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The Potential Impact of Electric Aircraft Taxiing: A Probabilistic Analysis and Fleet Assignment Optimization

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On-board electric motors can be used to drastically reduce the fuel usage during the taxiing phase of aircraft, leading to cost reductions for airlines and lower amounts of harmful emissions. This study analyses the current state of this innovation and its potential impact on aviation. On a global level, full adoption of electric aircraft taxiing is expected to cause a reduction in jet fuel usage of 846 million kg per year, equivalent to 186 million euros of reduced costs and 2.67 million tonnes of carbon dioxide emissions. This results in a reduction of 0.3% of the total global carbon dioxide emissions of the aviation sector. Locally, airports and their surroundings will benefit significantly from the reduced emissions, because a substantial fraction of airport emissions are due to the taxiing phase. Analysis of the effect of electric aircraft taxiing to key stakeholders such as airlines shows that American airlines would reap substantially larger benefits than European competitors because of consistently higher taxi times in the United States. Low-cost carriers are expected to see smaller impact than traditional hub-and-spoke airlines, due to short taxi times in the secondary airports they predominantly fly to. KLM could save 17.3 million kg of jet fuel annually, representing a cost of 3.8 million euros, which would potentially increase profits by 3%, and a carbon dioxide emission of 55 million kg. Since the road to full adoption is still long, a strategic analysis of the fleet shows the marginal yearly cost reduction per installed electric taxiing system starts at 82 thousand euros for the first product, which reduces to 10 thousand after 100 systems have been installed. Especially the flights between Amsterdam and London, Paris and Manchester should be assigned to aircraft with electric taxiing systems, because these flights would have the most impact given their relatively low flight distance and high taxi times.

I. Introduction

The main area of interest of the proposed research is to find how aircraft taxiing can be improved in terms of costs and environmental effects, examining multiple alternatives to solve the issues at stake and including information that has not previously been used to this end. This area is likely to be the most feasible first step towards an aviation sector with lower environmental effects. Two main solutions have been proposed in the past decade to accomplish substantial reduction in fuel usage in the taxiing phase, both cutting the utilization of the main engines drastically.

Aircraft can either be towed by an external vehicle or be propelled by an internal motor designated for taxiing. Both solutions are potentially feasible, but each with differing advantages and flaws. Due to these differences, future airports

are likely to combine the two concepts in a balanced way for optimal results.

The period of time that aircraft spend taxiing is of vital importance to the impact of electric aircraft taxiing, but taxi times vary greatly within and across airports. This variability should be taken into account when assessing the

benefits of electric aircraft taxiing. This study will use probabilistic data on taxi times from airports around the world, both for the taxi-out and the taxi-in phase, and match this with corresponding flight schedule data featuring airline-specific commercial flights. The taxi time serves as major input to determine the amount of fuel burned during this flight phase, which in turn gives information on costs and emissions.

Two main goals are attached to this research work. Firstly, it is desirable to achieve an accurate estimate of the global impact of implementing electric aircraft taxi systems (ETS) in aircraft. Secondly, an airline point of view is taken to find the optimal fleet adjustments to be made together with the associated impact of those

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adjustments. Both are accomplished by means of a probabilistic analysis using airport-specific taxi time distributions.

II.Methodology

A. Assumptions

Several assumptions are made to make the analysis possible. Firstly, the fuel flow of the main engines during the taxi phase is assumed to have a mean level of 11.97 kg per minute, while the electric taxiing system would use 2.17 kg per minute, following the research of Wijnterp et al. (2014) [22].

Next to that, the weight of the electric taxiing system is assumed to be 400 kg at the baseline scenario, because this is the maximum design weight across the currently available concepts, namely the weight of the EGTS concept of Safran Technologies. This weight is used to compute the inflight fuel penalty. To translate fuel savings to cost reductions, the jet fuel price is assumed to be 0.22 euro per kg, following the Jet Fuel Price Monitor of IATA.

Finally, the warm-up and cool-down times are assumed to be 5 and 3 minutes, following the study of Vaishnav (2014) [10]. As a last assumption, the minimum turn-around time is taken to be equal for all aircraft types in this analysis.

B. Taxi Time Modelling

For each of the 433 airports in the study, the taxi in and the taxi-out time is to be modelled. The data provides the necessary distributional parameters for fitting a probability curve, namely the mean, the standard deviation and the tenth and ninetieth percentiles. As found by [23], a Gumbel distribution is most suitable to the modelling of taxi times. Consequently, the initial fit is a Gumbel distribution by using the appropriate mean μ and standard deviation σ to find the right scale β and location γ parameters, as in Equations 1 and 2, in which γ represents the Euler-Mascheroni constant.

$$\beta = \sqrt{\frac{6\sigma^2}{\pi^2}} \quad (1)$$

$$\lambda = \mu - \beta\gamma \quad (2)$$

The next step involves fitting the distribution such that the lower bound of either warm-up or cool-down time are included while the tenth and ninetieth percentiles are correctly included too. This is done by generating a large number of samples from the original distribution, removing the values below the lower threshold and after that adjust the distribution in an iterative manner by removing samples until the percentiles fit, while keeping in mind the mean. The final step involves interpolating the samples histogram, yielding the correct probability distribution.

C. Fuel Savings and Penalties

For each unique combination of origin, destination and aircraft type, the potential fuel savings are computed by subtracting the in-flight weight penalty from the savings during the ground taxi phases. To find the latter, the taxi time distribution is scaled by the reduction in fuel flow per minute, while the penalty is found by using the empirical form of the Breguet Range equation for the B737 fleet found by Wijnterp et al. (2014) [22], see Equation 3 in which ΔW_{AC} and S represent the additional aircraft weight and the flight distance.

$$F_{add} = \frac{\Delta W_{AC}}{1000}\left(9.10^{-6} S^2 + 0.048S + 2.34\right) \quad (3)$$

To adjust this to the other aircraft types in the data-set, a set of fuel data is used leading to a fuel factor that is to be multiplied by the penalty. The penalties are subtracted from the fuel savings probability distributions, such that the final product is a probability distribution providing information about the fuel savings of each flight.

D. Fleet Assignment Optimization

Once the probabilistic distribution of fuel savings are computed for each origin-destination and aircraft type combination, it is possible to design an algorithm that choose which aircraft are assigned to each of the flights in the schedule while maximizing the fuel savings from electric aircraft taxiing.

1. *Sets*
   - P: Aircraft $\{1, \dots, j, \dots, n_p\}$
   - A: Airports $\{1, \dots, k, \dots, n_a\}$
   - F: Flights $\{1, \dots, i, \dots, n_f\}$
     - F_k^+: Flights arriving at airport k
     - F_k^-: Flights departing from airport k
     - $F_k^+(\theta)$: Flights in F_k^+ such that $t_i^+ < \theta - \Delta t$
     - $F_k^-(\theta)$: Flights in F_k^- such that $t_i^- < \theta$
     - $F_{OT}(\theta)$: Flights that are operated by a different AC-type than flight θ
     - $F_{ACT}(j)$: Flights with other aircraft type than j

2. *Parameters*
   - t_i^+: Arrival time of flight i
   - t_i^-: Departure time of flight i
   - Δt: Minimum turn-around time (TAT)
   - c_{ij}: Cost function (fuel savings from flight i if assigned to aircraft j)
   - a_j^0: Airport at which aircraft j starts

3. *Decision Variable*
   - $x_{ij} \in \{0,1\}$, equals 1 if flight i is assigned to aircraft j, 0 otherwise

4. *Objective Function*

   The objective is to maximize the fuel savings (FS) of the system

   - $FS = \sum_{i \in F} \sum_{j \in P} c_{ij} \, x_{ij}$

5. *Constraints*

There are four constraints required for the optimization algorithm to function.
The first constraint makes sure that not more than one aircraft is scheduled per flight.
The second constraint causes airport continuity for all airports except the starting one. In this way, An aircraft can only leave an airport if it has landed there at least one turn-around time earlier.
Constraint 3 is similar, but specifically targets the starting airport. The main difference being that the starting airport starts off by having one more departures than arrivals.
Constraint 4 makes sure that there is continuity in the aircraft type per aircraft with ETS. It dictates that an aircraft can only be assigned to a flight, if the designated aircraft type for that flight corresponds with the aircraft type of other flights assigned to that aircraft. If a certain ETS aircraft is assigned to a flight, the corresponding decision variable x_{ij} will be 1. Consequently, the right-hand side of the constraint becomes 0, such that the left-hand side also must be 0 or lower. Looking at the left-hand side, this means that the summation of all flights with a different aircraft type specification cannot be assigned to the ETS aircraft in question. On the other hand, this limit is raised to n_f if the decision variable is 0, such that the summation in that case could include all flights of other aircraft types.

1. $\sum_{j \in P} x_{ij} \leq 1$, *for* $i \in F$
2. $\sum_{i' \in F_k^+(t_i^-)} x_{i'j} - \sum_{i' \in F_k^-(t_i^-)} x_{i'j} \geq x_{ij}$, for $i \in F_k^-, j \in P, k \in A/\{a_j^0\}$
3. $\sum_{i' \in F_k^+(t_i^-)} x_{i'j} - \sum_{i' \in F_k^-(t_i^-)} x_{i'j} \geq x_{ij} - 1$, for $i \in F_k^-, j \in P, k = a_j^0$
4. $\sum_{i' \in F_{ACT}(j)} x_{i'j} \leq \left(x_{ij} - 1\right) * -n_f$, *for* $i \in F, j \in P$

III.Results

This section presents the results of the performed analyses and follows the structure of the methodology above. The most crucial figures and tables resulting from the analyses are shown, but it should be noted that the created models could be used to yield more extensive results. For example, the airline KLM is chosen as main focus point, but any of the 824 airlines in the data-set can be looked at in a similar manner in more detail using the developed models.

A. Taxi Time Modelling

The distribution of taxi times, both at departure and at arrival, is modelled using the Gumbel distribution. For each of the 433 airports, the program computes the distribution such that it fits the input data. Figure 1 show the taxi-in and taxi-out time distribution at Amsterdam Airport Schiphol.

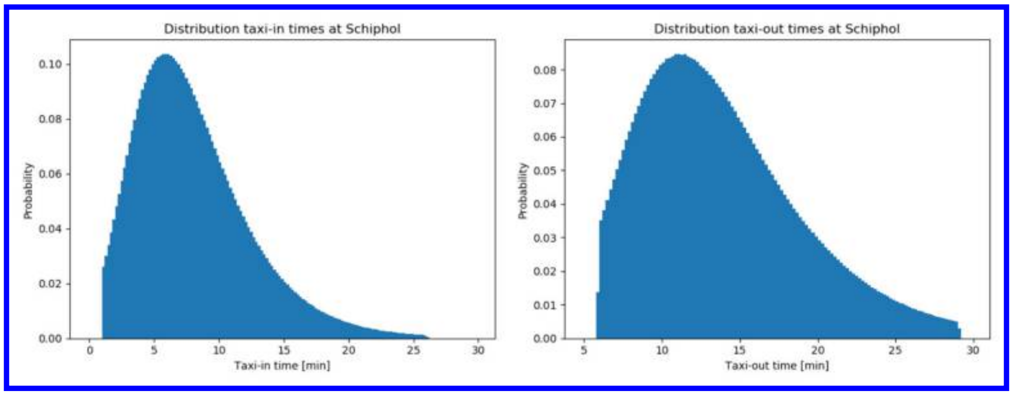

Figure 1: Distribution of taxi in and taxi-out times at Amsterdam Airport Schiphol

The curves show that taxiing times before take-off are considerable longer, with mean 13.9 minutes compared to 8.0 minutes at taxi-in, and contain more outliers causing a heavier right-side tail. The origin of this difference is likely the presence of situations in which aircraft have to wait due to delays in earlier departing aircraft, airport traffic jams so to say, while arriving aircraft spend their delayed arrivals loitering around the airport in designated airspace [24]. The lower bounds of the figures indicate the parameters used for warm-up and cool-down time. The difference in taxi times between airports can be substantial. Table 1 shows an overview of the difference between the three most and the three least efficient airports in terms of mean taxi-out times. Especially at the high taxi time airports, electric aircraft taxiing has serious potential to reduce costs and emissions because every minute of taxiing the main engines burn kerosene.

Table 1. Top three and bottom airports in terms of taxi-out time.

Airport (IATA Code)	*Taxi-out time [min]*
New York (JFK)	34.6
Philadelphia (PHL)	29.2
Washington (IAD)	28.7
Mosjoen/Kjaerstad (MJF)	2.2
Svolvaer/Helle (SVJ)	2.2
Stokmarknes/Skagen (SKN)	2.0

B. Global Impact

By using the airport taxi time distributions together with the flight schedule, a global estimate of the impact is computed and shown in figure 2. Combining the large number of individual distributions forms a normal distribution with a mean of 846 million kg of fuel that could be saved on a yearly basis if electric aircraft taxiing would be adopted on a global scale. This translates to 2.67 million tonnes of carbon dioxide emissions that could be reduced. This appears to be in line with the estimate of Vaishnav (2014) [10], stating the United States domestic aviation industry could save 1.5 million tonnes of carbon dioxide, representing 1% of the total aviation emissions. In terms of costs, the currently low oil price (0.22 euro/kg jet fuel) causes the total cost reduction to be 186 million euros. The question is whether this cost reduction is worthwhile for airlines. This might differ per airline, which will be discussed later in this section.

C. Impact on KLM

A detailed analysis of the situation at the Dutch airline KLM yields the outcome that a 100% adoption of electric taxiing systems brings a reduction of 17.3 million kg of fuel annually, representing a cost of 3.8 million euros.

The average profit of KLM in the years 2011-2018 has been 128 million euros. That means the theoretical impact of electric aircraft taxiing on KLM could be an improvement of 3% on its annual profits. Even though that is purely the fuel cost side of this operational change, without taking into account potential costs for acquisition, installment and maintenance, it still is a substantial change for the better. Combined with a carbon emission saving of 55 million kg, it should absolutely be considered for the future.

Table 2: Savings per flight for KLM

	Retour route	*Potential fuel savings per flight [kg]*	
1	AMS-LHR	201.64	London
2	AMS-CDG	169.07	Paris
3	AMS-FRA	157.75	Frankfurt
4	AMS-MAN	147.60	Manchester
5	AMS-DUS	132.16	Dusseldorf
6	AMS-CPH	130.52	Copenhagen
7	AMS-EDI	130.01	Edinburgh
8	AMS-BRU	129.40	Brussels
9	AMS-MXP	128.11	Milan
10	AMS-MUC	128.08	Munich

Before making large investments to bring about the full fleet transformation from old-fashioned jet engine taxiing to electric taxiing, airlines are likely experimenting on a smaller scale with such innovation projects. For that reason, it is interesting to look at the impact per aircraft or per flight. An overview of the routes with the highest potential saving sis given in table 1. Then, later on in this section, results will be presented showing optimal adoption strategies in terms of flight network and how many aircraft to transform. In the flight schedule used in this study, KLM features a yearly 161 thousand flights. This means that the mean fuel reduction per flight lies at 107 kg, as can be seen in the figure. Again, the probability distribution appears to be normal and this is caused by the convolution of many different distributions. This is dictated by the Central Limit Theorem (CLT). The uncertainty related to the mentioned mean fuel saving is indicated by the curve. The 95% confidence interval is fixed at [97, 118] kg jet fuel. Looking at the costs and emissions related to this outcome, the average KLM flight with a range no higher than 4000 km would have the impact of a cost reduction of 24 euros and a carbon dioxide emissions reduction of 338 kg.

The optimal adoption strategy of electric taxiing systems for KLM can be examined by means of the fleet assignment optimization performed in this study. A full week of operations are simulated, in which the algorithm chooses on which routes in the flight schedule the aircraft with installed electric taxiing systems should fly ideally. The computation of these schedule changes is done for an adoption of electric taxiing systems to up to 100 aircraft. Note that the current operational fleet size of KLM is 116 aircraft.

Figure 2 shows the marginal annual cost reduction accomplished by adding electric taxiing systems to the fleet. To make this more clear, it tells us that if KLM installs ETS on one of its aircraft, it will cause a yearly cost reduction of 82 thousand euros. However, if after this first system a second system is installed, the additional yearly cost reduction caused by this second system will be 72 thousand euros. As can be seen from the chart, this cost reduction number reduces all the way to 10 thousand euros after installing 100 electric taxiing systems. This phenomenon is also known as the law of diminishing returns. To find the potential cost reduction for KLM, an estimation must be made of the lifetime left on the aircraft on which the electric taxiing systems are to be installed. The current average lifetime of the Boeing 737 fleet of KLM is 12.6 years [25], while previous 737 models have been in service in the KLM fleet for 22 and 25 years (737-300 and 737-400, respectively) [26]. Assuming a negligible discount rate in the current economy, this leads to an average remaining lifetime of approximately 11 years.

This result shows that, from a cost perspective, KLM should invest in a first electric taxiing system if the estimated costs of this installment are lower than 900,000 euros. For example, if an ETS company offers to install their systems with an initial cost per product of 550 thousand euros, KLM is advised to invest in no more than 18 systems.

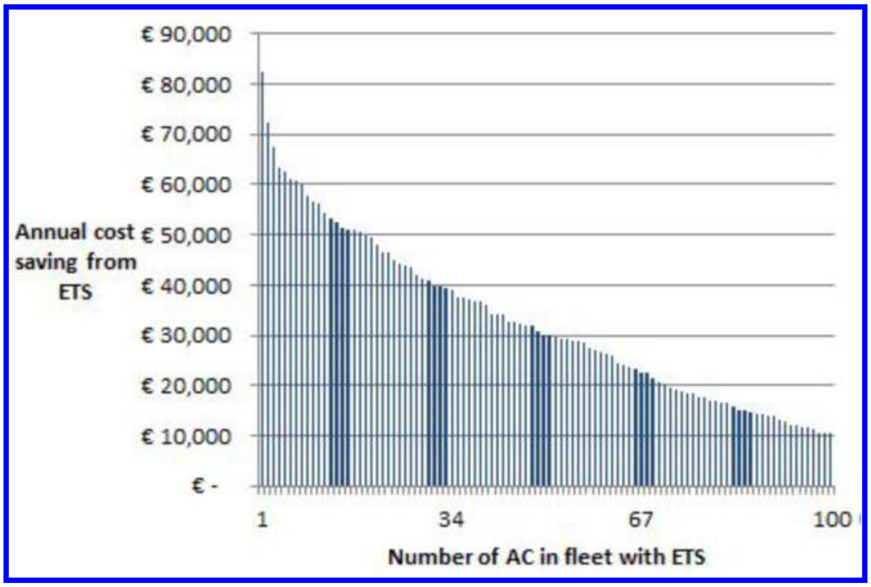

Figure 2: Marginal annual cost savings per additional

Figure 2 shows the evolution of the network of KLM after the introduction of the first 10 electric taxiing systems. The airports of Paris (CDG) and London (LHR) clearly have a large impact with their high taxi times (26 and 31 minutes of combined taxi-in and taxi-out time) and relatively short flight ranges to Amsterdam (430 km and 357 km). However, an interesting development is that after the first few electric taxiing systems have been installed, flights to Manchester Airport (MAN) are selected most often, as these see, to fit best in the schedule for each aircraft equipped with ETS. Other popular destinations are Edinburgh (EDI) and Frankfurt (FRA).

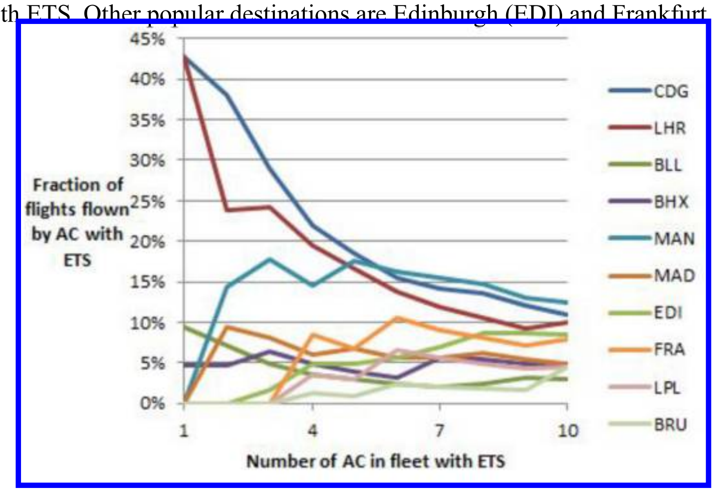

Figure 3: Development of KLM network after introduction of ETS aircraft

D. Airline Comparison

For a total of ten airlines, the results have been computed to find what their potential reduction in fuel from ETS could be. An overview of the results is shown in Table 2. There are several insights to be gathered from this outcome. Firstly, the major difference between European and American airlines (American, Delta and United) is interesting. All three American airlines show more than twice the impact per flight compared to KLM. The main reason for this is the high taxi time at many airports in the United States. Furthermore, the low-cost carriers Transavia, Ryanair and EasyJet have relatively low expected fuel savings per flight, which might seem counterintuitive. The most probably origin of this outcome is that these airlines largely fly to secondary airports, which are often smaller and cope with fewer flights, leading to lower taxi times than the busier primary airports of large cities.

Airline	Per flight [kg]	Annual [mln kg]
KLM	107.2	17.32

Transavia	60.8	1.48
British Airways	141.9	27.66
Air France	95.8	39.29
Lufthansa	100.0	56.72
Ryanair	75.7	27.03
EasyJet	100.0	28.03
American	232.8	54.73
Delta	245.8	34.18
United	251.9	49.64

Table 2. Comparison of potential impact of ETS on key airlines.

IV.Sensitivity analysis

The performed analyses take into account the variability in taxi times in each of the airports, but this is only one factor that brings uncertainty with it. Four other causes of uncertainty have been examined to find the degree of their effects.

Firstly, the weight of the electric taxiing system is researched, after which the oil price and the engine warm-up and cool-down times are analyzed. Lastly, the range limit used by airlines is looked at to see the impact at several different range intervals.

A. Weight of ETS

The weight of the electric taxiing system is the disadvantage of this internal-motor alternative to aircraft taxiing. Carrying it in the air costs additional fuel, which is exactly the opposite of its desired effect. Looking at the existing electric taxiing system concepts that are powered through the auxiliary power unit of the aircraft, a weight of 200-450 kg appears to be a reasonable margin, though modifications to the APU and/or adding batteries to might add significantly more weight. This curve is computed for the KLM fleet, seeing the 107 kg fuel savings at 400 kg ETS weight as assumed throughout the earlier analysis.

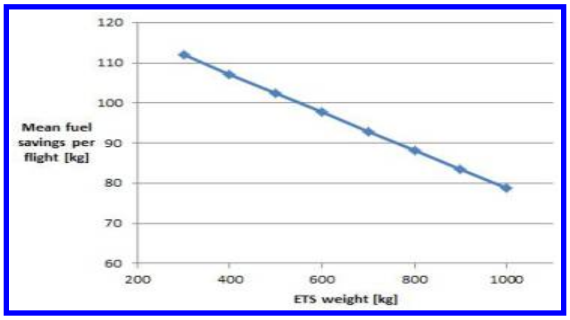

Figure 4: Impact of ETS weight on fuels savings for KLM

B. Jet Fuel Price

Figure 5 shows the sensitivity of the cost savings to the jet fuel price. Given the global turmoil in the oil market in recent times combined with the pandemic crisis of 2020, this price is very volatile. That volatility is very important to the investment decision of airlines in the case of electric taxiing. This innovation has the most cost reduction potential if the oil price rises.

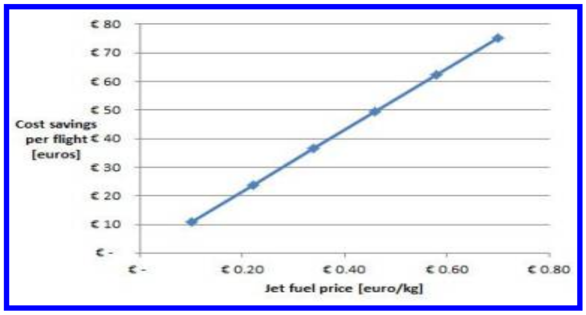

Figure 5: Sensitivity of impact to the price of jet fuel

C. Warm-up and Cool-down Time

The main analysis of this study is done using the current estimations of mean warm-up and cool-down times for the main engines of the aircraft before take-off and after landing, namely 5 and 3 minutes respectively. However, these phases can in the future be improved by innovations such as pre-heating and post-cooling of the engine. The impact on electric aircraft taxiing of these innovations is shown in Figure 6.

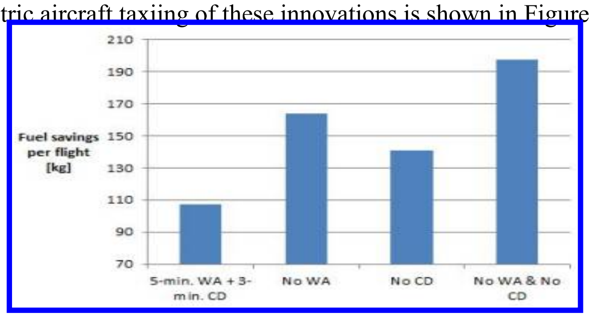

Figure 6: Sensitivity of impact to warm-up (WA) and cool-down (CD) time

D. Range

The last sensitivity parameter is the range limit. If airlines are free to assign their electrically taxiing aircraft on routes, which flight ranges have the most impact? To answer this question, the marginal annual fuel savings are computed in Figure 11. It shows that especially the flights between 500 and 1000 km are important to include in the network of the ETS aircraft.

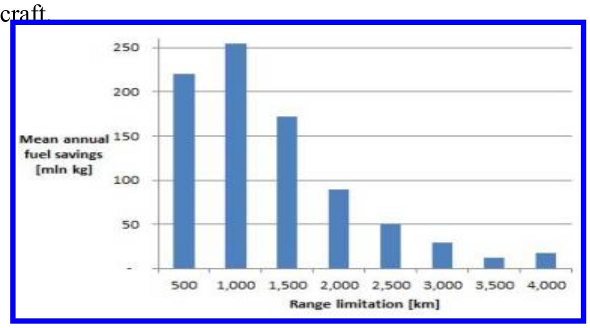

Figure 7: Sensitivity of flight range limitation

V.Discussion

The innovation of electric aircraft taxiing is expected to show promising results in the future, but this is still dependent on design adequacy, policy-making and external circumstances. The performance of the available concepts will not only have to be extremely reliable, but also meet the safety regulations. Political decision-making is expected to present obstacles as airports have less direct benefits from electric aircraft taxiing than airlines. This is because airlines accomplish cost reductions, while airports benefit only in terms of reduced emissions while they do have to facilitate the required infrastructure and processes to accommodate sustainable taxiing. The target of the European Commission is a first step, but getting all stakeholders on board will take serious regulation. At the moment, the low jet fuel prices represent an external circumstance that reduces the need for airlines to adopt this innovation. Furthermore, this analysis has not included potential costs of electric taxiing such as acquisition, installation and maintenance, but focused purely on reduction in fuel.

This study is an attempt to more clearly show the impact of electric aircraft taxiing such that stakeholders are able to make decision with more accurate information at hand. However, several points of discussion concerning the analysis have to be noted. Firstly, the 2020 pandemic has serious effects on the number of flights, causing the results of this study to be less accurate. This consequences stems not only from the reduced flight frequencies of aircraft in the fleets of airlines, but also because the taxi times are expected to be reduced due to less busy airports.

VI.Conclusions

Looking at the current state of electric taxiing, external systems are to a higher degree industry ready than on-board systems. External systems are definitively part of the solution, but due to logistical issues likely to be limited in number. These could therefore be used for long-haul aircraft models, while future short-haul aircraft models can be propelled by an on-board system. Clear advantages of the on-board systems are the fuel reduction they cause, autonomous push-back from the gate and lack of logistical complexity, while its main disadvantage is the in-flight fuel penalty caused by its weight. The reduction in fuel usage therefore depends on the flight range and taxi time, but during the taxiing phase ETS achieve a fuel reduction of 9.8 kg per minute, equivalent to 82%. The analysis in this study shows the global impact of electric taxiing is expected to be a reduction in jet fuel usage of 846 million kg per year, in the scenario that all aircraft are equipped with an electric taxiing system. In terms of costs and climate effects, this is equivalent to a cost reduction of 186 million euros with the current low oil prices and a reduction of 2.67 million tonnes of carbon dioxide emissions. Given the total annual aviation emissions of 915 million tonnes carbon dioxide, this means that ETS could reduce 0.3% in emissions. Locally however, airports and their surroundings will benefit seriously from the reduced emissions, because 56% of airport emissions are due to the taxiing phase.

Analysis of the effect of electric aircraft taxiing to key stakeholders such as airlines shows that airlines in the US would reap substantially larger benefits than European competitors because of consistently higher taxi times in the United States. Low-cost carriers are expected to see smaller impact than traditional hub-and spoke airlines, due to short taxi times in the secondary airports they predominantly fly on.

A special focus on KLM shows that the Dutch airline could save 17.3 million kg of jet fuel annually, representing a cost of 3.8 million euros, increasing profits by 3%, and a carbon dioxide emission of 55 million kg. Since the road to full adoption is still long, a strategic analysis of the fleet shows the marginal cost reduction per installed electric taxiing system starts at 82 thousand euros for the first product, which reduces to 10 thousand after 100 systems have been installed. Especially the flights between Amsterdam and London Heathrow, Paris Charles de Gaulle and Manchester Airport should be assigned to aircraft with electric taxiing systems, because these flights would have the most impact given their relatively low flight distance and high taxi times.

A sensitivity analysis leads to additional insights to the effect of warm-up and cool-down times and the flight range of aircraft with electric taxiing systems. Especially the reduction in warm-up time is expected to be beneficial for the impact, while flights with ranges between 500 and 1000 km are likely to be the most important in absolute terms.

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