left[\left(0{,}75 \cdot FF_i + FF_{APU_i}\right) \cdot \left(t_{out_i} + t_{in_i} - 6\right) + \left(FF_i + FF_{APU_i}\right) \cdot 6\right] \qquad [\text{kg}] \qquad (14)$$

If only taxi-out operations are analysed then the FC_{SE} equation (14) becomes:

$$FC_{SE} = \sum_{i=1}^{n} N \cdot \left[\left(0{,}75 \cdot FF_i + FF_{APU_i}\right) \cdot \left(t_{out_i} - 3\right) + \left(FF_i + FF_{APU_i}\right) \cdot 3\right] \qquad [\text{kg}] \qquad (15)$$

5.3. CALCULATION OF AIRCRAFT GAS EMISSIONS DURING TAXI

By consuming fuel, aircraft emit gases that are harmful to the Earth's global ecosystem. Although most of the damage done to the atmosphere comes from aircraft emissions at high altitudes, emissions on the ground must not be ignored as they have a direct effect on airport environment and its surrounding areas.

ICAO has defined a so-called Landing to Take-Off (LTO) cycle which is used to calculate aircraft emissions below 3000 feet above airport elevation. An LTO cycle consists of approach, landing, taxiing, take-off and initial climb. Since this thesis is concerned only about alternative taxi operations, only the emissions during taxi phase will be calculated.

This subchapter gives equations to calculate how many kilograms of a certain gas are emitted per mass of fuel burned during a specific taxi operation. Factors defining the rate of gas emissions per one kilogram of jet fuel depend on the type of aircraft and were calculated according to the values estimated by EU ETS for carbon dioxide, and by values given in ICAO Airport Air Quality Manual[84] for other gases. Equations are given for Boeing 737NG and Airbus A320 aircraft only, because they will be the first to be equipped with an electric taxi system. Equations are given for carbon dioxide (CO_2), unburned hydrocarbons (HC), mono-nitrogen oxides (NO_x), carbon monoxide (CO) and sulphur dioxide (SO_2). For Boeing 737NG, the equations are as follows:

$$m_{CO_2} = m_f \cdot 3{,}15 \quad \text{[kg]} \tag{16}$$

$$m_{HC} = m_f \cdot 8{,}2 \cdot 10^{-4} \quad \text{[kg]} \tag{17}$$

$$m_{NO_x} = m_f \cdot 0{,}014 \quad \text{[kg]} \tag{18}$$

$$m_{CO} = m_f \cdot 0{,}008 \quad \text{[kg]} \tag{19}$$

$$m_{SO_2} = m_f \cdot 0{,}001 \quad \text{[kg]} \tag{20}$$

Where m_{CO2}, m_{HC}, m_{NOx}, m_{CO}, m_{SO2} and m_f are masses of carbon dioxide, unburned hydrocarbons, mono-nitrogen oxides, carbon monoxide, sulphur dioxide and fuel spent during a taxi operation, respectively. All of the variables are expressed in kilograms.

For Airbus A320 family, the equations are as follows:

$$m_{CO_2} = m_f \cdot 3{,}15 \quad \text{[kg]} \tag{21}$$

$$m_{HC} = m_f \cdot 7{,}4 \cdot 10^{-4} \quad \text{[kg]} \tag{22}$$

$$m_{NO_x} = m_f \cdot 0{,}012 \quad \text{[kg]} \tag{23}$$

$$m_{CO} = m_f \cdot 0{,}008 \quad \text{[kg]} \tag{24}$$

$$m_{SO_2} = m_f \cdot 0{,}001 \quad \text{[kg]} \tag{25}$$

Other than the slight differences in hydrocarbon and mono-nitrogen oxide emissions, the equations for Airbus A320 family are analogous to the ones for Boeing 737NG.

Calculating the mass of any gas is therefore quite simple. One must simply input the value of FC_{all}, FC_{SE}, or FC_{ex} as the value of m_f.

[84] *ICAO Document 9889: Airport Air Quality Manual*. ICAO; 2011.

5.4. CONSIDERATIONS THAT COULD HAVE AN EFFECT ON FUEL EFFICIENCY INDEX

There are many more factors, other than the ones already described in this chapter, which could play an important role in determining fuel efficiency of electric taxi systems. Some of these factors are described in the following sections of this subchapter. Generally, the considerations presented here could prove difficult to quantify which is why they were left out of the final model. However, they remain here as a reminder to the reader that the model itself is idealistic, and that the results of the analysis in chapter 6 should be viewed as such as well. On the same note, any subsequent research should try to take note of these considerations to create a better version of the model.

5.4.1. MOVEMENT SPEED DURING ELECTRIC TAXI

Maximum aircraft taxi speed is often defined as the speed of a *brisk walk* or a *slow jog*. Most air carriers choose to keep this definition for maximum taxi speed in their Operating Manuals, while some others define precise speeds in knots. Aircraft taxi speeds usually range from 5 to 20 knots, which depends on many factors. Generally, four maximum taxi speeds can be defined according to a situation in which an aircraft is:

a) 30 knots: maximum taxi speed on runways, for example during backtrack operations
b) 20 knots: maximum taxi speed on taxiways, if not limited otherwise
c) 10 knots: maximum taxi speed in turns
d) 3-5 knots: maximum speed of pushback

Once again, it should be noted that these speeds are only general assumptions. Air carriers that desire faster turnaround times, such as low-cost carriers, will taxi their aircraft at higher speeds. Others might limit the maximum speed on taxiways even more restrictively than the assumption presented here.

The model assumes that the taxi speed during all-engine taxi, single-engine taxi, and during electric taxi, is the same. However, in reality this might not be true. The existing APUs on Boeing 737NG and Airbus A320 family cannot provide enough power to the electric motor to produce sufficient torque for taxiing at speeds higher than about

12 knots.[85] If an aircraft is usually taxiing at higher speeds than this then its taxi times would increase. This of course increases total fuel consumption during taxi. It also incurs additional time-related costs. The time-related costs could be offset by benefits offered by faster pushback capability but only for shorter taxi distances.

To facilitate the need for higher electrical power, Airbus has suggested a hybrid electric taxi method, somewhat similar to single-engine taxi. The hybrid method involves an aircraft with its APU on and one of its engines started and running at idle. Electric taxi system is used to move the aircraft on the ground. The working engine's generator could provide additional power necessary to produce enough torque to get the aircraft to move at speeds of up to 20 knots.[86] However, the idea of electric taxi is to have an independent aircraft system that will provide better fuel and time savings compared to both all-engine and single-engine taxi operations. Using hybrid taxi would be similar to using single-engine taxi in terms of fuel savings, although somewhat better considering that the engine would be running at idle. In addition, dealing with both the electric taxi system and one engine running at the same time might be too much of a workload increase for the pilots. Because of that, hybrid taxi is not considered in the model.

5.4.2. UTILIZATION OF ELECTRIC TAXI SYSTEMS

The model assumes that electric taxi operations are possible in all situations in which taxi-out and taxi-in times are 5 minutes and 4 minutes long or longer, respectively. Therefore, only the taxi time is considered as a factor in determining whether or not an electric taxi system will be utilized. However, assuming that electric taxi will be utilized in 100% of cases is not plausible. Weather, pilot workload, air carrier and airport operating procedures could all have an effect on utilization of electric taxi systems.

In adverse weather, such as snowy or icy conditions, it may not be possible to use electric taxi systems for taxi operations. Although it is claimed that a main landing gear electric taxi solution will be utilisable in any weather condition this could only be true if sufficient modifications are made to the APU unit. The torque generated by the electric motor with the existing APU units might not be enough to provide adequate performance in such conditions. Other than snowy or icy conditions, high temperature

[85] Nicolas Y. *Taxiing aircraft with engines stopped*. FAST, Airbus technical magazine. 2013 January. p. 6. Available from: http://www.airbus.com/support/publications/
[86] Ibid. p. 7.

environments also present a problem because they can cause electric motor failures by speeding up its deterioration.

The nose gear electric taxi solution has another possible disadvantage because only 5% to 20% of the total aircraft load is carried by the nose gear.[87] Because of this, the adherence of the nose gear to the ground is less than that of the main landing gear. The traction might be too low, especially on sloped surfaces and at high aircraft masses in adverse conditions. Moreover, this consideration suggests another unfavourable situation. Nose gear adherence depends on the position of the centre of gravity. An aft centre of gravity position lowers the nose gear adherence therefore decreases the performance of an electric taxi system. In section 3.2.2 it was concluded that an aft centre of gravity position is the most desirable because it lowers fuel consumption in flight. Now, an opposite situation is desirable to ensure adequate performance of an electric taxi system. Air carriers could determine which measure for fuel efficiency is more desirable for them and should plan aircraft loading accordingly. Although weather data for flight planning, and aircraft loading data as well as centre of gravity position is readily available before a certain flight takes place, it is difficult to predict such data for long time periods such as a year or a season. Historical weather data could be used to determine a number of days in a year for an airport in which electric taxi systems could not be used, however this is beyond the scope of this thesis and remains as a recommendation for future research.

Everyday situations that affect pilot workload could also affect the willingness of pilots to use electric taxi systems. Taxi phase, including pushback, is one of the high workload phases of flight. During taxi phase, one of the pilots is responsible for taxiing an aircraft while the other could be going through final flight preparations and checklists. Crew situational awareness about the airport environment in such cases could be diminished because only one of the pilots is looking out of the cockpit. Workload in such cases could increase significantly if an unexpected task or issue arises, such as changes in taxi clearances or possible technical problems. Low visibility also increases workload because pilots need to be extra careful to avoid obstacles while taxiing. Should the use of an electric taxi system mean an additional increase in workload for the pilots, they could decide not to use it. Just how much of an increase in workload will electric taxi bring to

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[87] Sadraey MH. Aircraft Design: *A Systems Engineering Approach*. Wiley; 2012. ISBN: 978-1-119-95340-1. p. 534

the cockpit has yet to be determined. The goal is that electric taxi operations present little or no workload increase for pilots. Unexpected situations during taxi occur at random and are therefore very difficult to predict which is why they were left out of the model. In general, pilots who have had the chance to test electric taxi systems seem to be looking forward to the new technology, stating that the system is flexible and responsive while being beneficial for the environment[88], and that it would give them more independence from ground crews.[89]

5.5. MODEL ASSUMPTIONS

To conclude chapter 5, all of the model's assumptions are listed for easier reference. Once again, it is important to note that this is an idealistic model and as such yields idealistic results to describe approximate fuel efficiency benefits. The assumptions are as follows:

a) Fuel flow during all-engine taxi-in operations is equal to fuel flow during all-engine taxi-out operations.
b) Main engines are off during the period of operation of an electric taxi system.
c) During the period of operation of an electric taxi system the APU is working on full electrical load and has a corresponding fuel flow.
d) APU is assumed to be on during any taxi operation.
e) Engine warm-up takes exactly 3 minutes and electric taxi system can be used for taxi only when the taxi-out time is 5 minutes long or longer.
f) Engine cool-down takes exactly 3 minutes and electric taxi system can be used for taxi only when the taxi-in time is 4 minutes long or longer.
g) All-engine taxi-out and taxi-in data for certain flights is included in the analysis regardless of the inability to use an electric taxi system in case the taxi times are shorter than the ones under *d* and *e*.

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[88] *Pilots test drive "remarkable innovation" during EGTS Pilots Days* [Internet]. 2014 [updated 2014 June 29; cited 2015 August 30]. Available from: https://aerospace.honeywell.com/news/pilots-test-drive-%E2%80%9Cremarkable-innovation%E2%80%9D-during-egts%E2%84%A2-pilots-days

[89] *WheelTug Successfully Tests Electric Drive System on Boeing 737NG* [Internet]. 2012 [updated 2012 June 25; cited 2015 August 30]. Available from: http://www.reuters.com/article/2012/06/25/idUS55809+25-Jun-2012+MW20120625

h) Single-engine taxi procedures can be used only when the taxi-out time is 5 minutes long or longer, and when the taxi-in time is 4 minutes long or longer.

i) Single-engine fuel flow is either 75% of the default flight planning value (11.5 kg/min) or 75% of the actual fuel flow, depending on which data is used.

j) Taxi speed during all-engine taxi, single-engine taxi and electric taxi, is the same.

k) Possible effects on utilization of electric taxi systems described in subchapter 5.3 are disregarded in the model.

6. DATA FOR THE MODEL AND ANALYSIS OF MODEL RESULTS

The model for the analysis of the effect of electric taxi implementation on fuel consumption and aircraft gas emissions that was developed in chapter 5 was used to calculate the possible increase in fuel efficiency for Croatian national air carrier Croatia Airlines. The input data presented in subchapter 6.1 was provided by Croatia Airlines, namely by Mr. Dino Kučić, a sustainable development specialist at Croatia Airlines. Chapter 6.1 is therefore focused on the description of input data, while chapter 6.2 is focused on the analysis of the data.

6.1. INPUT DATA

Considering the fact that Croatia Airlines' flight operations are heavily affected by seasonality it was decided that it would be best to analyse the busiest and the least busy month of the current year for the purpose of calculating possible fuel efficiency increase. The analysed months were February 2015, as the least busy, and July 2015, as the busiest.

Croatia Airlines has a fleet of two Airbus A320, four Airbus A319 and six Dash 8-Q400 aircraft. Since the electric taxi systems are currently aimed at Boeing 737NG and Airbus A320 families of aircraft, only the flights operated by the six Airbuses were considered in the model. Because of seasonality only the most common destinations operated by the company's Airbuses were considered. For February the destinations considered were Amsterdam (Schiphol), Dubrovnik, Frankfurt (International), London (Heathrow), Paris (Charles de Gaulle), Split, and Zagreb. For July the considered destinations were Amsterdam (Schiphol), Barcelona, Dubrovnik, Frankfurt (International), London (Gatwick), London (Heathrow), Paris (Charles de Gaulle), Rijeka, Skopje, Split, and Zagreb. The number of LTO cycles was obtained from the publicly available Croatia Airlines summer and winter timetables.

Table 3 shows all the destinations with the number of LTO cycles per month and the total number of LTO cycles. It can be seen that the number of flights in July for selected destinations was higher by 348 more than in February, which is almost 70% higher and proves the seasonality in flight operations. The highest number of LTO cycles were done in Zagreb, which is logical because Zagreb is the base of operations for the air carrier. The greatest effects of seasonality can be seen by looking at the number of LTO cycles in Split and Dubrovnik. Split had more than double the amount of flights operated by Airbus fleet, while Dubrovnik had exactly five times more Airbus operated flights in July than in February.

*Table 3. Croatia Airlines LTO cycles per destination for Airbus fleet only (*N/A – not applicable)*

Destination (IATA code)	February	July
Amsterdam (AMS)	28	32
Barcelona (BCN)	N/A*	12
Dubrovnik (DBV)	28	140
Frankfurt (FRA)	112	156
London (LGW)	N/A	8
London (LHR)	36	32
Paris (CDG)	28	56
Rijeka (RJK)	N/A	4
Skopje (SKP)	N/A	20
Split (SPU)	56	116
Zagreb (ZAG)	220	280
TOTAL per month	**508**	**856**
TOTAL	**1364**	

This data was inputted as the variable N in the model in equations (3), (9), and (14) to calculate fuel consumption during all-engine, single-engine and electric taxi. According to those equations the other necessary data was average main engine fuel flow per destination FF_i, average APU fuel flow per destination $FF_{APU\ i}$, average taxi-out time per destination $t_{out\ i}$, and average taxi-in time per destination $t_{in\ i}$. Croatia Airlines was kind to provide all of this data for the purpose of this thesis.

Table 4 shows on the next page the input data for fuel flow variables. Values for fuel flow during single-engine taxi were calculated according to the assumption that fuel flow is at 75% value of all-engine taxi fuel flow during single-engine taxi operation. This value was advised by Croatia Airlines, therefore the exact fuel flow data for single-engine taxi was not obtained from Croatia Airlines. The 75% coefficient is included in equation (14) which is why single-engine fuel flow values are not shown in Table 4. Furthermore, since it is assumed that the fuel flow during taxi-in operations is the same as fuel flow during taxi-out operations, and because only taxi-out data was available, the taxi-in fuel flow values are not shown in Table 4. Average APU fuel flow value calculated by Croatia Airlines is 2.34 kg/min and is used in all equations to determine the fuel consumption variables.

Table 4. Average all-engine taxi-out fuel flow values and APU fuel flow for Croatia Airlines Airbus fleet

Destination (IATA code)	February	July	APU fuel flow
	All values in kilograms per minute		
Amsterdam (AMS)	15	16	2.34
Barcelona (BCN)	N/A	17	
Dubrovnik (DBV)	20	19	
Frankfurt (FRA)	16	17	
London (LGW)	N/A	19	
London (LHR)	15	15	
Paris (CDG)	19	20	
Rijeka (RJK)	N/A	14	
Skopje (SKP)	N/A	11	
Split (SPU)	13	13	
Zagreb (ZAG)	21	21	
AVERAGE	**17**	**17.29**	

Table 5 shows the input data for taxi-out and taxi-in variables.

Table 5. Average taxi-out and taxi-in times per destination for Croatia Airlines Airbus fleet

Destination (IATA code)	February		July	
	Taxi-out	Taxi-in	Taxi-out	Taxi-in
	All values in minutes			
Amsterdam (AMS)	19	11	16	12
Barcelona (BCN)	N/A	N/A	13	7
Dubrovnik (DBV)	9	4	9	4
Frankfurt (FRA)	18	11	16	12
London (LGW)	N/A	N/A	21	8
London (LHR)	21	9	21	10
Paris (CDG)	17	11	16	12
Rijeka (RJK)	N/A	N/A	8	4
Skopje (SKP)	N/A	N/A	10	5
Split (SPU)	9	3	9	4
Zagreb (ZAG)	9	6	9	5
AVERAGE	**14.6**	**7.9**	**13.5**	**7.5**

From Table 5 it can be seen that taxi times are highest at big European airports such as Gatwick and Heathrow in London, followed by Charles de Gaulle in Paris, Schiphol in Amsterdam, and Frankfurt International airport. Croatian airports have the lowest taxi-out and taxi-in times which is most probably because Croatian airports that were considered in this analysis all have only one runway and one major taxiway. Taxi times are only slightly shorter in July than in February. The air carrier probably taxied its aircraft faster to avoid risk of losing their designated slot times because of high traffic at airports during summer season. Taking account of the assumptions made in subchapter 5.5 it can be seen that taxi-in time for Split airport in February does not meet the requirement for electric and single-engine taxi. This means that the calculation of fuel consumption during electric and single-engine taxi in Split in February assumed that all-engine taxi is used in all taxi-in operations.

6.2. ANALYSIS OF MODEL RESULTS

Since none of the electric taxi systems have been certified for commercial use yet, this analysis is restricted to assumptions described in subchapter 5.5. This is why it's important to state again that the results presented in this analysis are idealistic and should be checked with actual data once electric taxi systems get certified. Because checking the data is not possible at this moment, it remains as a recommendation for future research.

Data presented in subchapter 6.1 was inputted in equations (3), (9), and (14) to obtain the fuel consumption values for all-engine taxi FC_{all}, single-engine taxi FC_{SE}, and electric taxi FC_{ex}. Fuel consumption per destination and per month as well as total monthly and both months total fuel consumption obtained by this model are presented in Table 6. The fuel consumption data shows that Zagreb airport yielded the highest fuel consumption for the Croatia Airlines Airbus fleet both in February and in July, which is logical since it is the air carrier's base of operations and also had the highest number of LTO cycles. The second one to follow was Frankfurt International airport in both February and July. Both destinations yielded increased fuel consumption values in July compared to February due to a higher number of LTO cycles and despite the fact that Frankfurt had lower taxi times in July while taxi times in Zagreb remained almost the same. The third destination to follow shows seasonal differences in flight operations. In February, the third destination according to fuel consumption was London Heathrow airport, followed closely by Paris Charles de Gaulle. July showed Dubrovnik as the third destination followed closely by Paris. This is because the LTO cycles in Dubrovnik in July were five times higher than in February while taxi times remained the same. Paris had exactly two times more LTO cycles in July with a one minute decrease in taxi-out time and a one minute increase in taxi-in time. Destinations operated by the Airbus fleet during summer only, namely Barcelona, London Gatwick, Rijeka and Skopje, yielded the lowest fuel consumption values. Differences from all-engine taxi in Table 6 show that while single-engine taxi operations could have saved 31 457 kg in February, electric taxi operations could have saved 125 828 kg of fuel. In July the savings are, of course, higher because of higher number of operations. Single-engine operations could have saved 47 783 kg while electric taxi operations could have saved 191 132 kg of fuel.

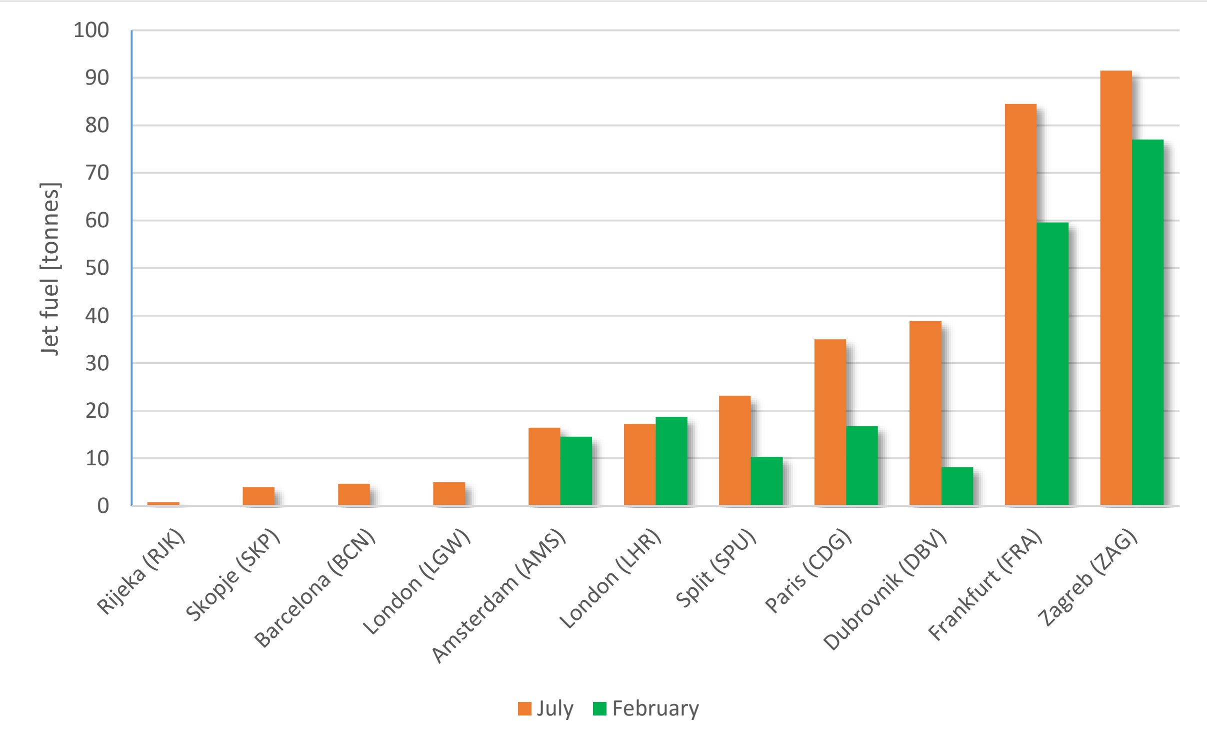
Table 6. Fuel consumption values per month and destination for Croatia Airlines Airbus fleet, for all methods of taxi

Destination (IATA code)	February			July		
	All-engine	Single-engine	Electric taxi	All-engine	Single-engine	Electric taxi
	All values in kilograms					
Amsterdam (AMS)	14565.60	12045.60	4485.60	16432.64	13616.64	5168.64
Barcelona (BCN)	N/A	N/A	N/A	4641.60	3927.60	1785.60
Dubrovnik (DBV)	8131.76	7151.76	4211.76	38838.80	34183.80	20218.80
Frankfurt (FRA)	59568.32	49264.32	18352.32	84477.12	69891.12	26133.12
London (LGW)	N/A	N/A	N/A	4950.88	4076.88	1454.88
London (LHR)	18727.20	15487.20	5767.20	17201.28	14201.28	5201.28
Paris (CDG)	16730.56	13804.56	5026.56	35029.12	28869.12	10389.12
Rijeka (RJK)	N/A	N/A	N/A	784.32	700.32	448.32
Skopje (SKP)	N/A	N/A	N/A	4002.00	3507.00	2022.00
Split (SPU)	10308.48	9216.48	5940.48	23132.72	20493.72	12576.72
Zagreb (ZAG)	77022.00	66627.00	35442.00	91492.80	79732.80	44452.80
TOTAL	**205053.92**	**173596.92**	**79225.92**	**320983.28**	**273200.28**	**129851.28**
Difference from all-engine taxi	N/A	**31457**	**125828**	N/A	**47783**	**191132**

BOTH MONTHS TOTAL	All-engine	Single-engine	Electric taxi
	526037.20	**446797.20**	**209077.20**

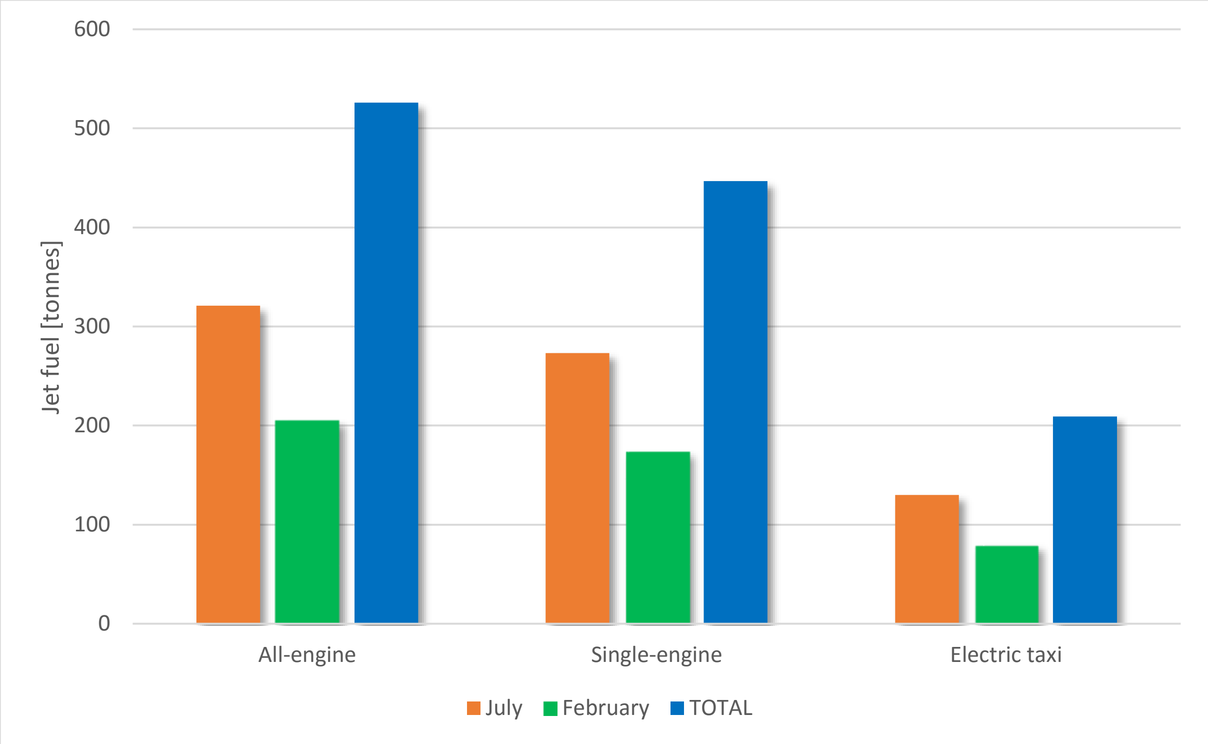
Fuel consumptions values for all-engine taxi shown in Table 6 are also shown in Graph 6 to better illustrate the effects of seasonality. The destinations are sorted according to their July fuel consumption values. The lowest value, Rijeka, is displayed on the far left of the graph and the highest one, Zagreb, on the far right. Dubrovnik experienced the largest effect of seasonality, followed by Split and Paris.

Looking at the numbers in Table 6 it can be seen that, according to the model developed in chapter 5, fuel consumption during single-engine and electric taxi operations is lower than during all-engine taxi operations in all destinations. These results are mathematically logical according to equations (3), (9) and (14).



Graph 6. Fuel consumption during all-engine taxi per destination for Croatia Airlines Airbus fleet

In order to illustrate how much single-engine taxi and electric taxi lower fuel consumption, a comparison between total values for February and July, and combined total values, is given in Graph 7. The graph clearly illustrates the benefits electric taxi brings in terms of fuel consumption. Single-engine taxi brings only a slight reduction in fuel consumption according to the model, while electric taxi reduces fuel consumption more than twice.



Graph 7. Total fuel consumption values per month and combined total for different types of taxi operations

Just how much exactly can be shown in terms of Fuel Efficiency Index *FEI* described in subchapter 5.1. Values shown in Table 6 were inputted in equations (1) and (2) for this purpose. The results are given in Table 7.

Table 7. Fuel Efficiency Index and Single-engine Fuel Efficiency Index per destination for Croatia Airlines Airbus fleet

Destination (IATA code)	February		July	
	FEI_{SE}	FEI	FEI_{SE}	FEI
Amsterdam (AMS)	0.82699	0.30796	0.82863	0.31453
Barcelona (BCN)	N/A	N/A	0.84617	0.38469
Dubrovnik (DBV)	0.87948	0.51794	0.88015	0.52058
Frankfurt (FRA)	0.82702	0.30809	0.82734	0.30935
London (LGW)	N/A	N/A	0.82347	0.29386
London (LHR)	0.82699	0.30796	0.82559	0.30238
Paris (CDG)	0.82511	0.30044	0.82415	0.29659
Rijeka (RJK)	N/A	N/A	0.89290	0.57160
Skopje (SKP)	N/A	N/A	0.87631	0.50525
Split (SPU)	0.89407	0.57627	0.88592	0.54368
Zagreb (ZAG)	0.86504	0.46015	0.87147	0.48586
AVERAGE	**0.84659**	**0.38637**	**0.85114**	**0.40454**
BOTH MONTHS AVERAGE	FEI_{SE}		FEI	
	0.84936		**0.39746**	

The both months average value of Single-engine Fuel Efficiency Index FEI_{SE} was calculated to be 0.84936. February had a better FEI_{SE} but lower only by a value of 0.00277, while July had a higher FEI_{SE} by only 0.00178. This means that on average the single-engine taxi operations would be 15.06% more fuel efficient than all-engine taxi.

The both months average value of Fuel Efficiency Index *FEI* was calculated to be 0.39746. February was again better but only by a margin of 0.01109 while July lagged by a margin of 0.00708. These results show that on average electric taxi operations would be 60.25% more fuel efficient than all-engine taxi.

These values do not correlate well with the ones calculated by Ithnan et al.[90] which showed an average of 25.3% decrease in fuel consumption for single-engine taxi operations compared to all-engine taxi, and an average of 40% decrease in fuel consumption for electric taxi. Ithnan et al. stated that their model was also based on assumptions but exactly which ones is unknown. This is why it wasn't possible to make a comparison between the models. Therefore it is unknown why there are differences in results, but it is assumed that the differences stem from the assumptions of this model that were listed in subchapter 5.5 and because the model developed by Ithnan et al. was used to calculate savings per specific airport, namely Amsterdam Schiphol and Kuala Lumpur International. The savings in their model were based on entire airport traffic and were not limited to one air carrier.

The highest values of *FEI* indices were calculated for Split airport in February, FEI_{SE} value of 0.89407 and *FEI* value of 0.57627. The second and third highest in February were Dubrovnik and Zagreb. The reason why Split had the highest *FEI* indices was because the taxi times were short and because the average taxi-in time in February was only 3 minutes which means that it was assumed that single-engine or electric taxi operations were not considered an option. Dubrovnik and Zagreb took second and third place because of short taxi times compared to other destinations.

The second highest *FEI* indices of all were calculated for Rijeka airport in July, FEI_{SE} value of 0.89290 and *FEI* value of 0.57160. Taxi times shorter than any other destination were the most contributing factor for these values. The second and third place in July were taken by Split and Dubrovnik, respectively, followed by Skopje and Zagreb. Again, the reason for these values were low taxi times.

[90] Ithnan MI, Selderbeek T, Beelaerts van Blokland WWA, Lodewijks G. *Aircraft Taxiing Strategy Optimization*. Technology University of Delft, the Netherlands; 2013.

Taxi time is therefore the most contributing factor that affects *FEI* indices. The lower the taxi times, the higher the *FEI* indices. But fuel flow is a contributing factor as well and, interestingly, the lower the fuel flow, the higher the *FEI* indices are. This is because in case of a low fuel flow there would be only slight changes in efficiency for single-engine and electric taxi operations.

To conclude this chapter, aircraft gas emissions values were also calculated according to equations (21), (22), (23), (24) and (25). The values were calculated for all-engine, single-engine and electric taxi operations for carbon dioxide, hydrocarbons, mono-nitrogen oxides, carbon monoxide and sulphur dioxide. Since the tables showing the values of each gas for each destination per month were too big to include in this text, they are given separately in Attachments A (February) and B (July). They show that over one million kilograms of carbon dioxide were produced by taxi operations only during all-engine taxi operations of the Airbus fleet in July. Other gases show much smaller amounts but should not be ignored because of their adverse effect on the Earth's ecosystem and human health. Had all of the taxi operations done in July been single-engine, the emissions of carbon dioxide would be reduced by about 151 tonnes. Electric taxi method shows an even greater decrease of almost 604 tonnes had all of the July taxi operations been electric taxi. Croatia Airlines Airbus fleet emitted about 36% less gas emissions in February than in July. Table 8 shows percentage decrease in gas emissions i.e. efficiency of single-engine and electric taxi compared to all-engine taxi, and electric taxi compared to single-engine taxi, in terms of gas emissions for February and July separately as well as for both months combined.

Table 8. Percentage decrease in all gas emissions (CO_2, HC, NO_x, CO, SO_2) for different methods of taxi

Month	Single-engine to All-engine taxi	Electric taxi to All-engine taxi	Electric taxi to Single-engine taxi
February	15.341%	61.363%	54.362%
July	14.886%	59.546%	52.470%
COMBINED	**15.064%**	**60.254%**	**53.205%**

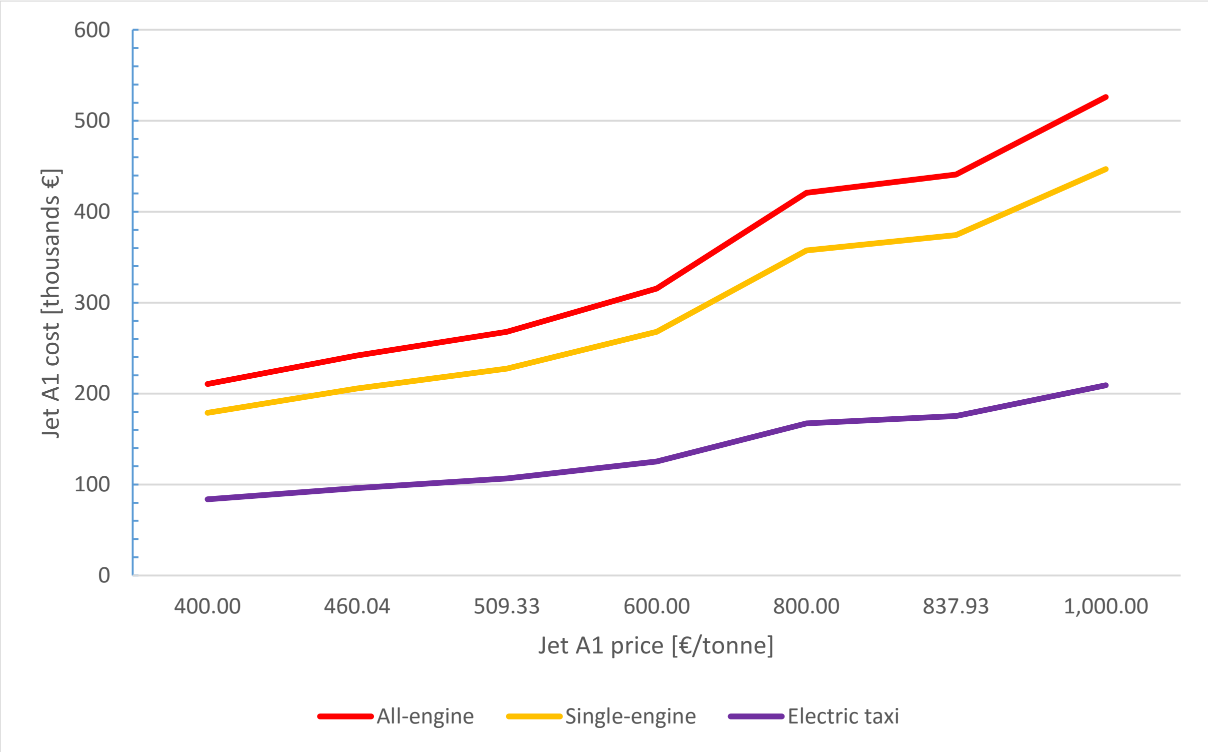
The percentage decrease in gas emissions is equivalent to fuel consumption decrease described earlier which is mathematically logical because the equations for emissions use the same fuel consumption variables and simply multiply them by a specific factor to obtain the amount of gas emissions in kilograms. Percentage decrease of carbon dioxide calculated by Ithnan et al. is equivalent to their calculated fuel consumption decrease but percentage decrease values for hydrocarbons, carbon monoxide and mono-nitrogen oxides are different. This is probably because their gas emissions model took more factors into consideration.

For illustrative purposes it might be interesting to see the results of this analysis displayed in terms of money. Since exact fuel prices at which Croatia Airlines bought fuel in February and July this year were not obtainable, Table 9 shows how much money per month Croatia Airlines would have to pay for their Airbus aircraft for each type of taxi method and for several different fuel prices.

Table 9. Cost of taxi fuel and potential savings per month for different taxi methods in respect of different fuel prices, for Croatia Airlines Airbus fleet.
** Jet A1 price in July 2015; ** Jet A1 price in February 2015; *** Highest Jet A1 price – August 2012*

Fuel price €/tonne	February				
	All-engine	Single-engine	Electric taxi	SE savings	E-taxi savings
	All values in euros				
400.00	82 021.57	69 438.77	31 690.37	**12 582.80**	**50 331.20**
460.04*	94 333.01	79 861.53	36 447.09	**14 471.48**	**57 885.91**
509.33**	104 440.11	88 418.12	40 352.14	**16 021.99**	**64 087.98**
600.00	123 032.35	104 158.15	47 535.55	**18 874.20**	**75 496.80**
800.00	164 043.14	138 877.54	63 380.74	**25 165.60**	**100 662.40**
837.93***	171 820.83	145 462.07	66 385.78	**26 358.76**	**105 435.06**
1 000.00	205 053.92	173 596.92	79 225.92	**31 457.00**	**125 828.00**
Fuel price €/tonne	**July**				
	All-engine	**Single-engine**	**Electric taxi**	**SE savings**	**E-taxi savings**
	All values in euros				
400.00	128 393.31	109 280.11	51 940.51	**19 113.20**	**76 452.80**
460.04*	147 665.15	125 683.06	59 736.78	**21 982.09**	**87 928.37**
509.33**	163 486.41	139 149.10	66 137.15	**24 337.32**	**97 349.26**
600.00	192 589.97	163 920.17	77 910.77	**28 669.80**	**114 679.20**
800.00	256 786.62	218 560.22	103 881.02	**38 226.40**	**152 905.60**
837.93***	268 961.52	228 922.71	108 806.28	**40 038.81**	**160 155.24**
1 000.00	320 983.28	273 200.28	129 851.28	**47 783.00**	**191 132.00**

Jet fuel prices have been decreasing recently and are currently below 500 euros per tonne.[91] Specific values in Table 9 present the Jet A1 fuel price in July and February, marked with one and two asterisks, respectively. The value marked with three asterisks presents the highest ever Jet A1 fuel price recorded in August 2012.[92] Graph 8 further illustrates how the cost of fuel rises in respect of different fuel prices. The graph presents combined February and July values. Although jet fuel prices have been decreasing recently, air carriers must have in mind their volatility that was demonstrated in recent years and should not rely on them being low for a long period of time. According to Table 9 and Graph 8, electric taxi can yield significant savings per month when compared to all-engine taxi, even during the least busy month of the year.



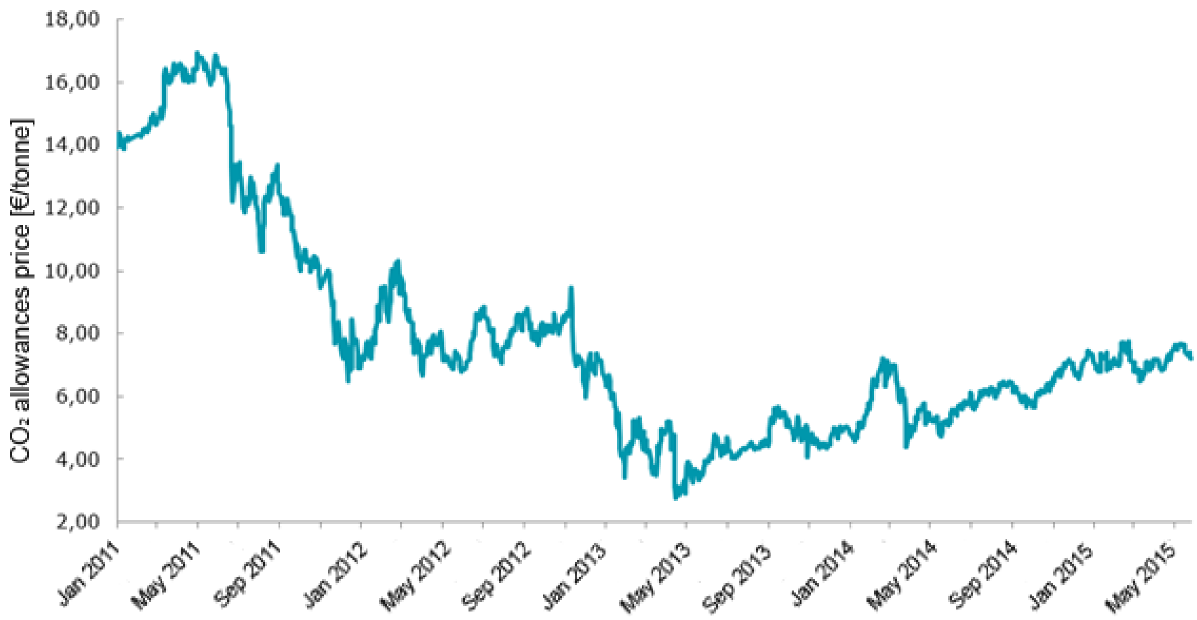
Graph 8. Combined February and July Jet A1 cost for Croatia Airlines Airbus fleet in respect of different fuel prices

Further savings in terms of money could be obtained from reduced carbon dioxide emissions. EU ETS requires European air carriers to buy allowances for carbon emissions, the price of which has varied over the years. Graph 9 shows the development of carbon

[91] *Fuel Price Analysis* [Internet]. 2015 [updated 2015 August 21; cited 2015 August 30]. Available from: http://www.iata.org/publications/economics/fuel-monitor/Pages/price-analysis.aspx

[92] *Jet Fuel Monthly Price - Euro per Gallon* [Internet]. 2015 [updated 2015 August; cited 2015 August 30]. Available from: http://www.indexmundi.com/commodities/?commodity=jet-fuel&months=60&currency=eur

dioxide prices over the recent years. At the start of emissions trading the prices were relatively high, up to 17 euros per tonne of carbon dioxide. The prices decreased as the carbon market stabilised and reached an all-time low in April 2013. Since then the prices kept rising and that same trend continues today. According to the graph the latest carbon dioxide allowances price was about 7 euros per tonne of CO_2.



Graph 9. Carbon dioxide allowances price in EU ETS system[93]

Table 10 on the next page shows the cost of carbon dioxide allowances and potential savings in the same manner Table 9 did for jet fuel. The scale of these savings might seem small at current price of carbon compared to potential jet A1 costs savings, but considering that the trend of carbon prices has been increasing almost linearly since April 2013 it is only a matter of time before such savings become significant.

To finally conclude this analysis it is once again emphasized that the model developed is idealistic and the results it yields should be viewed as such as well. It does not take into account some factors which could affect the results significantly. Another one of such factors is the cost-of-weight i.e. how much the fuel consumption would increase during cruise as a downside of carrying an additional aircraft system on board. This consideration is out of the scope of this thesis and is a recommendation for possible

[93] Obtained from Belektron d.o.o. (September 2015)

future research in this area. Overall, however, it can be said that electric taxi could provide a significant amount of savings which are both beneficial environmentally and financially for air carriers.

Table 10. Cost of carbon dioxide allowances in EU ETS and potential savings per month for different taxi methods in respect of different carbon prices, for Croatia Airlines Airbus fleet

Carbon price €/tonne	February				
	All-engine	Single-engine	Electric taxi	SE savings	E-taxi savings
	All values in euros				
7	4 521.44	3 827.81	1 746.93	**693.63**	**2 774.51**
8	5 167.36	4 374.64	1 996.49	**792.72**	**3 170.87**
9	5 813.28	4 921.47	2 246.05	**891.81**	**3 567.22**
10	6 459.20	5 468.30	2 495.62	**990.90**	**3 963.58**
12	7 751.04	6 561.96	2 994.74	**1 189.07**	**4 756.30**
15	9 688.80	8 202.45	3 743.42	**1 486.34**	**5 945.37**
20	12 918.40	10 936.61	4 991.23	**1 981.79**	**7 927.16**
Carbon price €/tonne	**July**				
	All-engine	**Single-engine**	**Electric taxi**	**SE savings**	**E-taxi savings**
	All values in euros				
7	7 077.68	6 024.07	2 863.22	**1 053.62**	**4 214.46**
8	8 088.78	6 884.65	3 272.25	**1 204.13**	**4 816.53**
9	9 099.88	7 745.23	3 681.28	**1 354.65**	**5 418.59**
10	10 110.97	8 605.81	4 090.32	**1 505.16**	**6 020.66**
12	12 133.17	10 326.97	4 908.38	**1 806.20**	**7 224.79**
15	15 166.46	12 908.71	6 135.47	**2 257.75**	**9 030.99**
20	20 221.95	17 211.62	8 180.63	**3 010.33**	**12 041.32**

7. CONCLUSION

Ever since the first heavier-than-air powered flight of the Wright Flyer in 1903, aviation industry has been depending on derivatives of oil to power all kinds of aircraft. Today, living in a world without oil is unimaginable, but there is a problem. Burning oil and its derivatives produces gases that are harmful to the Earth's ecosystem and human health. Aviation, and other industries as well, have become too dependent on oil so it would be impossible to simply switch to a different, renewable or at least more efficient, energy source. This is why it is important for sustainable development policies to be developed and implemented by all stakeholders in the aviation industry.

The goal to reduce greenhouse gas emissions to 50% of their 2005 levels by year 2050 is a very ambitious one, but nevertheless important to prevent extreme climate change. Because of the inability of the aviation industry to switch to a new energy source in the short-term (up to year 2050) it is very important to control aircraft gas emissions by other means. Existing fuel efficiency measures have proven to be very successful in terms of reducing fuel consumption and aircraft gas emissions and should therefore be implemented as much as possible by all air carriers. Although emissions trading systems are an additional financial expense for air carriers, they have an important role in stimulating the development and implementation of existing and new fuel efficiency measures.

Measures that focus solely on reducing aircraft mass might not be enough to improve fuel efficiency in the future. This is why it is necessary to develop new, alternative measures that reduce fuel consumption and gas emissions by different means. One of such measures is electric taxi. Although the model developed in this thesis is idealistic, the results it has given show that implementation of electric taxi could provide significant fuel savings and aircraft gas emission reduction during taxi operations. It was found that electric taxi could provide fuel savings and aircraft gas emission reduction of about 60% during taxi, when compared to all-engine taxi within the constraints listed in subchapter 5.5. Even for an air carrier with a small fleet like Croatia Airlines this could be profitable, especially when considering the fact that personnel education, installation and maintenance of WheelTug, the electric taxi system that's closest to commercial use, is offered for free. The savings would be proportionally larger for air carriers with larger fleets.

However, it is recommended that a follow-up research is done after any of the electric taxi systems gets certified for commercial use. In case of WheelTug, a follow-up research would especially be beneficial for air carriers that operate Airbus A320 family fleets outside of the United States. This is because Boeing 737NG will probably be the first aircraft to get the necessary certification by the FAA in 2017, while Airbus A320 family is expected to get it a year later. During that time a follow-up research could be done in real flight operations. Assuming that the savings for both aircraft types are similar, having actual and accurate operational data about fuel savings that electric taxi brings when compared to all-engine taxi could convince more air carriers to get it installed.

In case of any future research on this matter, it is recommended to obtain actual fuel consumption data during electric taxi operations and during equivalent all-engine taxi operations. That data could then be used to calculate actual *FEI* values which could then be compared to *FEI* values calculated in this thesis. Moreover, if it is determined that taxi times during electric taxi are longer than during all-engine taxi for equivalent taxi distances, then the increase of fuel consumption due to longer taxi times should be taken into account. It would also be important to take account of an increase in fuel consumption during flight because having an additional system on board increases aircraft mass, thus fuel consumption and gas emissions as well. Electric taxi would therefore be responsible for a slight decrease in fuel efficiency during flight for short-haul and medium-haul flight operations. A more elaborate research could also attempt to quantify the effect of weather and other factors on utilization of electric taxi systems.

However, electric taxi gives much more than just fuel savings and gas emission reductions. Its other important benefits that were beyond the scope of this thesis include time savings on the ground, for example shorter turnaround and pushback times, reduced foreign object damage risk which leads to better engine efficiency, reduced brake wear, increased gate and taxiway throughput, increased safety of ground crews on aprons, reduced noise in airport environment, and others. All of these benefits should be further researched to determine the overall impact of electric taxi on air carriers and airports.

Electric taxi is definitely the future of fuel efficiency measures and aviation itself. It has been proven to have great potential in reducing fuel consumption and aircraft gas emissions. If this new technology gets adopted by enough air carriers it will be a big step towards reaching IATA's ambitious emission reduction goal. Possible future development of electric taxi systems for more aircraft types could bring that goal even closer to achievement.

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LIST OF ABBREVIATIONS AND ACRONYMS

AMS	IATA code for Amsterdam Schiphol airport
APM	Aircraft Performance Monitoring
APU	Auxiliary Power Unit
BCN	IATA code for Barcelona airport
CDG	IATA code for Paris Charles de Gaulle airport
CH_4	Methane
CI	Cost Index
CO	Carbon monoxide
CO_2	Carbon dioxide
DBV	IATA code for Dubrovnik airport
DDT	Dichlorodiphenyltrichloroethane
EASA	European Aviation Safety Agency
EEA	European Economic Area
EFB	Electronic Flight Bag
EGTS	Electric Green Taxiing System
EU	European Union
EU ETS	European Union Emissions Trading System/Scheme
FAA	Federal Aviation Administration
FCOM	Flight Crew Operating Manual
FL	Flight Level
FMS	Flight Management System
FRA	IATA code for Frankfurt International airport
H_2O	Dihydrogen monoxide
HC	Hydrocarbons
IAS	Indicated Airspeed
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
LED	Light-Emitting Diode

LGW	IATA code for London Gatwick airport
LHR	IATA code for London Heathrow airport
LTO	Landing to Take-Off
MMEL	Master Minimum Equipment List
MRO	Maintenance, Repair and Overhaul
N_2O	Nitrous oxide
NASA	National Aeronautics and Space Administration
NM	Nautical Miles
NO_x	Mono-nitrogen oxides
O_3	Ozone
OH	Hydroxyl radical
plc	Public Limited Company
RJK	IATA code for Rijeka airport
SKP	IATA code for Skopje airport
SO_2	Sulphur dioxide
SPU	IATA code for Split airport
STC	Supplemental Type Certificate
US	United States
USA	United States of America
ZAG	IATA code for Zagreb airport

LIST OF VARIABLES

FC_{all}	total fuel consumption during all-engine taxi in kilograms	[kg]
FC_{ex}	total fuel consumption during electric taxi in kilograms	[kg]
FC_{SE}	total fuel consumption during single-engine taxi in kilograms	[kg]
FEI	Fuel Efficiency Index	
FF	Average main engine fuel flow	[kg/min]
FF_{APU}	Average APU fuel flow	[kg/min]
m_{CO}	Carbon monoxide mass	[kg]
m_{CO2}	Carbon dioxide mass	[kg]
m_f	Mass of fuel	[kg]
m_{HC}	Hydrocarbons mass	[kg]
m_{NOx}	Mono-nitrogen monoxide mass	[kg]
m_{out}	Taxi fuel mass	[kg]
m_{SO2}	Sulphur dioxide mass	[kg]
n	Number of destinations	
N	Number of LTO cycles per destination	
$t_{ex,in}$	Average taxi-in time during electric taxi	[min]
$t_{ex,out}$	Average taxi-out time during electric taxi	[min]
t_{in}	Average taxi-in time during all-engine taxi	[min]
t_{out}	Average taxi-out time during all-engine taxi	[min]
$t_{SE,in}$	Average taxi-in time during single-engine taxi	[min]
$t_{SE,out}$	Average taxi-out time during single-engine taxi	[min]

LIST OF FIGURES

LIST OF TABLES

LIST OF GRAPHS

ATTACHMENT A

Table 11. Gas emissions during taxi phase per destination, for February operations of Croatia Airlines Airbus fleet

All values in [kg]	February														
	All-engine Taxi					Single-engine Taxi					Electric Taxi				
Destination	CO2	HC	NOx	CO	SO2	CO2	HC	NOx	CO	SO2	CO2	HC	NOx	CO	SO2
Amsterdam (AMS)	45881.64	10.78	174.79	116.52	14.57	37943.64	8.91	144.55	96.36	12.05	14129.64	3.32	53.83	35.88	4.49
Dubrovnik (DBV)	25615.04	6.02	97.58	65.05	8.13	22528.04	5.29	85.82	57.21	7.15	13267.04	3.12	50.54	33.69	4.21
Frankfurt (FRA)	187640.21	44.08	714.82	476.55	59.57	155182.61	36.46	591.17	394.11	49.26	57809.81	13.58	220.23	146.82	18.35
London (LHR)	58990.68	13.86	224.73	149.82	18.73	48784.68	11.46	185.85	123.90	15.49	18166.68	4.27	69.21	46.14	5.77
Paris (CDG)	52701.26	12.38	200.77	133.84	16.73	43484.36	10.22	165.65	110.44	13.80	15833.66	3.72	60.32	40.21	5.03
Split (SPU)	32471.71	7.63	123.70	82.47	10.31	29031.91	6.82	110.60	73.73	9.22	18712.51	4.40	71.29	47.52	5.94
Zagreb (ZAG)	242619.30	57.00	924.26	616.18	77.02	209875.05	49.30	799.52	533.02	66.63	111642.30	26.23	425.30	283.54	35.44
TOTAL	**645919.85**	**151.74**	**2460.65**	**1640.43**	**205.05**	**546830.30**	**128.46**	**2083.16**	**1388.78**	**173.60**	**249561.65**	**58.63**	**950.71**	**633.81**	**79.23**

ATTACHMENT B

Table 12. Gas emissions during taxi phase per destination, for July operations of Croatia Airlines Airbus fleet

All values in [kg]	July														
	All-engine Taxi					Single-engine Taxi					Electric Taxi				
Destination	CO_2	HC	NO_x	CO	SO_2	CO_2	HC	NO_x	CO	SO_2	CO_2	HC	NO_x	CO	SO_2
Amsterdam (AMS)	51762.82	12.16	197.19	131.46	16.43	42892.42	10.08	163.40	108.93	13.62	16281.22	3.82	62.02	41.35	5.17
Barcelona (BCN)	14621.04	3.43	55.70	37.13	4.64	12371.94	2.91	47.13	31.42	3.93	5624.64	1.32	21.43	14.28	1.79
Dubrovnik (DBV)	122342.22	28.74	466.07	310.71	38.84	107678.97	25.30	410.21	273.47	34.18	63689.22	14.96	242.63	161.75	20.22
Frankfurt (FRA)	266102.93	62.51	1013.73	675.82	84.48	220157.03	51.72	838.69	559.13	69.89	82319.33	19.34	313.60	209.06	26.13
London (LGW)	15595.27	3.66	59.41	39.61	4.95	12842.17	3.02	48.92	32.62	4.08	4582.87	1.08	17.46	11.64	1.45
London (LHR)	54184.03	12.73	206.42	137.61	17.20	44734.03	10.51	170.42	113.61	14.20	16384.03	3.85	62.42	41.61	5.20
Paris (CDG)	110341.73	25.92	420.35	280.23	35.03	90937.73	21.36	346.43	230.95	28.87	32725.73	7.69	124.67	83.11	10.39
Rijeka (RJK)	2470.61	0.58	9.41	6.27	0.78	2206.01	0.52	8.40	5.60	0.70	1412.21	0.33	5.38	3.59	0.45
Skopje (SKP)	12606.30	2.96	48.02	32.02	4.00	11047.05	2.60	42.08	28.06	3.51	6369.30	1.50	24.26	16.18	2.02
Split (SPU)	72868.07	17.12	277.59	185.06	23.13	64555.22	15.17	245.92	163.95	20.49	39616.67	9.31	150.92	100.61	12.58
Zagreb (ZAG)	288202.32	67.70	1097.91	731.94	91.49	251158.32	59.00	956.79	637.86	79.73	140026.32	32.90	533.43	355.62	44.45
TOTAL	**1011097.33**	**237.53**	**3851.80**	**2567.87**	**320.98**	**860580.88**	**202.17**	**3278.40**	**2185.60**	**273.20**	**409031.53**	**96.09**	**1558.22**	**1038.81**	**129.85**

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METAPODACI

Naslov rada: MJERE ZA POBOLJŠANJE PROGRAMA UČINKOVITOG TROŠENJA GORIVA PRIMJENOM SUSTAVA ELEKTRIČNOG VOŽENJA

Autor: Dino Švragulja

Mentor: doc. dr. sc. Anita Domitrović

Naslov na drugom jeziku (engleski):

MEASURES FOR IMPROVING FUEL EFFICIENCY BY IMPLEMENTING ELECTRIC TAXI SYSTEM

Povjerenstvo za obranu:

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IZJAVA O AKADEMSKOJ ČESTITOSTI I SUGLASNOST

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U Zagrebu, 18-09-15

(potpis)