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Cost benefit and environmental impact assessment of operational towing

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One of the potentially most significant ways of decreasing emissions at airport is by towing the aircraft on the ground instead of using its main engines. In this paper we will give a high level overview of what the potential average and marginal fuel savings and impact on emissions is for some of the larger airports in Europe and the US. Especially for large hub airports, the savings are significant and are very likely more than enough to make the benefit of fuel saved outweigh the investment and cost of operating a fleet of towing vehicles.

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, require significant modifications to the aircraft. This paper will focus on the usage of towing vehicles. This research was partially made possible by two EU project: ClimOp and Aeon.

The ClimOP project [10], part of the EU's Horizon 2020 program, 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.Methodology

It is expected that implementation of towing at hub airports is more likely to produce significant fuel savings than at less busy ones, due to longer taxi times and more traffic that is evenly distributed through the day. Also, medium sized jets, such as the Boeing 737 and the Airbus A320, are the most likely candidates for towing, as most of the flights at large airports are performed by these and these are used throughout the day. Long-range widebody aircraft then to be operated mostly during the morning and early evening, but are expected to have a higher fuel saving per towing operation. Regional airports with a single runway are not very likely to be able to utilize towing vehicles effectively due to short taxi distances, though other benefits such as engine start during taxi, might still apply.

The data used for assessing the utilization of towing vehicles in this research is:

- A peakday extracted from a global Official airline guide (OAG) timetable for 2018 [1]
- Taxi times for 2018 published by Eurocontrol [2]

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

- ICAO Fuel and emissions data for aircraft extracted from the Aviation Environmental Design Tool (AEDT) [3][4]
- Estimated APU fuel consumption published by ICAO[5]

As this is a high-level analysis, all aircraft where represented by four different aircraft types with respect to fuel consumption:

- The Embraer 190 represents all Embraer E-jets and Airbus A220's.
- The Airbus A320-200 represents all A320 family aircraft, including the NEO.
- The Boeing 737-800 represents all B737 aircraft including the Max.
- The Airbus A350-900 represents al twin engine wide body aircraft.

Figure 1 illustrates how this data was combined into a table of fuel and emissions values per aircraft type and airport. To get an upper bound on what the savings could be, the workflow in figure 2 shows how this was combined in a global analysis, determining the maximum possible savings that could be achieved and the number of tow trucks required to achieve this. It should be noted that some tow trucks at some airport would not be utilized enough to make any economic or environmental sense.

In the final analysis, performed for more than 50 airports, an optimal assignment model was used, which then plans and assigns tow trucks to flights. An important parameter is that each additional tow truck used throughout the day must be offset a minimum amount of additional saved fuel. Figure 3 illustrates the workflow for the assignment model.

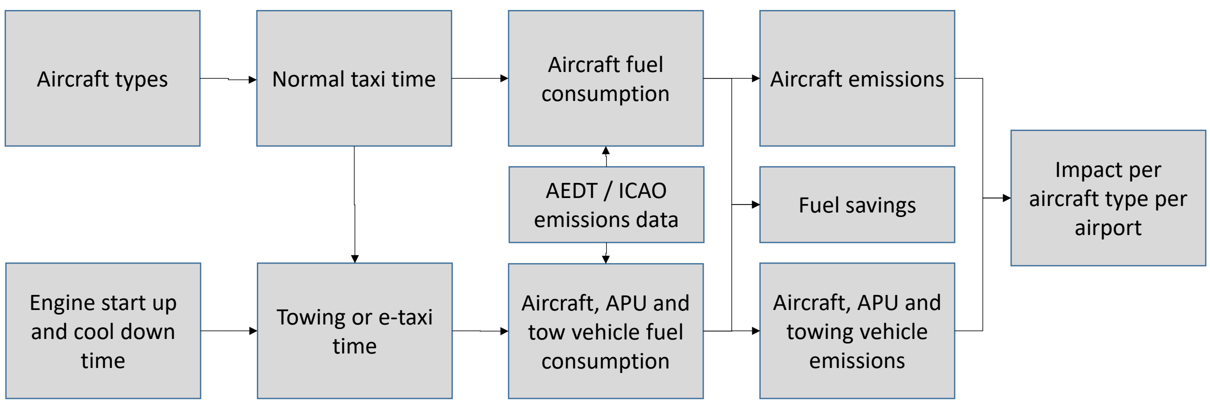

Figure 1: Calculation for determining impact numbers per aircraft type and airport

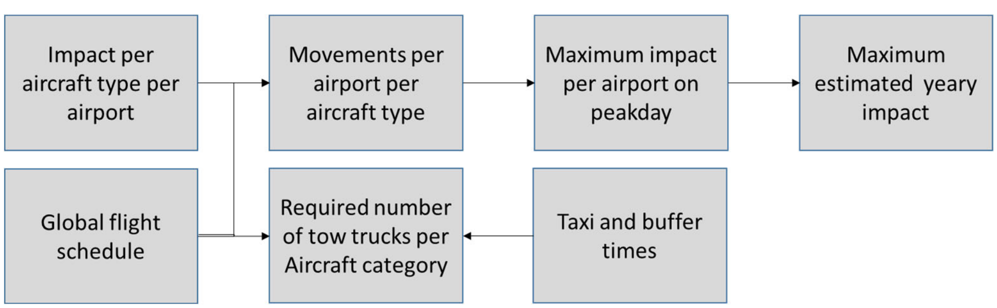

Figure 2: Calculating maximum total impact of introducing towing

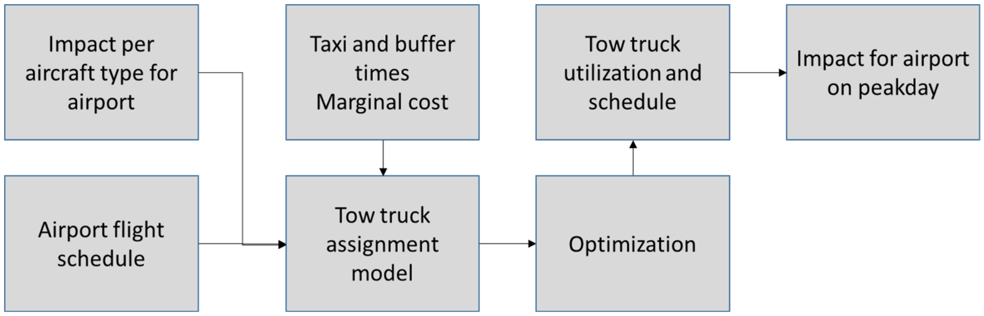

Figure 3: Optimizing Tow truck assignment workflow

1 Results for full deployment

Table 1 shows the calculated savings on fuel consumption on a peak day at 25 selected airports in Europe and the US and the number of tow trucks required for towing all these flight movements. For the number of vehicles it was assumed that each trip per towing vehicle required the taxi time plus 20 minutes return time. Then the simultaneous number of movements per 5 minute block where determined. Small trucks are used to tow small (regional) jets, medium trucks tow medium aircraft and heavy trucks tow all twin engine wide bodies.

As can be seen, Amsterdam (AMS) and Paris (CDG) have the highest number of tow trucks required whilst Los Angeles (LAX) and Chicago (ORD) to the highest total fuel savings of all airports in the table. When it comes to savings per tow truck, Istanbul and London Heathrow stand out, mostly due to the high taxi time due to (departure) delays as well as the relatively high percentage of heavy aircraft at Heathrow. A reasonable value for the cost of operating a tow truck, dependent on fuel price and the cost of the towing vehicle and staff, is currently in the order of 1000 kg of fuel savings per towing vehicle per day, which would be enough for all the airports in table 1.

Table 1: Number of tow trucks required and maximum potential daily savings for top 25 airports in Europe

Airport	Average Taxi In time (min)	Average Taxi Out time (min)	Small trucks	Medium trucks	Large trucks	All	Total fuel saving per peakday (kg)	Fuel savings per truck (kg)
LAX	5.8	13.1	10	51	13	74	675295	9126
ORD	6.0	13.5	9	37	11	57	549733	9644
JFK	5.4	18.1	5	28	25	58	509657	8787
DEN	8.9	18.2	9	36	7	52	458397	8815
ATL	9.2	22.4	9	38	12	59	434033	7356
EWR	7.1	21.4	9	26	10	45	395137	8781
MCO	7.6	18.3	1	36	8	45	346993	7711
DFW	9.1	17.3	13	27	6	46	288404	6270
LHR	8.5	21.0	2	39	24	65	275267	4235
MIA	5.4	12.8	3	27	14	44	252932	5748
CDG	5.1	13.7	17	43	19	79	236236	2990
AMS	13.8	20.8	22	42	16	80	222625	2783
FRA	11.7	19.0	10	52	16	78	211397	2710
CLT	9.6	19.9	9	21	6	36	206909	5747
IST	5.6	11.8	0	27	12	39	192039	4924
MAD	6.5	11.3	8	41	14	63	189451	3007

FCO	7.3	11.8	6	47	8	61	171002	2803
LGW	8.6	22.3	4	40	7	51	160579	3149
BCN	5.8	11.2	2	45	8	55	154376	2807
MUC	9.5	16.3	10	42	8	60	116935	1949
DUB	11.5	20.2	11	26	6	43	96718	2249
ZRH	4.9	10.4	10	27	9	46	75200	1635
MXP	5.1	12.2	6	23	5	34	75169	2211
CPH	11.2	21.7	0	29	6	35	74629	2132
ORY	4.4	10.3	2	32	3	37	71974	1945

III. Mathematical formulation of the optimum assignment model

The mathematical model is used to determine the trade-off between the number of tow trucks deployed and the fuel saving, by using a minimum marginal cost per towing vehicle in kilograms of fuel per day. It is very similar to a basic gate assignment model. This was run for all airports in parallel batches using IBM CPlex on a server with 128 cores and 512 GB of RAM.

2 Variables

z_F : Total fuel savings
z_V : Total marginal fuel savings per towing vehicle
y_V : Vehicle v is used (binary)
$x_{o,v}$: Operation o is towed by vehicle v (binary)

3 Sets

O: Operations (arrivals and departures)
O_v: Operations compatible with towing vehicle v
V: Towing vehicles v
V_o: Towing vehicles compatible with operation o
T_O: Time intervals where a towing operation starts

4 Parameters

C_V: Marginal cost per vehicle
$C_{F,o}$: Fuel saving per operation (if towed)

5 Objectives

Maximize $Z = z_F - z_V$

$$z_V = \sum_{v \in V} C_V y_V$$

$$z_F = \sum_{v \in V} \sum_{o \in O_v} C_{F,o} x_{o,v}$$

The objective Z of the model consists of two parts. Z_v is the marginal cost of deploying a vehicle per day, in equivalent kilograms of fuel and Z_F is the total amount of fuel saving. Functionally this implies that an extra vehicle will only be deployed if the extra fuel savings outweigh the cost of that vehicle.

6 Constraints

$$\sum_{v \in V_o} x_{o,v} \leq 1, o \in O$$

The first constraint allows each flight to be only towed by one, to avoid multiplying the benefits.

$$\sum_{o \in O_{v,t}} x_{o,v} - y_V \leq 0, v \in V, t \in T_O$$

The second constraint ensures that each towing vehicle can only tow one aircraft at a time, where the time also takes into account repositioning and an uncertainty buffer.

Next to this, a range of administrative constraints are used to calculate fuel consumption and emissions impact on an agregate level. For brevity these will not be descibed here. It should be noted that currently time required for charging electric truck as well as emissions from the electric grid are not taken into account.

IV.Results Amsterdam Schiphol

Table 2 shows the savings in fuel per movement that is being towed at Amsterdam airport Schiphol (AMS). It is assumed that during taxi in engines will remain running for 2 minutes for starting the APU and engine cool down, while engines will all be running for 4 minutes on taxi out for engine warm up, resulting in saving on idle engine fuel consumption for approximately 6 minutes on taxi in and almost 10 minutes on taxi out minus APU fuel.

Table 2: Savings per aircraft type per towing operation at AMS

Type	Size	Peak day operations	Fuel savings per taxi in (kg)	Fuel savings per taxi out (kg)
E190	Small	133	84.0	146.4
B737	Medium	193	105.0	183.0
A320	Medium	156	97.4	169.6
A350	Heavy	104	277.8	484.0

For Amsterdam an analysis was done using the 2018 peak day. Figure 4 shows the number of simultaneous taxi movements at each time and thus indicates the requirement for the number of towing vehicles throughout the day, which can be seen to vary significantly. While many vehicles are required for the morning and afternoon peaks, during other times fewer are required. One cause for this is that AMS has clear inbound and outbound peaks and adapted runway configurations for the hub and spoke operation of KLM and partner airlines.

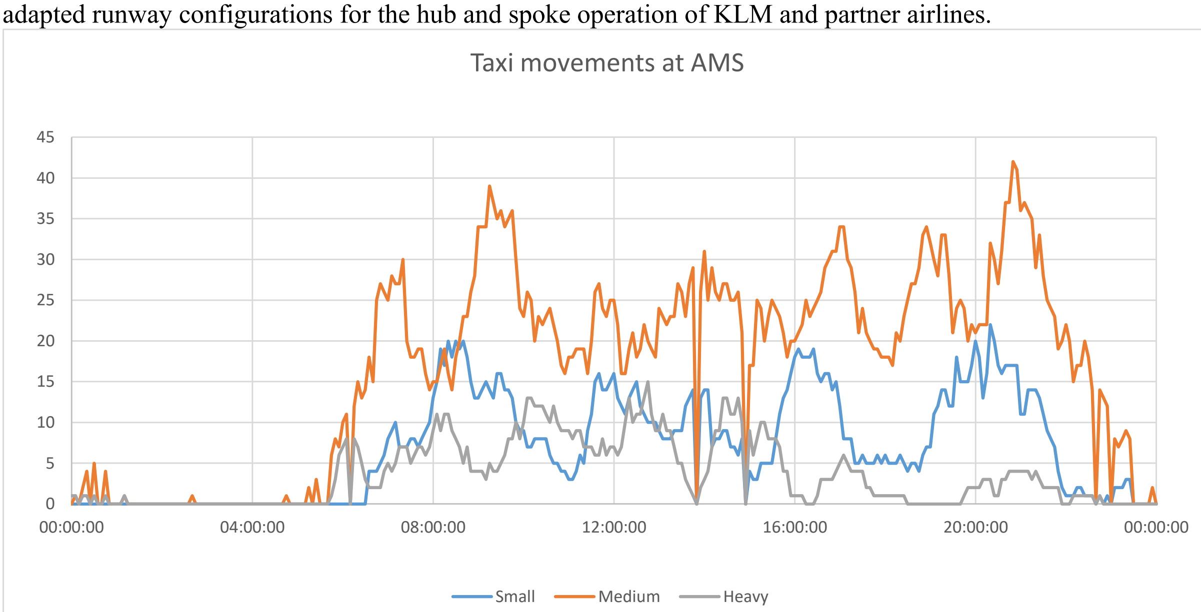

Figure 4: Simultaneous taxi movements throughout the day at AMS

Figure 5 shows how the deployed number of trucks per size varies with the marginal cost in fuel per truck. While for medium and heavy, the full number of trucks stay fairly constant to a value of about 1000 kg per fuel per day, it drops much earlier for the smaller tow trucks, which apparently are used much less effectively throughout the day if all regional aircraft are being towed.

Figure 6 shows the effect of deploying a number of trucks on the total fuel savings per truck type. Towing medium sized aircraft, such as the Airbus A320 and Boeing 737 clearly has the highest total impact, but also requires the largest number of trucks. Heavy aircraft require many fewer trucks while still providing relatively large overall savings. The fuel savings for small trucks is relatively small and reducing the number of trucks does not reduce the fuel savings as significantly as with the medium and heavy trucks.

Figure 7 finally shows the average savings per truck as a function of the number of trucks. Heavy trucks clearly provide more savings per truck than medium, while the savings per small truck are clearly the lowest. While heavy trucks are likely more expensive than medium trucks and small trucks are less expensive still, staff costs per truck, especially if the trucks need to be manned, will not vary by much. Small trucks would thus likely be the least cost effective to deploy at Amsterdam. For heavy and medium trucks, towing all movements seems to be effective enough with an average fuel saving of 1563 kg per medium truck and 2672 kg per heavy truck on a peak day. For small trucks towing all movements would lead to only 956 kg of savings per truck.

For Amsterdam a logical fleet size would probably be 15 heavy trucks and 42 medium trucks, and thus able to tow all movements in optimal conditions. Potentially around 10 of the small trucks could be deployed, accepting that not all regional aircraft movements can be towed.

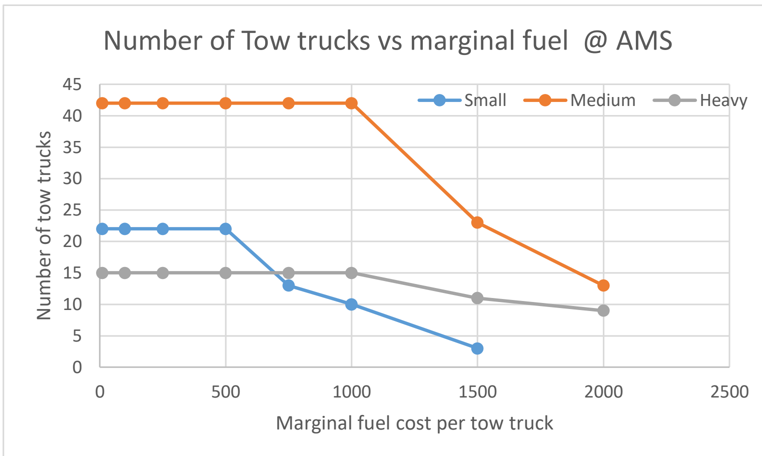

Figure 5: Number of truck deployed vs. marginal fuel cost per truck on a peak day @ AMS

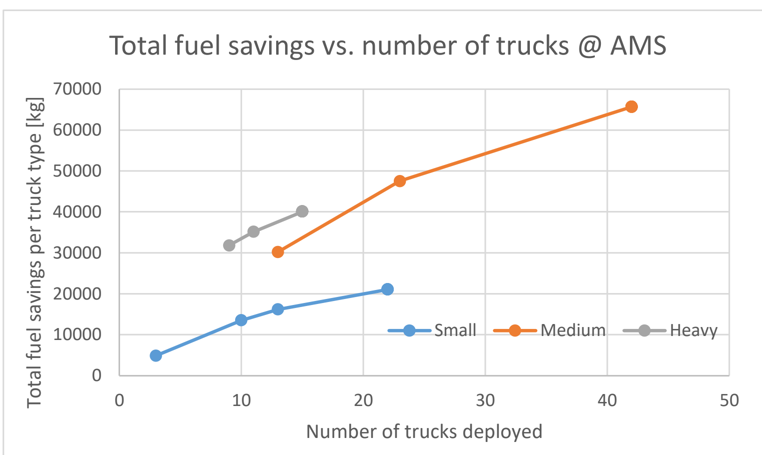

Figure 6: Total fuel savings vs. number of trucks deployed on a peak day @ AMS

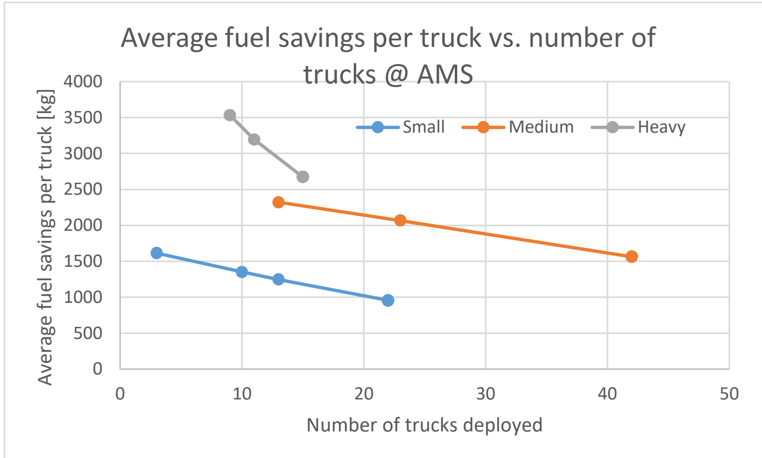

Figure 7: Average fuel saving per truck vs. number of trucks deployed on a peak day @ AMS

V.Results Paris Charles de Gaulle

Table 3 shows the savings in fuel per movement that is being towed at CDG. It is assumed that during taxi in engines will remain running for 2 minutes, while engines will all be running for 4 minutes on taxi out, resulting in saving on idle engine fuel consumption for approximately 7.5 minutes on taxi in and almost 12.3 minutes on taxi out.

Table 3: Savings per aircraft type per towing operation at AMS

Type	Size	Peak day operations	Fuel savings per taxi in (kg)	Fuel savings taxi per out (kg)
E190	Small	65	100.1	172.5
B737	Medium	43	125.1	215.7
A320	Medium	328	116.0	200.0
A350	Heavy	95	331.1	570.5

Compared to Amsterdam, Paris CDG has a traffic structure which is a more constant throughout the day, which is mostly due to the two-by-two runway configuration leading to very limited trade-off between the maximum arrival and departure capacity. This also means that taxi movements are a bit more constant throughout the day, as shown in figure 8.

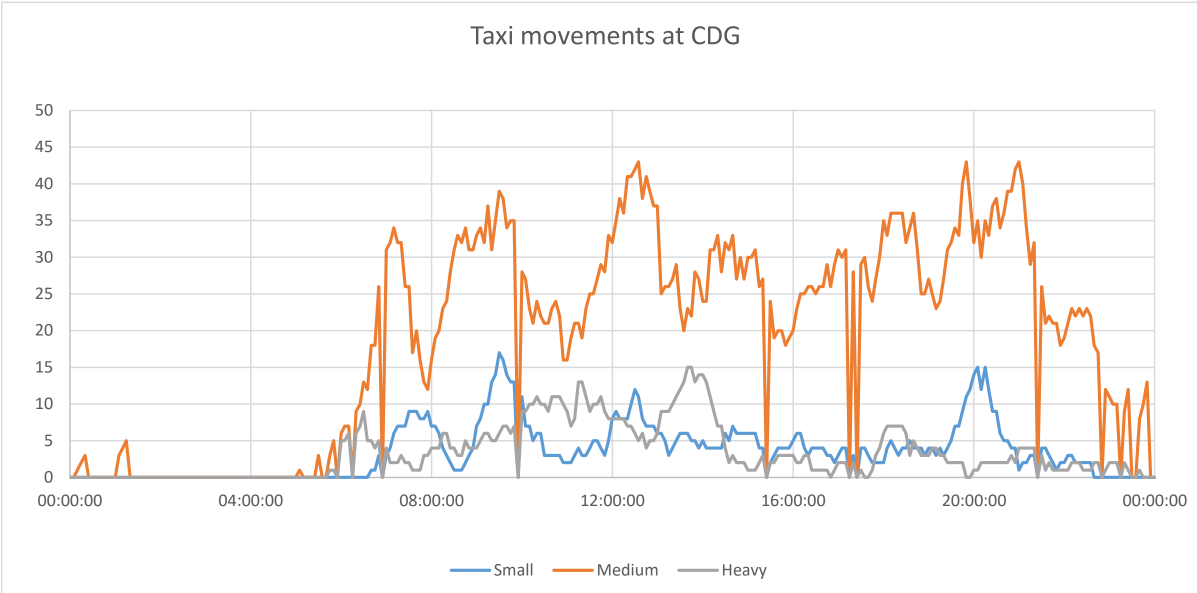

Figure 8: simultaneous taxi movements throughout the day at CDG

Figure 9 shows how the deployed number of trucks per size varies with the marginal cost in fuel per truck. While for medium and heavy, the full number of trucks stay fairly constant to a value of about 1000 kg per fuel per day, it drops much earlier for the smaller tow trucks, which apparently are used much less effectively throughout the day if all regional aircraft are being towed. Compared to Amsterdam, especially the medium trucks seem to be utilized more effectively and only drop off after 1500 kg of fuel per truck on the peak-day.

Figure 10 shows how the total fuel savings per truck vary with the number of trucks deployed. Heavy and medium trucks give the highest overall fuel savings, while smaller trucks do not seem very effective in comparison.

Figure 11 shows that the heavy and medium trucks will be much easier to deploy from a cost-benefit perspective than the small trucks, even if these are likely to be less expensive to build and/or purchase, while the medium and heavy trucks are comparable. Of course, also here the need for a dedicated driver per towing vehicle would make the business case significantly more difficult, especially for the smaller trucks.

For Paris CDG the cost benefit of implementing operational towing thus looks a bit stronger than for AMS, especially with respect to the heavy and medium trucks. For large trucks the average saving is 3209 kg of fuel per vehicle, for medium trucks 2075 kg per vehicle and for small trucks it is only 934 kg per vehicle.

For CDG a reasonable fleet size seems to be 15 heavy trucks and 43 medium trucks, which would then be able to tow al movements in optimal conditions. Additionally, around 6 small trucks could be deployed which would only move a limited number of regional aircraft movements.

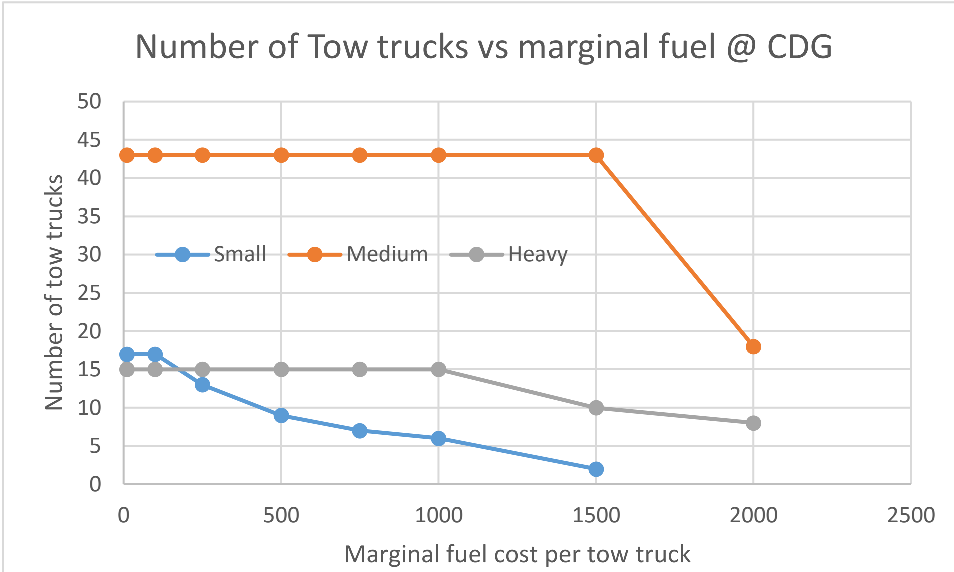

Figure 9: Number of trucks deployed vs. marginal fuel cost per truck on a peak day @ CDG

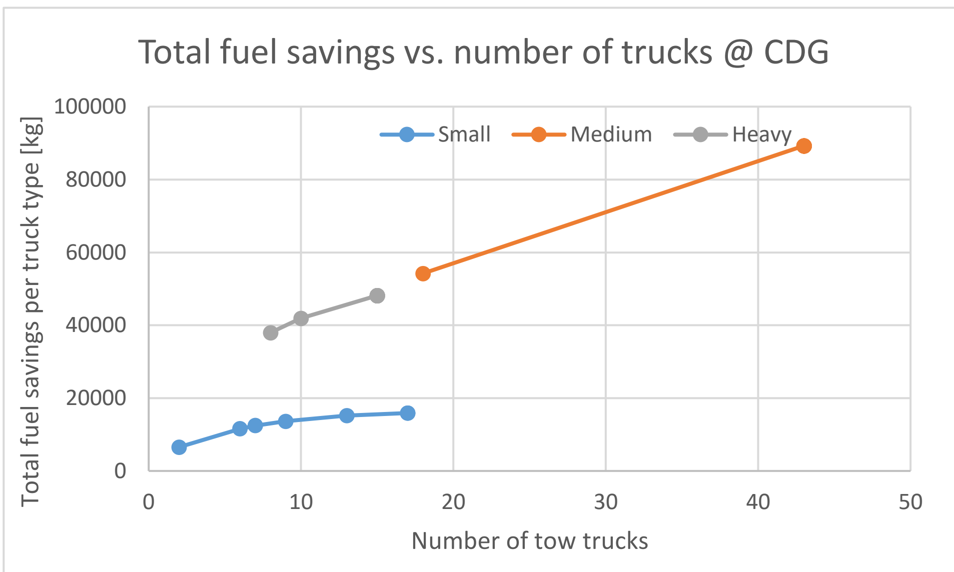

Figure 10: Total fuel savings vs. number of trucks deployed on a peak day @ CDG

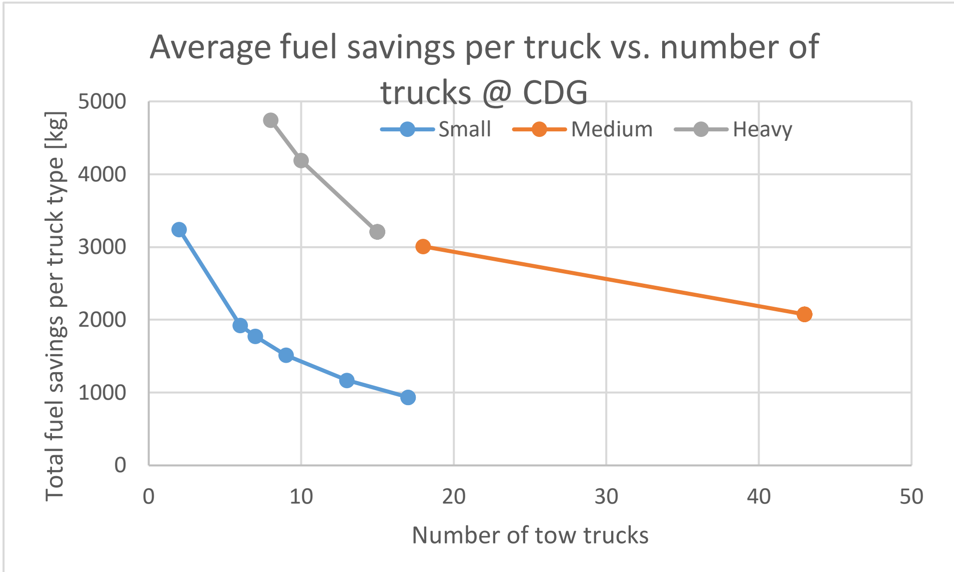

Figure 11: Average fuel saving per truck vs. number of trucks deployed on a peak day @ CDG

VI.Global results

The results for ten airports with the highest savings and Milan Malpensa (MXP), as an example of a more moderate non-hub airport, are shown in figures 12, 13 and 14. In general higher taxi times mean more savings, but if high delays are present, reducing those delays should take preference over using tow trucks. Savings per vehicle will need to be larger for large vehicles, to offset the larger capital and operating costs of these vehicles. If vehicles need to be manned, these costs will be the same independent of the size of the vehicle and thus this would have less impact on the larger vehicles.

For towing small aircraft, shown in figure 12, New York JFK has the highest saving if only a few trucks are deployed, while Amsterdam (AMS) need the most trucks to tow all movements. Chicago O'Hare (ORD) has the highest overall savings, which is equal tot the number of trucks times the savings per truck. US airports in general seem to have a better business case in number of trucks and savings per truck. London Heathrow (LHR) can only deploy a few trucks and savings per truck are low, due to low utilization due to a limited number of flight with smaller regional aircraft due to severe slot limitations, making operating smaller regional aircraft less attractive.

For towing medium aircraft, shown in figure 13, JFK can achieve the highest marginal saving per vehicle while ORD is better when operating more vehicles. An notable airport is Los Angeles (LAX) for which the marginal profit per towing vehicle remains above 2000 kg of fuel per truck for all trucks and seems to have a very stable flight schedule for medium aircraft. AMS, currently trialing two Taxibots for medium aircraft, has the lowest savings per truck after MXP. In general, the number of tow trucks for medium aircraft is much higher than for the small category.

For towing heavy aircraft, shown in figure 14, the spread is much larger than for medium aircraft. JFK has the highest savings overall as well as the highest savings per truck. This is probably due to the long taxi time to congestion, especially at the departure runway. Towing does help reduce fuel consumption and emissions, but ideally taxi times should be solved other means, such as having better departure management to avoid having a large departure queue. Atlanta (ATL) has the lowest savings, though even here the savings are between 2500 and 5000 kg per truck per day. Same as for the medium trucks, LAX has a marginal profit per truck that stays well above the 2000 kg threshold and is thus represented by a single data point.

For Milan Malpensa (MXP) we see that the margins are lower for all vehicles. For small vehicles the business is very slim and the savings are unlikely to cover the costs. For medium size the business case looks comparable to other airports at a per vehicles basis, though the number of required vehicles is a bit lower. Having only 3 to 5 heavy vehicles could make the cost of basic infrastructure and the spare vehicles (required for delay and maintenance) relatively high.

Overall, the business case for medium vehicles seems strong due to the large number of vehicles and total savings whilst for heavy vehicles the savings per vehicles are high. The small towing vehicles have the worst business case, though maybe these vehicles can be designed in a way that they can also tow medium sized aircraft.

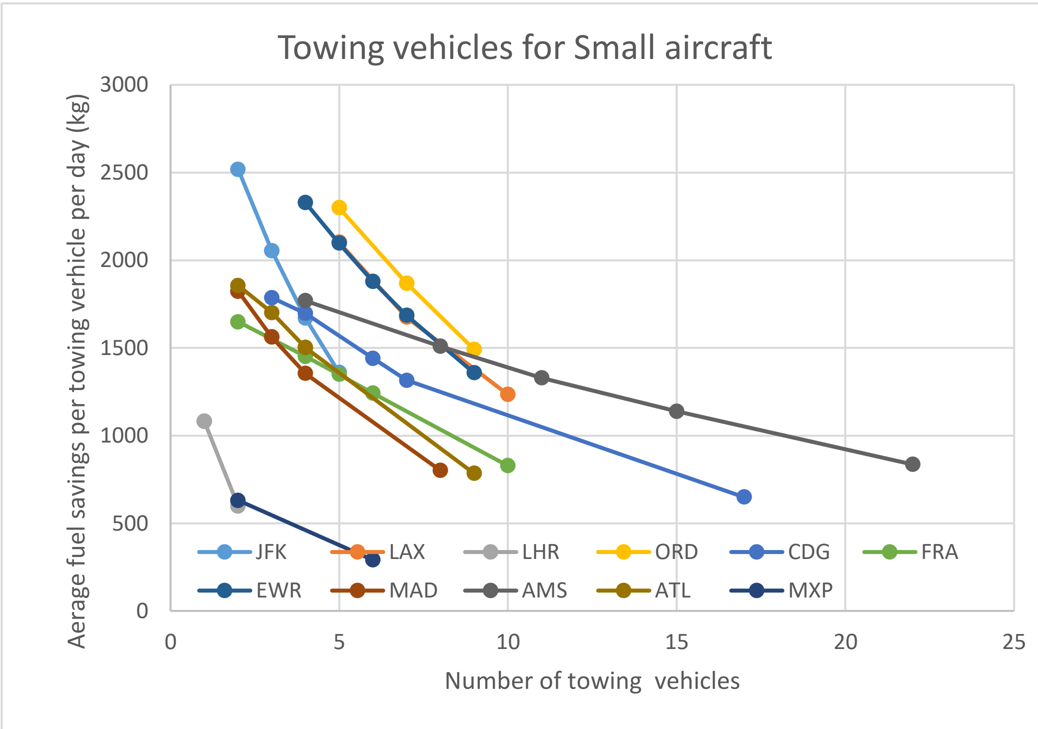

Figure 12: Average fuel saving per towing vehicles for small (regional) aircraft vs. number of towing vehicles for 10 large airports in the EU and US

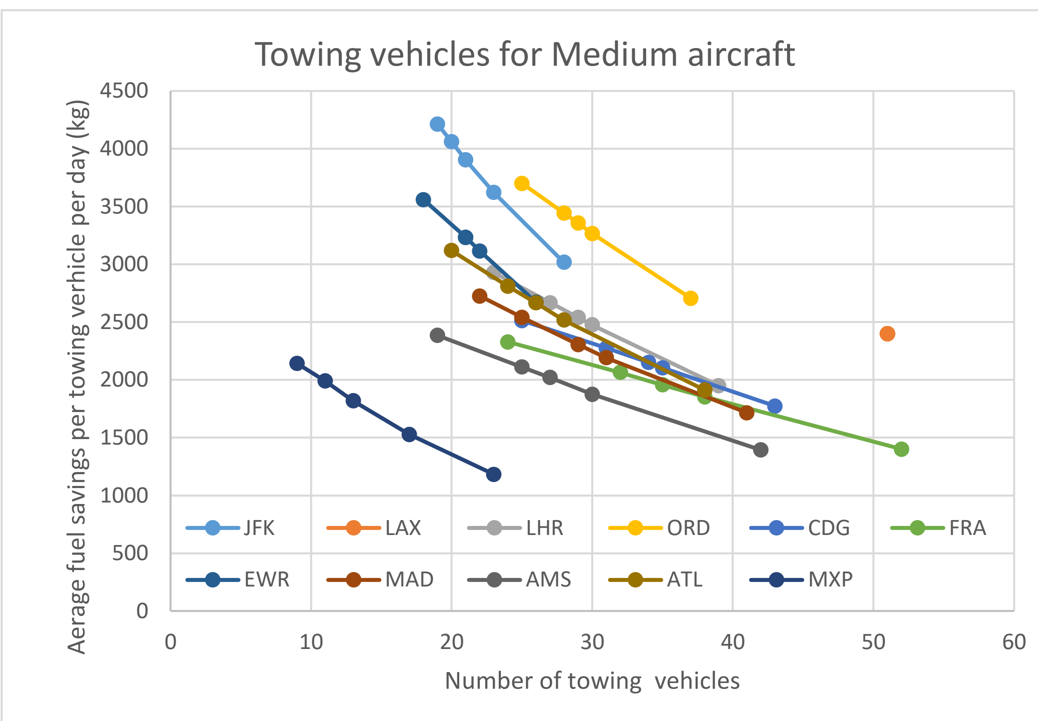

Figure 13: Average fuel saving per towing vehicles for medium (B737 and A320) aircraft vs. number of towing vehicles for 10 large airports in the EU and US

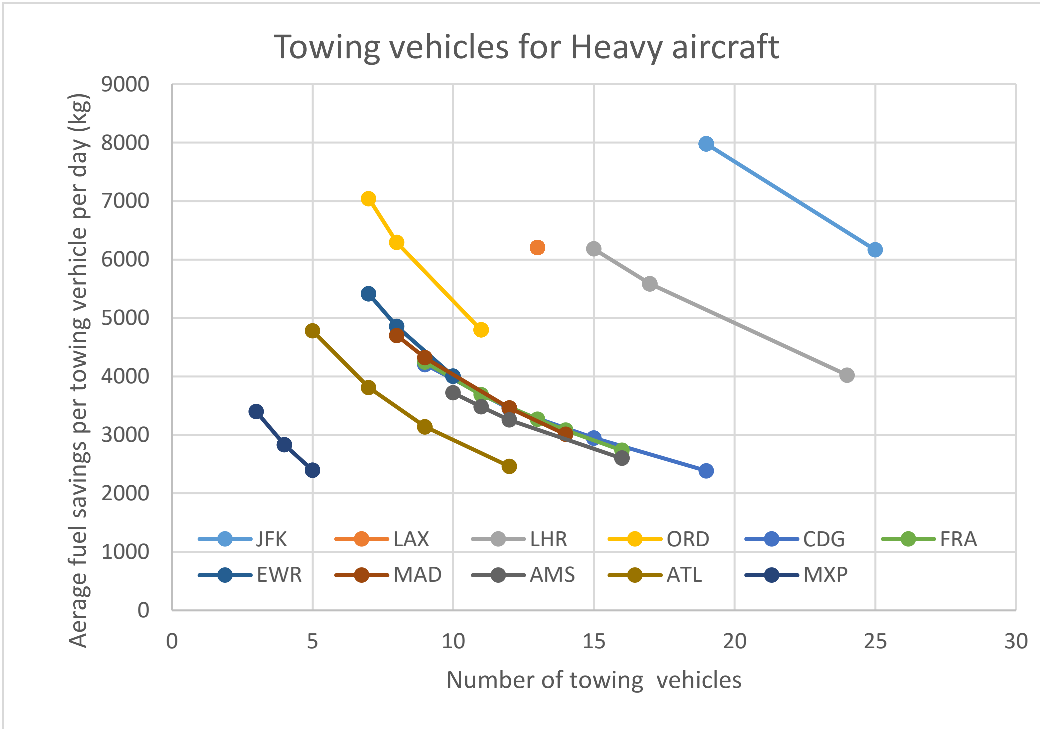

Figure 14: Average fuel saving per towing vehicles for heavy (widebody) aircraft vs. number of towing vehicles for 10 large airports in the EU and US

All emissions decrease linearly with fuel consumption, leading to graphs similar to those for fuel consumption only with different values on the vertical axis. For small aircraft savings can be up to 8 tons of CO2, 125 kg of CO, 11 kg of NOx and 12kg of HC per vehicle per day. For medium trucks the values are up to 13 tons of CO2, 150 kg of CO, 21 kg of NOx and 8 kg of HC per truck per day. For heavy the values are up to 25 tons of CO2, 190 kg of CO, 40 kg of NOx and 9 kg of HC per day.

Figure 15 givens an impression of savings in NOx emissions per vehicle for all vehicles combined. Airport with more heavy operations and thus vehicles will score better, as these have highest fuel and thus emissions saving per operation. JFK clearly has the higher saving per vehicle. LAX, LHR and ORD are a bit lower for the same reason while the rest is similar around 5 - 15kg NOx per vehicle per day.

As more vehicles are deployed at each airport, the number of operations per vehicle will decrease. Figure 16 shows that this is basically true for all airports, and the trend is near linear. In this graph the medium vehicles will dominate, as these are deployed in higher numbers. Most notably AMS, Frankfurt (FRA) and LAX have a high number of operations per towing vehicle.

Another trend is that with fewer trucks, focus will be on outbound movements as the taxi times for departures are generally significantly higher than for arrivals, making the potential savings higher. On sidenote, aircraft already need a truck for pushback anyway this only where the truck disconnects will change where on inbound, attaching a tow truck after landing is an additional action. Figure 17 does show this trend, but the effect is limited to a maximum of 60% outbound, with the exception of MXP, which goes up to 72%. This is most likely caused by the traffic schedule and not having as clear inbound and outbound peaks.

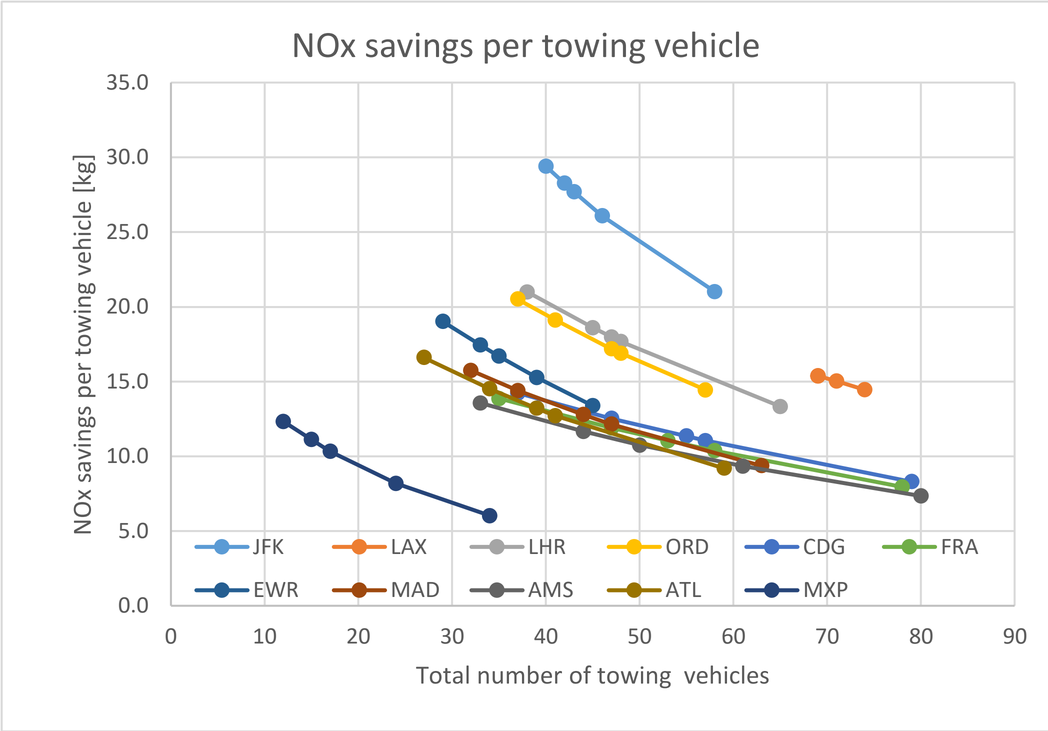

Figure 15: NOx savings per vehicle (combined)

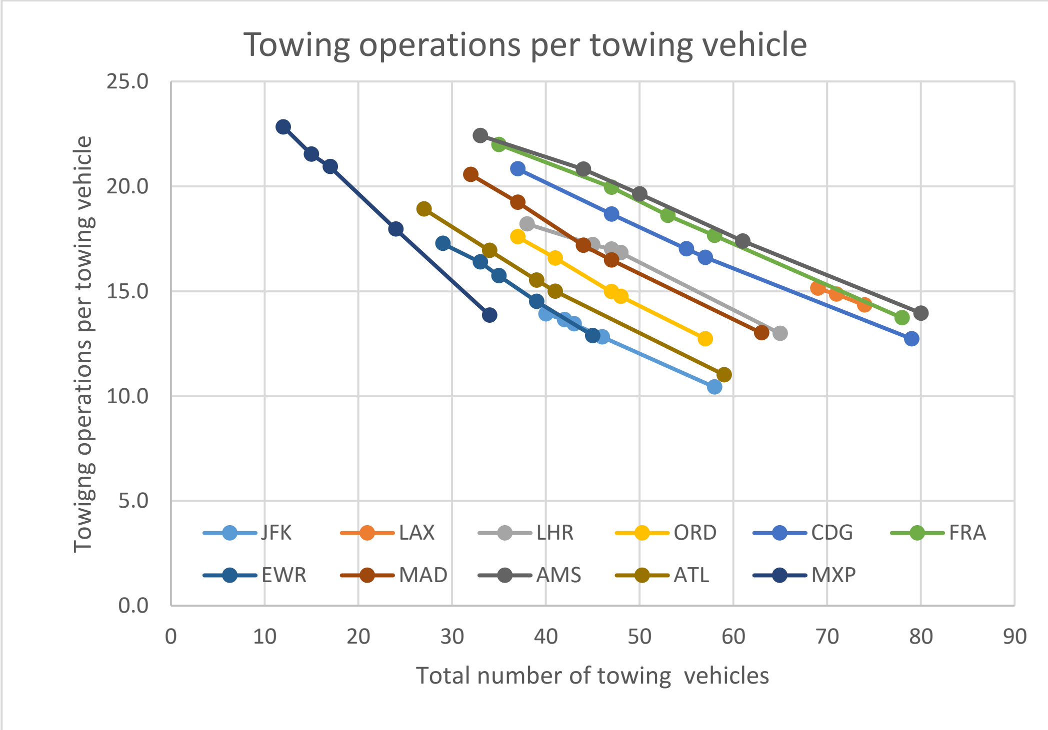

Figure 16: Number of operations per towing vehicle (combined)

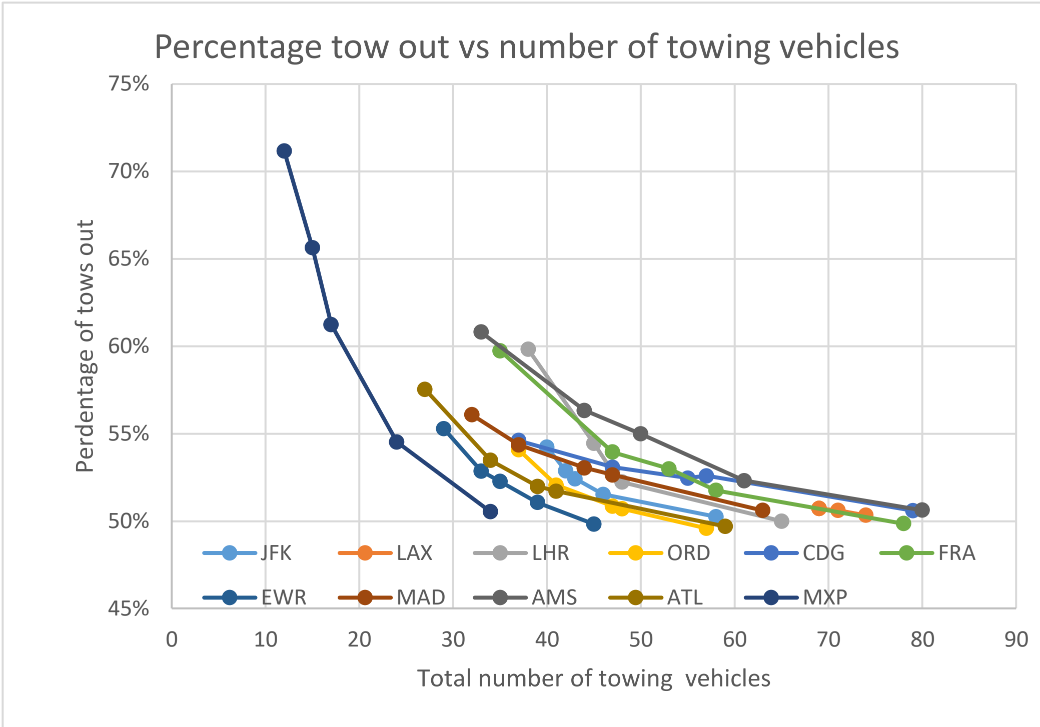

Figure 17: Percentage of outbound taxi tows vs total taxi tows

VII.Conclusions

This research based on 2018 data shows that for larger airports in the US and Europe there seems to a reasonable business case in implement towing, assuming each towing vehicle needs to offset more than of 1000 kg of fuel on a peakday. More specific research should be done at each airport with a more accurate schedule and specific taxi times before further implementation.

Further analysis shows that at large airport towing heavy aircraft makes sense from a savings per vehicle point of view while for medium aircraft the total savings seems significant enough. For smaller, regional aircraft, utilization would be relatively low, limiting the business case for these aircraft. It could make sense to only operate a few of these smaller towing vehicles and accept that not all aircraft can always be towed or integrate an autonomous eTaxi system in these aircraft.

It should be noted again that this research was done on a high level. Fuel and emissions from towing vehicles were not taken into account. If electric vehicles where to be used, time constraints for charging would need be added as well as emissions from electricity generation. For better accuracy, more variation in aircraft types should be taken into account, as well as more actual taxi times taking into account the used gate and runway per flight as well as actual congestion.

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