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Cost benefit and environmental impact assessment of autonomous eTaxi

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One of the proposed methods of decreasing fuel consumption and emissions at airport is by equipping aircraft with electric motors for movement on the ground. In this paper a high level determination is given on what the potential average and marginal fuel savings and impact on emissions is for some of the larger airports and airlines in Europe and North America. The system could potentially be deployed on a selected sub fleet of aircraft, but fleet wide integration is not likely to result in cost covering benefits. The system is shown to be most beneficial on shorter flights between large airports, provided aircraft are not towed there.

I. Introduction

One way to limit the consumption of fuel and reduce emissions is to limit the usage of aircraft engine on the ground, which are inefficient at low speeds (low propulsive efficiency) and thrust settings (low thermodynamic efficiency). Two options that allow the engines to be started later during taxi out and shut down earlier during taxi in are currently being developed and implemented: Operation towing by a tow truck and integrating electrical motors on the wheels of the aircraft. Operational towing requires additional specialized towing vehicles and infrastructure on the ground, while electric motors, or autonomous eTaxi, requires significant modifications to the aircraft. Both solutions do currently require the aircrafts APU to be running to power systems and start the engines. This paper will focus on the usage of eTaxi.

The ClimOP project [10], part of the EU's Horizon 2020 programme, aims at understanding which aspects of aviation operations can be implemented to reduce the climate impact of the aeronautic industry. With its results, ClimOP aims to contribute to the FlighPath 2050 goals related to the 75% reduction in CO2 emissions, and the 90% reduction in NOx emissions, for a more sustainable aviation. One of the aspects is alterative methods of ground movements, including towing, autonomous eTaxi and single engine taxiing.

AEON [11] (Advanced Engine Off Navigation) is a European project funded by SESAR Joint Undertaking that aims at innovating airport ground operations with more environmentally friendly taxiing techniques for the aviation sector. In particular it aims to define a concept of operations for engine-off taxiing techniques, making use of novel technologies that are coming onto the market, such as Taxibots, E-Taxi and Single Engine Taxiing.

II.Data processing

Figure 1 shows the overall methodology for determining the potential impact of electric taxiing on a aircraft type for a given airline, dependent on the minimum fuel savings needed to offset the costs of equipping an aircraft with an eTaxi device, which is assumed to be in the order of 1000 kg per day.

[1] Insert Job Title, Department Name, and AIAA Member Grade (if any) for first author.

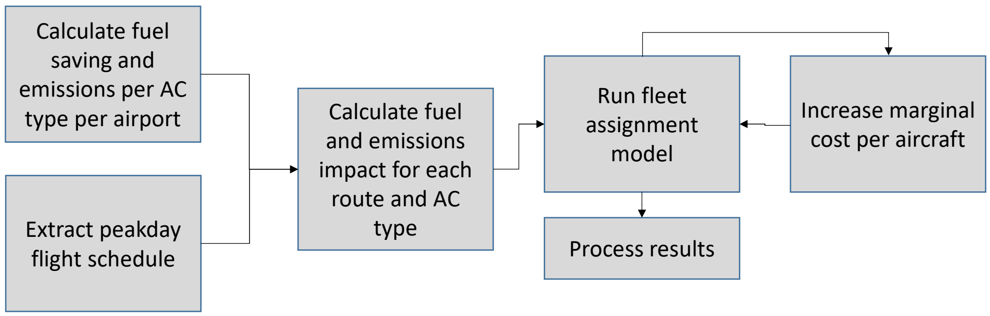

Figure 1: Overall methodology assessment

The basis of this research is a peakday extracted from a global Official Airline Guide (OAG)[1] timetable for 2018, which can then be filtered on airline, airport and aircraft type in a Microsoft Access database. The aircraft types are then reduced to four representative aircraft types with similar performance: An Embraer 190 (E190) representing all regional aircraft, an Airbus 320 (A320) representing all Airbus A320 series aircraft, a Boeing 737-800 (B738) representing all Boeing 737 family aircraft and an Airbus 350 (A350) representing all widebody aircraft. In further analysis, the E190 will be considered small, the B738 and A320 as medium and the A350 as heavy.

Next the impact of implementing an eTaxi device per operation at each airport is calculated as shown in Figure 2 using average taxi times for the summer or 2018 from Euroocntrol[2] and ICAO engine emissions data[4] extracted from the Aircraft Emission Design Tool (AEDT)[3]. It should be noted that outside Europe only large airports are taken into account in the taxi time dataset.

For each aircraft is assumed that taxi times will remain the same and for the last four minutes of taxiing out and the first two minutes of taxiing in the aircraft engines will still be running. For the remaining time the APU will be running at high power[5] to power the eTaxi system. For the E190, the A320 and the B737 this is taken as 125 kg/hr and for the A350 this is 315 kg/hr.

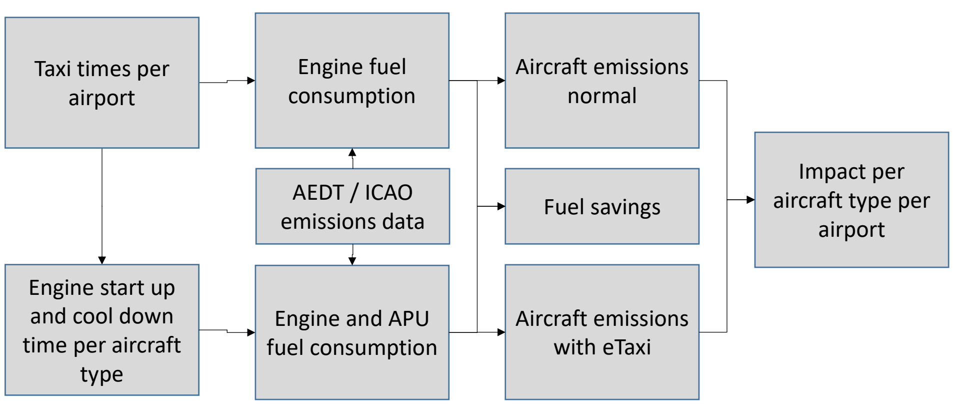

Figure 2: Fuel and emissions per flight with ETS per airport

The total fuel savings are then the fuel saving during taxi minus the extra fuel consumption during cruise, which was calculated using the Breguet range equation (1).

$$R = C \ln \frac{W_{TO}}{W_{TO} - W_{Fuel}} \qquad (1)$$

Where R [km] is the range, C [km] is the aircraft specific range parameter, which is an indication of the aerodynamic and propulsive efficiency of the aircraft, W_{TO} [kg] is the take-off weight and W_{fuel} [kg] is the weight of the used fuel.

From the equation above we can deduce that the fuel required increases with respect to the added weight according to the following equation, and the additional fuel consumption is thus independent of the actual take-off weight or fuel load and only depends on the range and the range parameter:

$$\frac{dW_{Fuel}}{dW_{TO}} = 1 - e^{-\frac{R}{C}}$$

The four representative aircraft and the main values are shown in table 1. The weight assumed for the ETS is a very rough estimation, as no flightworthy device is available yet and the total weight, including modifications to the APU and electrical system, are unknown.

Table 1 : Representative aircraft range parameter and ETS weight values

Aircraft	Size Category	Fuel flow normal taxi per engine [kg/sec]	NOx emissions normal taxi [g/kg]	NOx emissions cruise [g/kg]	Range parameter C [km]	Added weight by eTaxi device[kg]
E190	Small	0.088	3.69	16.22	21156	500
B738	Medium	0.110	4.36	17.89	19103	500
A320	Medium	0.102	4.22	17.23	23640	500
A350	Heavy	0.291	4.41	40.17	32650	1000

Together with ICAO emissions data, assuming climb thrust values for the cruise fuel consumption and the changes to taxi in and out fuel emissions and fuel consumption, a total impact of equipping an aircraft with an eTaxi device is calculated for each flight on each route, of which a few examples are shown in table 2.

Table 2 : Representative aircraft distance and ETS weight values compared to normal taxi

Orig	Dest	AC	Distance [km]	Cruise fuel [kg]	Taxi Out fuel [kg]	Taxi In fuel [kg]	Total Fuel [kg]	NOx impact [kg]
AMS	MXP	B738	797	20	-108	-43	-130	0.36
AMS	MXP	A320	797	17	-98	-39	-120	0.29
AMS	LHR	B738	370	10	-108	-72	-170	0.17
AMS	LHR	E190	370	9	-81	-54	-127	0.14
AMS	JFK	A350	5848	164	-287	-409	-532	6.58

III.Fleet assignment model

The processed data per aircraft per route is then used in a simplified fleet assignment model which that the flow of aircraft equipped with ETS through an airlines day schedule and used a fixed (marginal) cost for using ETS equipped aircraft per day through all the airports in the airlines network in time steps of one hour, as illustrated in figure 3. Having an eTaxi equipped aircraft start at any airport at the start of the day come with a (marginal) cost, which must be offset by the fuel savings throughout the day. The model does not track the number of non-equipped aircraft or individual aircraft and does not implicitly consider aircraft utilization, so it could be possible that more aircraft are required overall.

The model was run for all airlines in parallel batches per airline using IBM Cplex on a server with 128 cores and 512 GB of RAM.

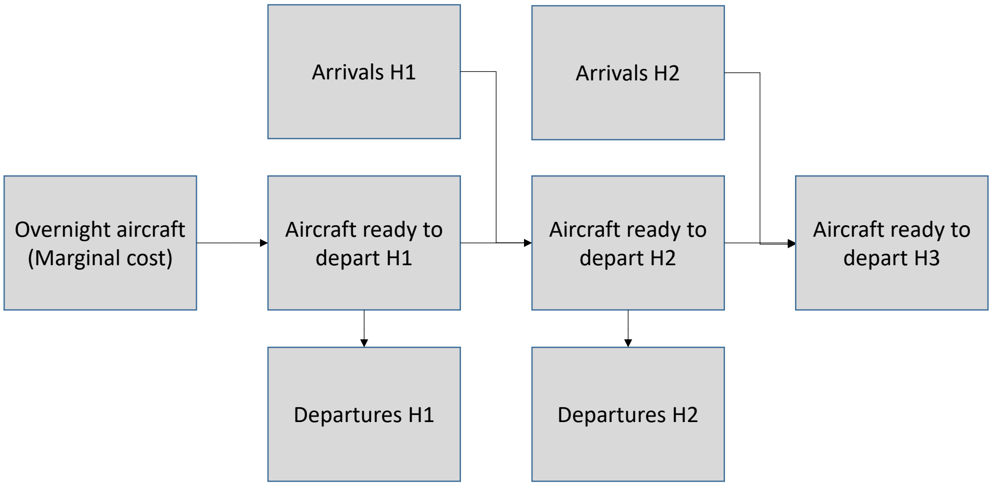

Figure 3: Flow model for aircraft equipped with ETS.

The model used two types of main variables, one indicating the number of aircraft at each airport at each time and one indication if a certain flight is operated by an eTaxi equipped aircraft. A brief mathematical description of the model, not showing administrative constraints that calculate fuel and emissions values at an aggregate level, is given below:

1 Variables:

$y_{a,v,t}$: Number of equipped aircraft type v stationed at airport a at time t (integer)
x_o: Operation o is flown by eTaxi equipped aircraft (binary)

2 Sets:

O: Operations (flights)
$O^{dep}_{v,a,t}$: Departures from airport a with aircraft type v at time t
$O^{arr}_{v,a,t}$: Arrivals at airport a with aircraft type v between time t-1 and t
V: Aircraft types
A_v: Airports visited by aircraft type v
$T_{v,a}$: Departure times of type v from airport a

3 Parameters:

C_V: Marginal cost per eTaxi equipped aircraft
$C_{F,o}$: Fuel saving per operation (if equipped with eTaxi vs normal)

4 Objectives

The total objective is the fuel saved z_F minus the marginal fuel cost z_v of equipping the aircraft.

Maximize: $Z = z_F - z_V$

$$z_V = \sum_{a \in A_v, v \in V} y_{a,v,0}$$

$$z_F = \sum_{o \in O} C_{F,o} x_o$$

5 Constraints

This model uses only a single constraint. At each time interval, the number of departing aircraft and aircraft remaining on the ground must be equal to the number of arriving aircraft and the aircraft that remained from the previous interval

$$\sum_{o \in O^{arr}_{v,a,t}} x_o - \sum_{o \in O^{dep}_{v,a,t}} x_o + y_{a,v,t-1} - y_{a,v,t} = 0, t \in T_{v,a} \cup a \in A_v \cup v \in V$$

The model is run from Excel retrieving data from Access and the optimization is the run in IBM CPlex in on a server with 128 cores (256 threads) and 512 GB of ram. Over 60 airlines were selected based on the number of flights. The marginal cost per aircraft was initially set at 10 kg and then varied from 200 kg to 3000 kg in steps of 200 kg.

IV.Overall results

Table 3 shows the results for a very low marginal cost of 10 kg of fuel per equipped aircraft and illustrates the total savings if all aircraft were to be equipped. Note that while fuel and CO_2 emissions are always reduced, especially NO_x emissions increase due to the added weight during cruise.

Table 3 : Fuel and emission impact for a marginal fuel costs of 10 kg of fuel per installed eTaxi device for medium aircraft.

		Equipped AC	Fuel (tons)	CO2 (tons)	CO (kg)	HC (kg)	NOx (kg)
AA	American Airlines	331	-278.4	-879.7	-4.02	0.320	836
UA	United Airlines	243	-194.5	-614.7	-1.55	0.376	711
U2	Easyjet	338	-192.7	-608.9	-2.98	0.239	643
FR	Ryanair	316	-136.9	-432.7	0.26	0.450	671
LH	Lufthansa	166	-117.9	-372.7	-2.54	0.039	289
DL	Delta Air Lines	143	-106.7	-337.3	-1.00	0.191	383
WN	Southwest Airlines	92	-96.6	-305.3	-1.43	0.094	253
VY	Vueling Airlines	128	-84.8	-268.0	-1.64	0.056	235
AF	Air France	85	-58.8	-185.9	-1.19	0.030	155
BA	British Airways	90	-58.5	-184.8	-1.20	0.027	150
EW	Eurowings	121	-61.2	-193.5	-0.95	0.074	202
AZ	Alitalia	64	-50.3	-158.9	-1.21	-0.003	104
B6	JetBlue Airways	57	-45.7	-144.5	-0.63	0.064	158
W6	Wizz Air	111	-42.7	-135.1	0.12	0.169	255
AS	Alaska Airlines	56	-41.8	-132.1	-0.60	0.054	140
IB	Iberia	52	-39.2	-123.8	-0.77	0.024	106

A. Fuel savings

Figures 4, 5 and 6 show the results of fuel savings per aircraft for respectively small (regional), medium (Boeing 737 and Airbus 320) and Heavy (widebody) aircraft. In each graph only the ten airlines with the highest maximum fuel saving are shown for clarity. The graphs were created by taking the total fuel savings per marginal cost and the number of equipped aircraft per marginal cost. The values for the lowest marginal cost are on the right, with the highest number of equipped aircraft. It should be noted that not all flights have been taken into account, due to unavailability of average taxi times at smaller airports. These are not likely to be the most suitable candidates for routes to fly anyway as savings will also likely be limited due to limited taxi times.

For small aircraft, in figure 4, especially JetBlue stands out with relatively high savings per aircraft between 1200 and 2800 kg per aircraft per day. This seems to indicate they are their flying regional aircraft on relatively short distances between airports with long taxi times. For other airlines, values for the first few aircraft are between 700 and 1500 kg and for equipping most aircraft is between 300 and 600 kg. Most likely, these aircraft fly between larger and smaller airports. Next to JetBlue, United Airlines seems to have the strongest business case and British airways the weakest, as their regional aircraft mostly fly to other (smaller) airports than London Heathrow. Only the mainline US carries go over 1000kg of average savings, probably due to long taxi out times at their main hubs. The overall business case seems limited compared to the medium and heavy aircraft.

For medium sized aircraft, values are much more comparable and between 500 and 4000 kg per aircraft per day for Vueling. Overall, the main US airlines American, United and Delta seem to have the strongest business case and

Air France the weakest. Ryanair has a notably poor business case, very likely due to their business model of flying to secondary airports with much more limited taxi times.

For Heavy aircraft, especially the US main airlines American, United and Delta stand out. This is probably due to their flying heavy aircraft from end even between their congested hubs. For other airlines, the savings are less significant.

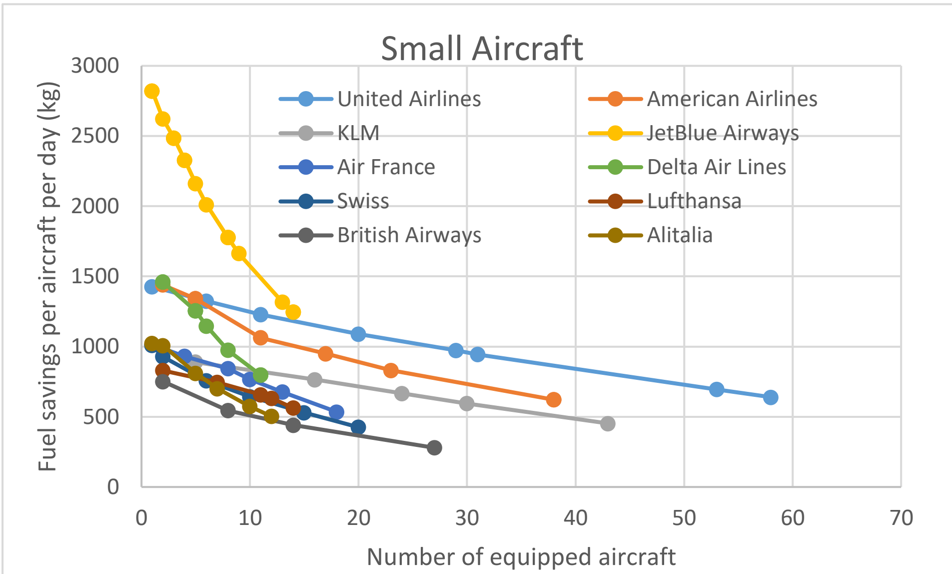

Figure 4: Total fuel savings for a peakday for small aircraft

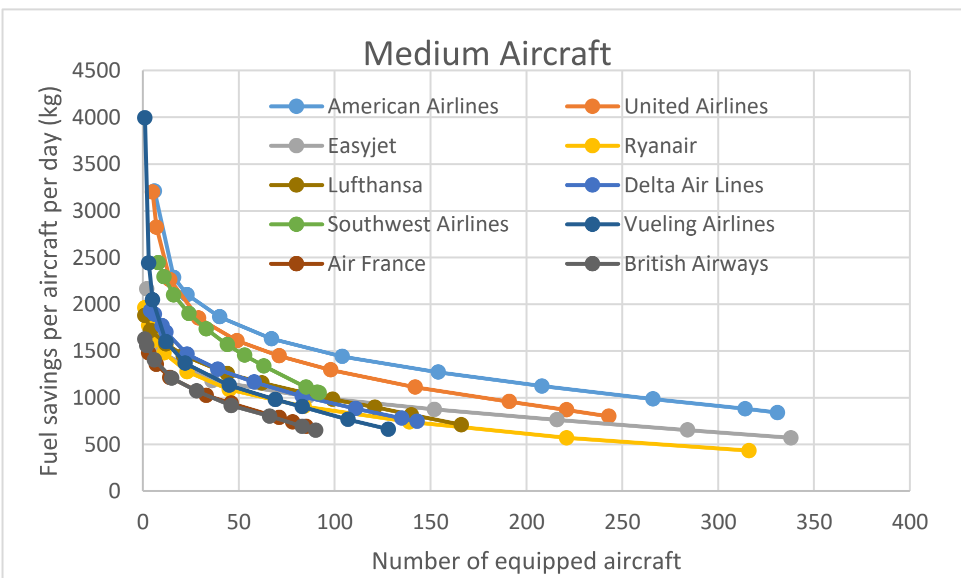

Figure 5: Total flight savings for a peakday for medium aircraft

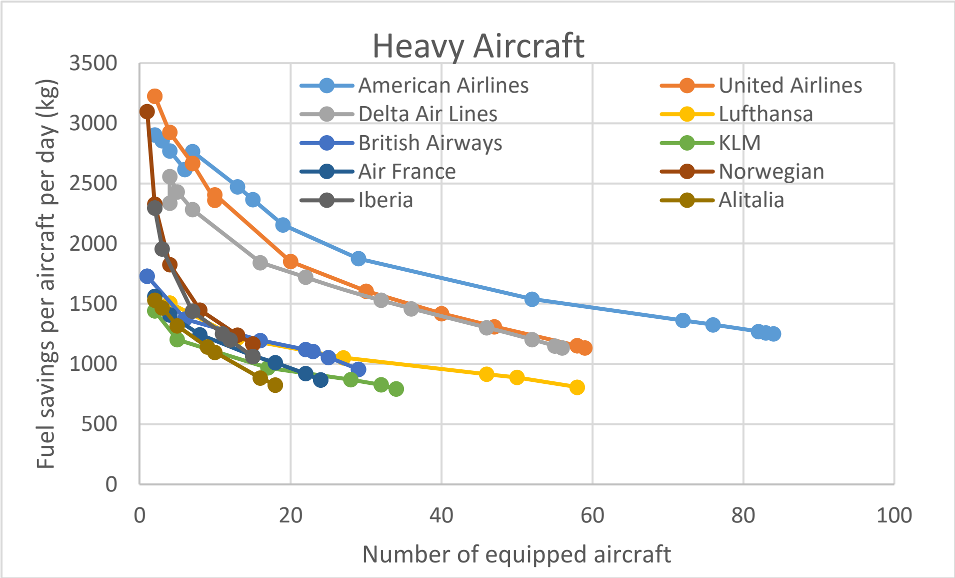

Figure 6: Total flight savings for a peakday for heavy aircraft

B. Emissions

In general, emissions decrease with fuel consumption, with a notable exception of Nitrous oxides (NOx). Figures 7, 8 and 9 how the impact of NOx emission for small, medium and heavy aircraft per aircraft per day. The increase is caused by the increased weight of the aircraft during cruise, especially on the heavy aircraft flying long range which seem to converge to an increase in 15 kg per day for larger fleets at every airline.

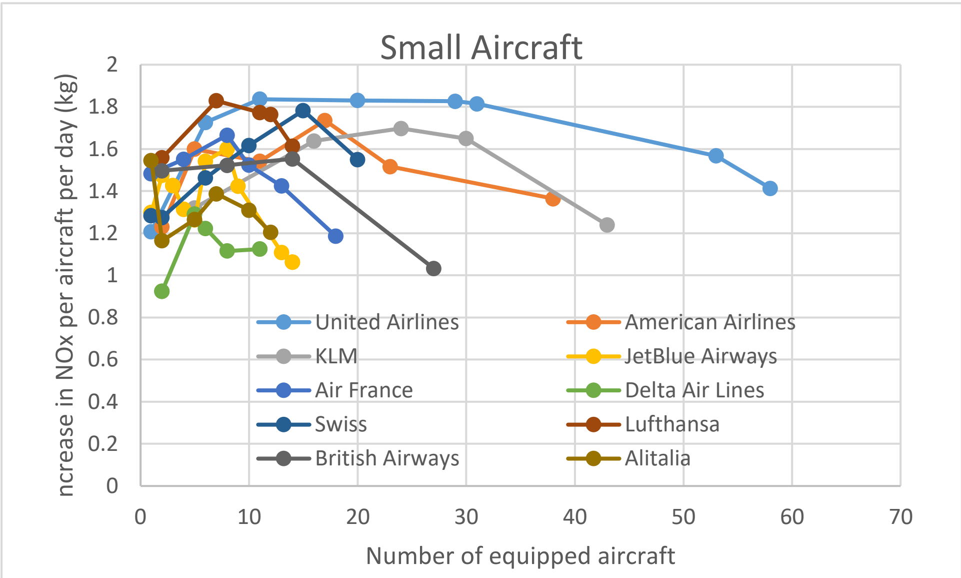

Figure 7: Average NOx impact for small aircraft

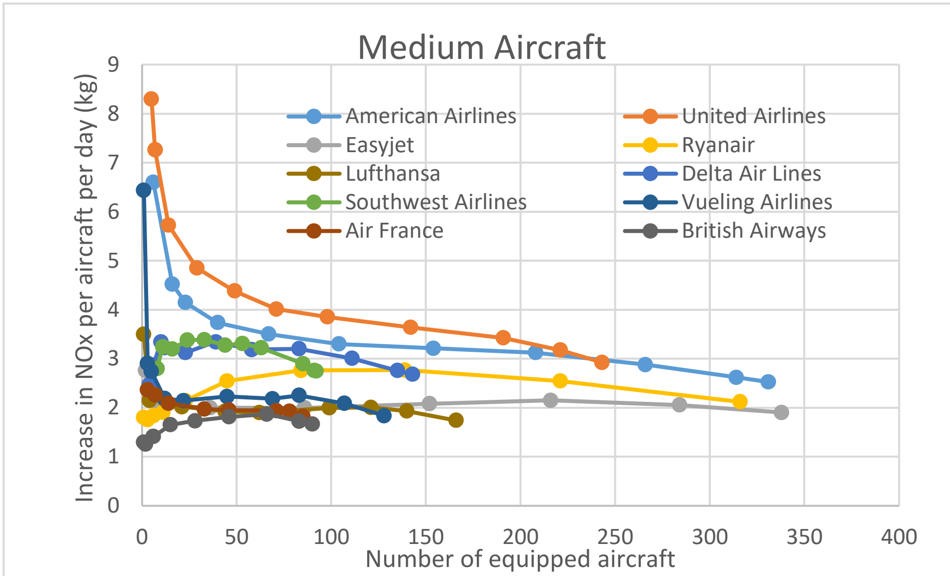

Figure 8: Average NOx impact for medium aircraft

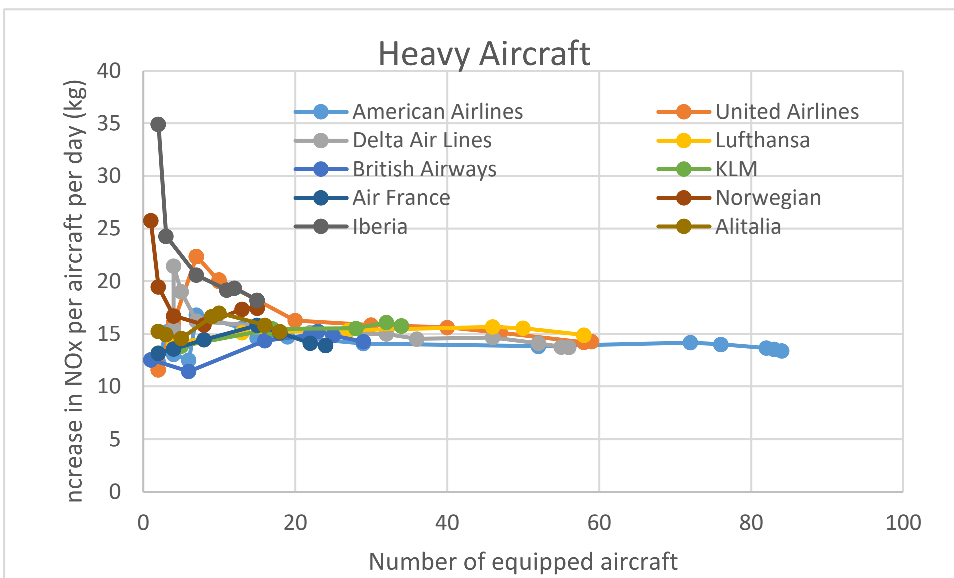

Figure 9: Average NOx impact for heavy aircraft

C. Trends

There is an overlap with airports likely to deploy towing and airports visited by autonomous eTaxi equipped aircraft. If towing is implemented at these airports, autonomous eTaxi is not likely to have any benefit. Table 4 illustrates that for medium sized aircraft and an average marginal cost of 1000kg, over 55% of the operations are at the main hub airports.

Table 4 : Top 10 airports with number of departures for a 1000 kg marginal eTaxi cost scenario for the top 10 European airlines and medium size aircraft

Airport	Departures	Percentage

BCN	141	8.4%
FRA	138	8.2%
FCO	129	7.7%
CDG	105	6.2%
MUC	105	6.2%
MAD	89	5.3%
LGW	73	4.3%
LHR	73	4.3%
TXL	41	2.4%
AMS	40	2.4%
Total	**973**	**55.5%**

Another expected result is that for eTaxi, focus should be on shorter routes (with lower fuel burn penalty) between airport with longer taxi times (thus more savings). To check this statement, the flights assigned eTaxi equipped aircraft in the previous analysis where cross referenced with the distance between airports and the total average taxi out and in time per flight.

Figure 10 shows a trend of increasing range with an increased number of flights, though there are deviations at the lower end, likely due to specific routes with a larger distance but relatively even longer taxi times.

Similarly, figure 11 shows that the average taxi time generally goes down with an increase in the number of flights, with some exceptions which are likely caused by flights between airports with short taxi times but relatively even lower distance.

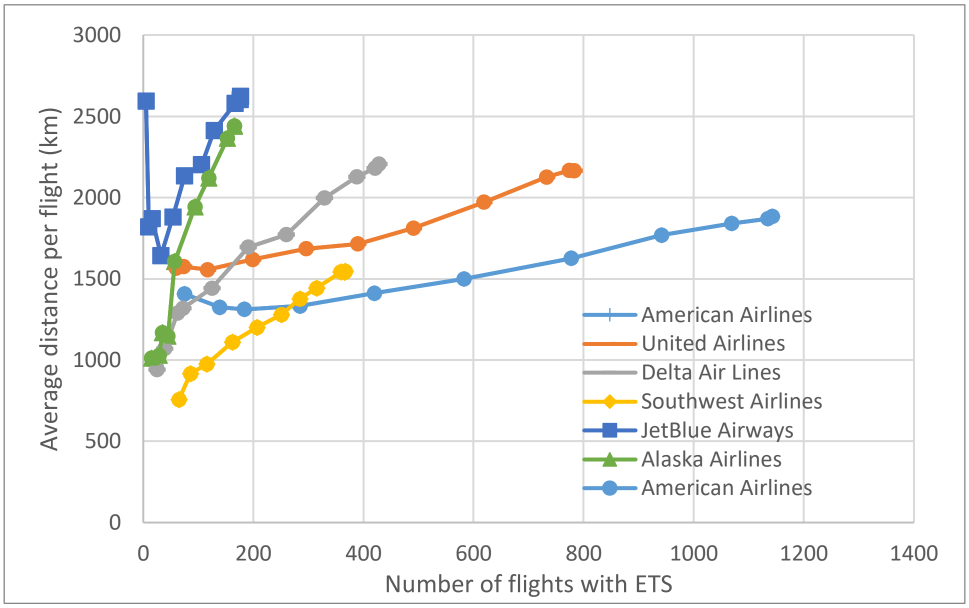

Figure 10: Impact of number of medium sized AC flights with ETS on average flight distance

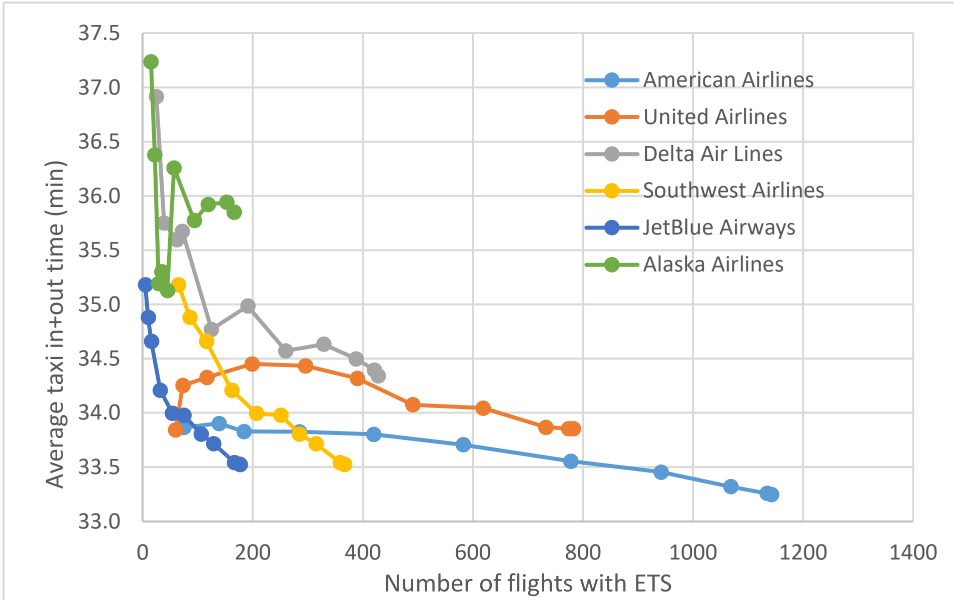

Figure 11: Impact of number of medium sized AC flights with ETS on average total flight taxi time per flight

D. Sensitivity analysis of implementing eTaxi for KLM

Figures 12 illustrates the impact of the weight of the ETS system and the marginal cost per installation for KLM 737 aircraft. As can be seen, both weight and marginal cost have a highly diminishing effect on the overall fuel and thus emissions savings. For a positive business case the installation cost should be recoverable with a 500 kg fuel saving per day and the weight should be as low as possible.

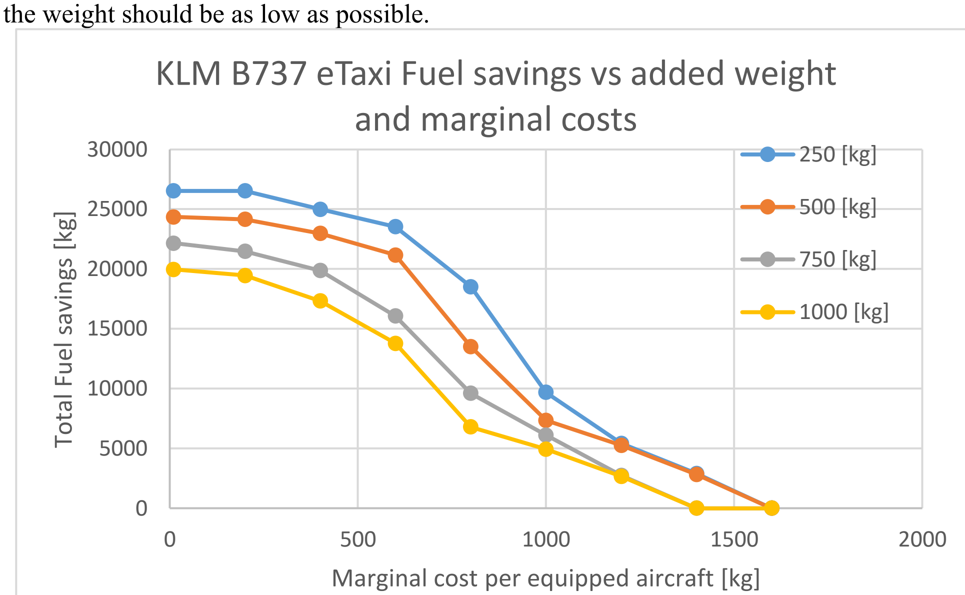

Figure 12 : Impact of weight and marginal cost on fuel savings per peak day on KLM 737 aircraft

V.Conclusions

There seems to be some positive business model for installing eTaxi systems on aircraft if the weight is low and the costs installing the system can be offset by the fuel savings. In general, an increase in NOx production due to increase fuel burn from increased weight during cruise can be expected, especially on heavy aircraft.

For small (regional) aircraft, the market seems small with respect to the number of aircraft but this could be due to the limited number of airports in the dataset. Additional research should take a more in depth look at these aircraft and their routes. For medium aircraft the number of aircraft potentially equipped, and the savings seem much higher. For heavy aircraft, there are fewer aircraft, but the savings per aircraft seem quite high.

One area of concern is that most of these aircraft should be operated into busy airports, which are most likely to implement operational towing, which would nullify the advantage of installing these systems. This could make the system interesting for regional aircraft where compatibility with tow trucks is an issue.

For further analysis taxi times for more airports should be taken into account, especially in the US, and more specific taxi time could be used that take into account gate, runway and congestion. Additionally, more aircraft types should be modelled, and a more recent flight schedule should be used.

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