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Design of a zero emission aircraft towing system

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Even though aircraft have become less pollutant over the years, the increase in air traffic results in a growing production of emissions in the aviation industry. In other words, the annual decrease in pollution due to more fuel efficient aircraft, cannot compete with the increase of pollution caused by air traffic growth. Unlike the aviation sector, most sectors can replace fossil fuels with alternate energy sources, but the airline industry is currently confined to kerosene for flight operations. On the ground, electric taxiing is an alternative to conventional taxiing, which would have less impact on the environment and could solve aircraft congestion problems at airports. This research focuses on the feasibility of an airport based electric towing system, which eliminates the need for using fossil fuels while on the ground as much as possible.

I. Introduction

The aviation sector, itself, has acknowledged their role in global climate change and are taking measures. For example, the following targets to mitigate CO2 emissions were set by the major aviation institutions (the Airports Council International (ACI), the Civil Air Navigation Services Organization (CANSO), the International Air Transport Association (IATA), International Civil Aviation Organization (ICAO), and the International Coordinating Council of Aerospace Industries (ICCAIA)) in 2010 [1,2]:

- to continuously improve CO2 efficiency by an average of 1.5 per cent per annum from 2009 until 2020;
- to achieve carbon neutral growth from 2020;
- to reduce carbon emissions by 50 per cent by 2050 compared to 2005 levels.

ICAO has passed a resolution in 2016 on a global market-based measure for international aviation to offset CO2 production growth starting in 2021[3]. The resolution initiates a scheme, called Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), that requires airlines to monitor their exhaust emissions on all international routes, and to offset the emissions produced on certain routes by purchasing emission units from projects that reduce emissions. It is expected that 80% of the emissions above the levels in 2020 will be offset through this scheme in the period 2021-2035[4].

Emissions can be measured using emission monitoring systems. Typically Continuous Emission Monitoring Systems (CEMSs) and Predictive Emission Monitoring Systems (PEMSs) are used to monitor air quality. CEMSs actually measure the air quality for emissions particles, and PEMSs predict the amount of emissions produced using models. A common method to estimate the amount of emissions produced is through the use of emissions indexes[5,6]. ICAO has a database containing the amounts of emissions an engine type produces at certain thrust settings, or emission indexes[7]. This database was produced through engine testing.

Kesgin applied this method when studying aircraft emissions at Turkish airports in 2006 [5]. One of the important conclusions from this study is that the taxiing phase causes around 72% of the LTO emissions, followed by the climbing phase with around 15% of the LTO emissions around Turkish airports. The take-off and approach phases cause around 7% and 6% of the LTO emissions respectively.

Even though electric taxiing systems will decrease the noise produced during taxiing, noise during taxiing has relatively little impact on the environment. Therefore, noise is not a driving factor for a new electric taxiing system. Noise is therefore not focused on in this study, even though an electric taxiing system has the benefit that it is quieter than conventional taxiing.

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II. Electric vehicle design

The concept for a 'Self-Contained Taxiing System' was first patented in 1974 to save fuel, reduce manpower necessary to move an aircraft about an airport, reduce noise and pollution, eliminate the need for equipment external to the aircraft to move the aircraft, drastically reduce breakaway thrust and reduce the spacing required between aircraft. The system describes how the APU of an aircraft could be used to power a device to drive the aircraft wheels for taxiing, thereby eliminating the need for the main engines or any external assistance[8]. This system became the foundation for the ETS.

One of the most promising ETS concepts is the TaxiBot; a semi-robotic towbarless aircraft tractor, connected to the NLG, that dispatches the aircraft during taxi out, so that the main engines can be off. The TaxiBot is controlled by the pilot, except during pushback, using the tiller and brake pedals for taxiing. This is done using a system that senses the steering movements. Having the pilot in command eliminates numerous issues with safety, accountability, and regulations. The tractor has an 800 hp hybrid-electric engine[9], and does not require any resources from the aircraft. There are two types of TaxiBot: a type for narrow-body aircraft, and a type for wide-body aircraft, thus are compatible with most commercial airliners.

With taxi speeds up to 23 knots, the aircraft is transported at similar speeds as conventional taxiing. The pushback operations and procedures of TaxiBot are identical to the conventional manner of taxiing. TaxiBot also claims that the life of the NLG is not shortened using its system, by protecting the NLG from exceeding the maximum fatigue loads. As this system is external to the aircraft, minor or no modifications are necessary to the aircraft, and no weight is added to the aircraft. As the TaxiBot is powered by a hybrid-electric engine, it is not entirely an ETS. However, significantly less fossil fuel emissions will be produced than conventional taxiing.

A. Batteries

Lithium-ion batteries are widely used in (electric) vehicles and home appliances. Reasons for using lithium-ion batteries are that they are rechargeable, have a high energy density, are relatively lightweight, have a slow degradation of their maximum energy capacity, do not self-discharge quickly, and are low maintenance.

Downsides of lithium-ion batteries are that they are expensive to manufacture, voltage and current need to be regulated, can catch fire or explode. Nowadays, lithium-ion batteries are rapidly replacing lead acid batteries. Lithium-ion batteries will therefore be the battery of choice for.

Energy density becomes a design requirement when mass and volume affect the design of a mobile power source. Energy density may refer to the amount of energy stored in a system per unit mass or unit volume. When mass is a design requirement, the amount of energy stored per unit mass is of interest and is also known as the specific energy, expressed in J/kg . When volume is a design requirement, the energy density is of interest and is expressed in J/m3. The power and energy densities of a lithium-ion battery are:

- Volumetric energy density [GJ/m^3]: 0.90 - 2.23
- Specific power density [kW/kg]: 0.30 - 1.50
- Specific energy density [MJ/kg]: 0.36 - 0.90

By first determining the amount of energy the aircraft needs at engine start-up and for taxiing, the mass and volume of the batteries required to power these processes can be calculated using the energy density to see if battery power is a feasible design option. A battery-powered system is not an option if the batteries are too heavy or large to carry on board or to be placed in a tug.

B. ETS concept

The most promising design for a new improved ETS is an electric towing system. The reasoning behind this is that no modifications need to be made to the aircraft, no weight is added to the aircraft, and wide-bodied aircraft can be transported as power does not necessarily need to be supplied by the APU. TaxiBot already is such a system, but TaxiBot is hybrid powered, and therefore does not purely run on renewable energy. The new system should preferably be fully electric. This can either be achieved by making the new ETS run on battery power or to have the ETS leach power from an electric network. The new ETS will consist of electric tugs transporting the aircraft around the airport like a towbarless tractor. The APU will no longer be needed during ground operations.

Aircraft will have to mount and dismount the tugs of the ETS, similarly to a towbarless tractor. There are two options for when this is done. The first option is that a tug stays with the aircraft from the moment the aircraft exits the runway on arrival until the moment the aircraft joins the runway queue on departure. The second option is that tugs abandon the aircraft when parked at the gate, to move on to other aircraft requiring a tug. The first option requires more tugs than the second option, but time is saved by not having to dismount and remount the aircraft and the tug can recharge at the gate. In both cases, the tugs have to relocate. The tugs will avoid traffic as much as possible, by only making use of free taxiways or service roads.

Heavier aircraft require more torque to overcome rolling drag than lighter aircraft Either the motors should be more powerful for heavier aircraft, or smaller tugs can be put in series to generate sufficient torque. Having tugs in series, will require more tugs around the airport, but this standard sized tug can be used for every aircraft type.

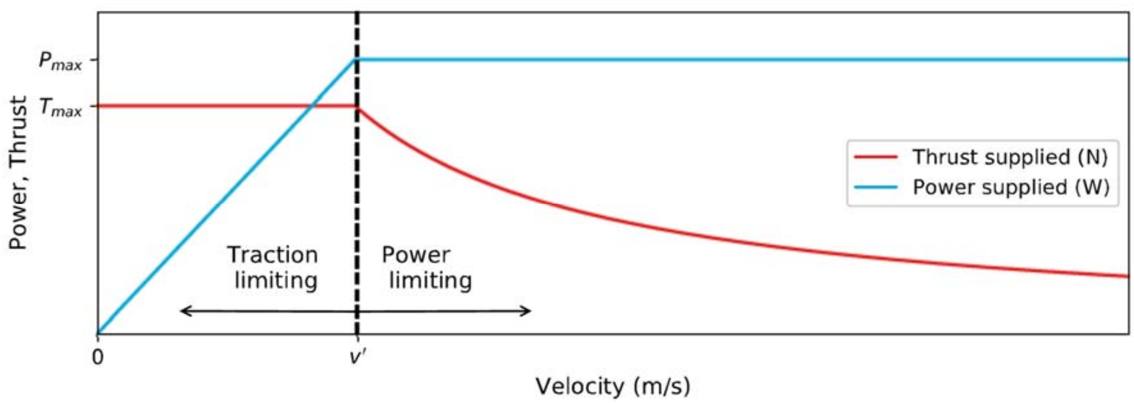

Figure 1: Power and Thrust vs. velocity

Battipede et. al designed an electric taxiing system powered by hydrogen fuel cells called CHAT[10]. According to their calculations, a 300kW motor is powerful enough to pushback even wide-bodied aircraft, but that it is not sufficient to accelerate the aircraft to conventional speeds. Their solution is to place the ETS tugs in series using a retractable towbar. This could be done with the new ETS as well, where tugs running on 200-300kW motors work in series to generate enough power to pull wide-bodied aircraft. Smaller motors are cheaper and weigh less than more powerful motors. 300kW motors are widely available and prices start at US$1,000. The right type and good quality motors will be more expensive, especially motors required to transport aircraft. Therefore it is assumed a 300kW electric motor costs US$50,000. For this research, the design choice was made for a single towbarless towing vehicle that uses the weight of the aircraft to generate traction, as illustrated in figure 1.

Not only does the towing vehicle need to be fully electric an tow the aircraft, in order to eliminate the need for running engines, it must also provide preconditioned air (PCA), and provide compressed air for the engine start up through an air starter unit (ASU). How these are connected or disconnected after landing and before take-off is mechanically challenging[11], but for now outside the scope of this research.

For this research three types of towing vehicles have been defined, with varying weight and power specifications, as shown in table 1. The medium vehicle is designed for aircraft up to the A320 and B737 series, the heavy vehicle is designed for aircraft up to the A340 and the super heavy for the B747 and A380. AS different aircraft have different weights, the performance of the aircraft tug combination will vary.

Table 1: Towing vehicle types

	Medium	Heavy	Super Heavy
Total mass [kg]	25,000	45,000	60,000
Battery mass [kg]	7,000	14,000	21,000
Battery volume [m3]	3.82	7.64	11.45
Battery capacity [kWh]	840	1,680	2,520
Max. power [kW]	1,400	2,800	4,200
Max. ASU/PCA power [kW]	436	783	783
Drive train	4x4	6x6	6x6

III. Methodology

A vehicle routing problem (VRP) will be used to determine the maximum fuel reduction by a fleet of fully electric towing vehicles. In this case, the total aircraft fuel consumption is minimized by deploying a fleet of fully electric towing vehicles to tow a set of flights. The optimization will determine which vehicles will tow which flights, and which flights will not be towed. Using the towing simulations data, the total fuel and energy consumption, and emission production can be calculated. Figure 2 gives an overview of the process.

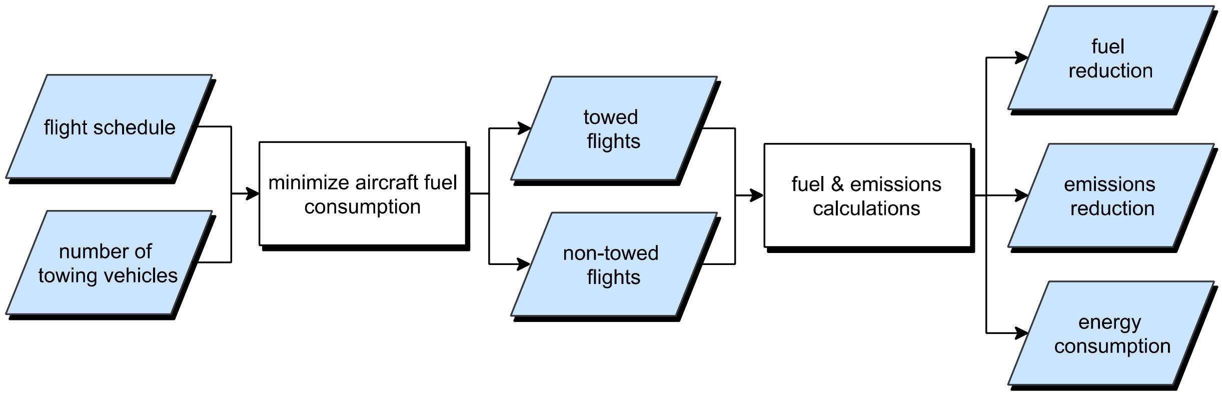

Figure 2: Determining fuel, emissions and energy savings

The main assumptions of the VRP model are that all events occur as scheduled, the towing vehicles can only tow aircraft in their respective category and that the towing vehicle can be fully charged in the minimum charging time.

A. Variables

$x_{i,j}^{k,r}$: binary variable; equals one if fully electric towing vehicle k tows flight i and j consecutively in route r.

y_j : binary variable; equals one if flight j is not towed.

f_j : fuel consumption of flight j when towed by a vehicle

F_j : fuel consumption of flight j when taxiing

N_v : number of towing vehicles in the fleet of type v

N_c : maximum number of rounds a towing vehicle is allowed to make

N_f : number of flights in the flight schedule

M : large positive integer

E_j :energy consumption by vehicle towing flight j

$e_{i,j}$:energy consumption by vehicle transferring between tows of flight i and flight j .

Q :energy capacity of the vehicle

C :minimum vehicle charging time

WC_i : engine warm-up or cool-down time of flight i (dependent on direction)

t_j^a : start time of the tow of flight j by a vehicle

t_i^f :end time of the tow of flight i by a vehicle

$t_{i,j}$: transfer time of a fully electric towing vehicle between tows of flight i and flight j

$t_{cool-down}$: time required for the engines to cool-down after landing before shutting off

$t_{warm-up}$: time required for the engines to warm-up before taking off.

B. Objective function

The objective is to minimize the total fuel consumption by selecting which towing vehicle will tow which flights in order. It consists of two parts; the left part is the total fuel consumption of towed flights, and the right part is the total fuel consumption of non-towed flights. Every flight will fall in one of two categories

$$\min z = \sum_{k=1}^{N_v} \sum_{r=1}^{N_c} \sum_{i=0}^{N_f - 1} \sum_{j=1}^{N_f} f_j x_{i,j}^{k,r} + \sum_{j=1}^{N_f} F_j y_j \tag{1}$$

C. Constraints

1. Vehicle to flight assignment

All flights should either be towed by or not towed. Additionally, a flight should be visited a maximum of one time by a vehicle. Similarly, a flight should be left a maximum of one time by a vehicle or not towed.

$$\sum_{k=1}^{N_v} \sum_{r=1}^{N_c} \sum_{i=0}^{j-1} x_{i,j}^{k,r} + y_j = 1 \qquad \forall j \in \{1, 2, ..., N_f\} \tag{2}$$

$$\sum_{k=1}^{N_v} \sum_{r=1}^{N_c} \sum_{j=2}^{N_f + 1} x_{i,j}^{k,r} + y_i = 1 \qquad \forall i \in \{1, 2, ..., N_f\} \tag{3}$$

2. Flow constraints

Every route a towing vehicle makes it will tow a number of flights. The flow constraint assures that if a vehicle k on route r moves to flight p (from flights i), it must also depart it (to flight j).

$$\sum_{i=0}^{p-1} x_{i,p}^{k,r} - \sum_{j=p+1}^{N_f + 1} x_{p,j}^{k,r} = 0 \qquad \forall p \in \{1, 2, ..., N_f\}, \forall k \in \{1, 2, ..., N_v\}, \forall r \in \{1, 2, ..., N_c\} \tag{4}$$

Similarly, if a vehicle k on route r departs the depot (0), it must also arrive back at the depot.

$$\sum_{j=1}^{N_f} x_{0,j}^{k,r} - \sum_{i=1}^{N_f} x_{i,0}^{k,r} = 0 \qquad \forall k \in \{1, 2, ..., N_v\}, \forall r \in \{1, 2, ..., N_c\} \tag{5}$$

A route r+1 for vehicle k can only be started if the previous route r has also been started:

$$\sum_{j=1}^{N_f} x_{o,j}^{k,r+1} - x_{o,j}^{k,r} \leq 0 \qquad \forall k \in \{1, 2, ..., N_v\}, \forall r \in \{1, 2, ..., N_c - 1\} \tag{6}$$

3. Timing constraints

Two flights can only be served in sequence if they fall within a certain time interval. Additionally, a rolling horizon prevents the vehicle from waiting on the apron for large amounts of time in between jobs, whilst it could return to the depot in the meantime. This reduces the amount of options for the optimization.

$$\sum_{k=1}^{N_v} \sum_{r=1}^{N_c} (t_j^a - t_i^f) x_{i,j}^{k,r} < T \qquad \forall i \in \{1, 2, ..., N_f - 1\}, \forall j \in \{2, 3, ..., N_f\} \tag{7}$$

Also, two flight can only be served if they have enough time between them for the vehicle to travel between them.

$$\sum_{k=1}^{N_v} \sum_{r=1}^{N_c} (t_j^a - t_i^f - t_{i,j}) x_{i,j}^{k,r} \geq 0 \qquad \forall i \in \{1, 2, ..., N_f - 1\}, \forall j \in \{2, 3, ..., N_f\} \tag{8}$$

Aircraft engines have to be warmed up before take-off and cooled down before shut down. Flights whose engines would be on the entire towing duration are rejected for towing.

$$\sum_{k=1}^{N_v} \sum_{r=1}^{N_c} \sum_{j=1}^{N_f + 1} (t_i^f - t_i^s - WC_i) x_{i,j}^{k,r} \geq 0 \qquad \forall i \in \{1, 2, ..., N_f\} \tag{9}$$

Ideally the timing constraints are pre-processed to limit the problem size.

4. Energy capacity

The energy required for all tows and ferries between tows on a route should not exceed the energy capacity of the towing vehicle.

$$\sum_{j=1}^{N_f+1}\sum_{i=0}^{N_f}\left(E_j+e_{i,j}\right)x_{i,j}^{k,r}\leq Q \qquad \forall k\in\left\{1,2,...,N_v\right\},\forall r\in\left\{1,2,...,N_c\right\} \tag{10}$$

A route is ended every time a towing vehicle returns to the towing vehicle depot, and a new route is started every time the towing vehicle leaves the depot. There should be sufficient time between the last tow of a route and the first tow of a new route for the vehicle to ferry to and from the depot, and charge in between.

$$\sum_{j=1}^{N_f}t_{0,j}x_{0,j}^{k,r+1}-\sum_{i=1}^{N_f}t_{i,0}x_{i,0}^{k,r}+M-M\sum_{j=1}^{N_f}x_{0,j}^{k,r+1}\geq C \quad \forall k\in\left\{1,2,...,N_v\right\},\forall r\in\left\{1,2,...,N_c-1\right\} \tag{11}$$

IV.Results per flight

Two airports and their respective schedules were analysed, Rotterdam the Hague (RTM) and Amsterdam airport Schiphol.

Rotterdam-The Hague Airport is a regional airport located in the Netherlands. The airport handles approximately 17,000 scheduled flights annually. It has a bidirectional runway (06/24), where both directions can be used for take-off and landings, depending on the wind conditions. The terminal apron is located approximately 400 meters from the southwest end of runway and approximately 2,300 meters from the northeast end of the runway. The apron has four transporter platforms (A-D) close to the terminal building. The flight schedule used for Rotterdam-the Hague Airport is the flight schedule for Tuesday 25th July 2017. On this day there were 39 movements in total of which 19 arrivals and 20 departures. All aircraft are in the medium category.

Amsterdam Airport Schiphol is a large international hub airport located in the Netherlands. The airport terminal configuration for civil aviation consists of a transporter platform (A), and seven finger piers (B-H), landlocked in between six runways (04/22, 06/24, 09/27, 18L/36R, 18C/36C, 18R/36L). Conventionally, Schiphol utilizes eight runway directions for arrivals and seven runway directions for departures. Runway 18R/36L is considered remote, with a driving distance of approximately 11 kilometers from the furthest pier. The apron is largely surrounded by a dual lane taxiway, with only a single way taxiway over a motorway to complete the ring.

The flight schedule data for Friday 13th October 2017 is collected using the "Flight API" from Schiphol's application developer website [12]. This date is selected due to the limited availability of data for other dates. The flight API is the best source available due to high detail, as it is an official Schiphol publication. It contains which gate and which runway is used. According to this flight schedule, 1430 aircraft movements took place; 714 movements were departures and 716 movements were arrivals. 86% are in the medium category, 12.1% heavy and 1.9% super heavy (747 and A380).

Conventional taxi movements and fully electric tows were analyzed for each movement on the flight schedule. Furthermore, the ferry movements of the fully electric towing vehicles were simulated for all possible gate-runway, runway-runway, and gate-gate combinations, as this data will be necessary in the towing vehicle routing problem. The analysis was performed using node-link models and flight schedules of both Rotterdam-the Hague Airport and Amsterdam Airport Schiphol [13], taking into account speed restrictions, deceleration and acceleration. The resulting differences for each flight in terms of towing energy requirement, aircraft fuel reduction and duration are shown in figure 3.

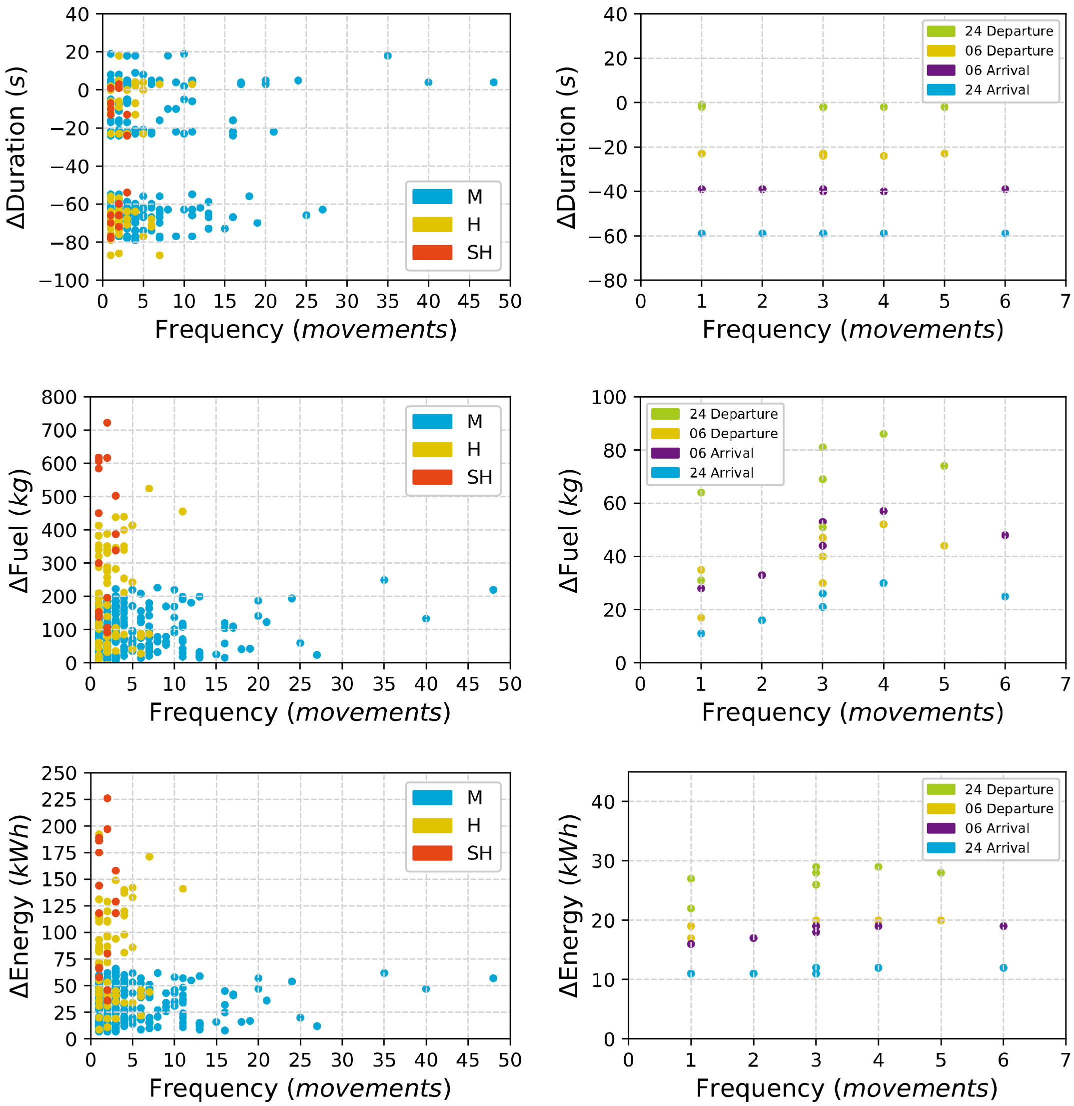

Figure 3: Time, fuel and energy difference between towing and taxiing for AMS (left) and RTM (right)

For the duration at RTM, it shows that conventional taxiing is faster than fully electric towing in all cases (as all values are negative). However, if the pure travel time is considered (the duration without time penalties or additional processes), towing is faster than taxiing. This is because the fully electric towing vehicle can accelerate faster than the aircraft that is limited at 0.7 m/s2. With the larger time penalty per turn for the electric towing vehicle, and with the additional time required for attaching the aircraft to the vehicle upon landing, conventional taxiing at Rotterdam-the Hague Airport is faster.

For the duration at AMS, the top cluster is composed solely out of departures, and the bottom cluster is composed solely out of arrivals. The fully electric towing system is slower than conventional taxiing for all arrivals. With departures, the fully electric towing system is slower in the majority of the cases, but in many cases the system is equally as fast or faster. No clear differences are observed between towing vehicle categories.

For fuel at RTM, the fully electric taxiing system saves fuel on all tows. The most fuel can be saved when the aircraft travels to or from the far end of the runway, i.e. arrivals on runway 06 and departures on runway 24. With runway 06 active, tows save between 7-57 kg of fuel per tow, averaging 36 kg per tow. If runway 24 is active, 11-76 kg of fuel can be saved per tow, with an average of 40 kg per tow.

For fuel at AMS, more fuel can be saved the heavier the aircraft category. This can be explained by the fact that more energy is required to transport a heavier mass over a certain distance, than with a lighter mass. It was observed that the difference in fuel consumed is larger for departures than for arrivals on average. This is because the aircraft are heavier during taxi-out than taxiing due to unburned fuel. The medium category towing vehicles can save 29-249 kg of fuel per tow, with an average of 106 kg per tow. Compared to Rotterdam-the Hague Airport, three times at as much fuel can be saved by this category towing vehicle due to the longer taxi routes. The heavy category towing vehicles can save between 17-524 kg of fuel per tow according to the simulations, with an average of 225 kg of fuel. The super heavy category towing vehicle can reduce fuel consumption by 113-722 kg per tow, with an average reduction of 383 kg.

For the energy at RTM, as conventional taxiing does not use battery power, the difference is purely the battery energy consumed by the fully electric towing system. For this reason, the sign of the y-axis is changed. As a form of verification, all values are positive meaning that more battery energy is consumed towing than conventionally taxiing. As with fuel consumption, the longer routes require more energy than the short routes. With runway 06 active, 16-20 kWh of energy is used per tow, with an average of 19 kWh per tow. When runway 24 is active, a tow requires 11-29 kWh of energy per tow, with an average of 20 kWh per tow.

For the energy consumed at AMS, a medium category towing vehicle consumes 7-66 kWh per tow, with an average of 33 kWh per tow. The reason why the maximum energy consumption per tow is much higher compared to maximum consumption per tow at Rotterdam-the Hague Airport, is because of the longer routes at AMS. The heavy category towing vehicles consume 9-192 kWh per tow, with an average of 79 kWh. The super heavy category utilizes 36-226 kWh per tow, averaging 125 kWh per tow. As with the difference in fuel consumption, departures consume more energy than arrivals on average, because the aircraft are heavier during tow-out than tow-in.

V.Results vehicle routing

The total and marginal fuel consumption of all flights at RTM (for both scenarios) are plotted against the fleet size of fully electric towing vehicles deployed in Figure 4. In both cases, the total fuel consumption decreases with increasing fleet size until a lower limit where all aircraft are towed. The lower limit is non-zero as fuel is consumed by the aircraft during engine warm-up and cool down. The curves are different for the two runways as the scenarios are different. For example, a departing flight to runway 06 travels a shorter distance than the same departing flight to runway 24. Therefore, more fuel can be saved from the departure to runway 24. The scenarios are different as well when zero towing vehicles are deployed.

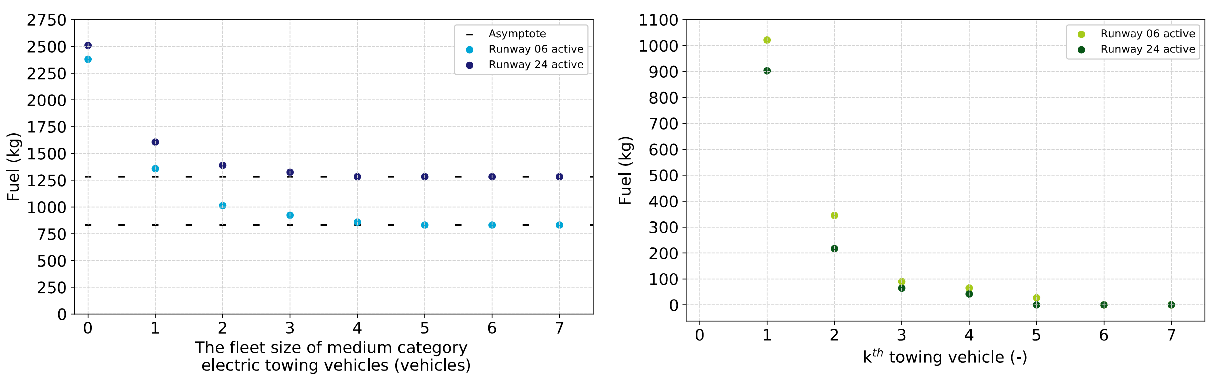

Figure 4: Fuel (left) and marginal fuel (right) results for RTM

In the scenario with runway 06 active, 2,379 kilograms of fuel is consumed by all the aircraft together if no fully electric towing vehicles are deployed. The total fuel consumption can be reduced by 1,548 kilograms (65%) by deploying five towing vehicles. Deploying more than five towing vehicles will have no effect on the total fuel consumption as all flights are towed as the marginal fuel reduction is lower every time an additional fully electric towing vehicle is deployed. The effectiveness of the first towing vehicle is the greatest, lowering the total fuel consumption by 1,021 kilograms (43%). The effectiveness of every new vehicle decreases due to the law of diminishing marginal utility.

The total fuel consumption by medium category aircraft at Amsterdam Airport Schiphol is plotted against the fleet size of medium category fully electric towing vehicles in Figure 5. The total fuel consumption by medium category aircraft is 170,105 kilograms with no towing vehicles deployed. The maximum reduction potential in fuel is 141,043 kilograms (83%) of fuel, which would require 42 fully electric towing vehicles. A fleet of eleven towing vehicles is sufficient to reduce the total fuel consumption by 50%, and a fleet of 24 towing vehicles is sufficient to reduce the total fuel consumption by 75%. The marginal fuel savings show that the utility of an extra towing vehicle decreases the larger the fleet size. The effectiveness of the first fully electric towing vehicle is the greatest, potentially decreasing the fuel consumption by 11,335 kilograms of fuel, which is 8% of the fuel reduction possible. Compared to RTM, the savings per vehicle are about a factor 10 higher for the first vehicle, of which a factor of 3 is 'apparently caused by a higher savings per tow.

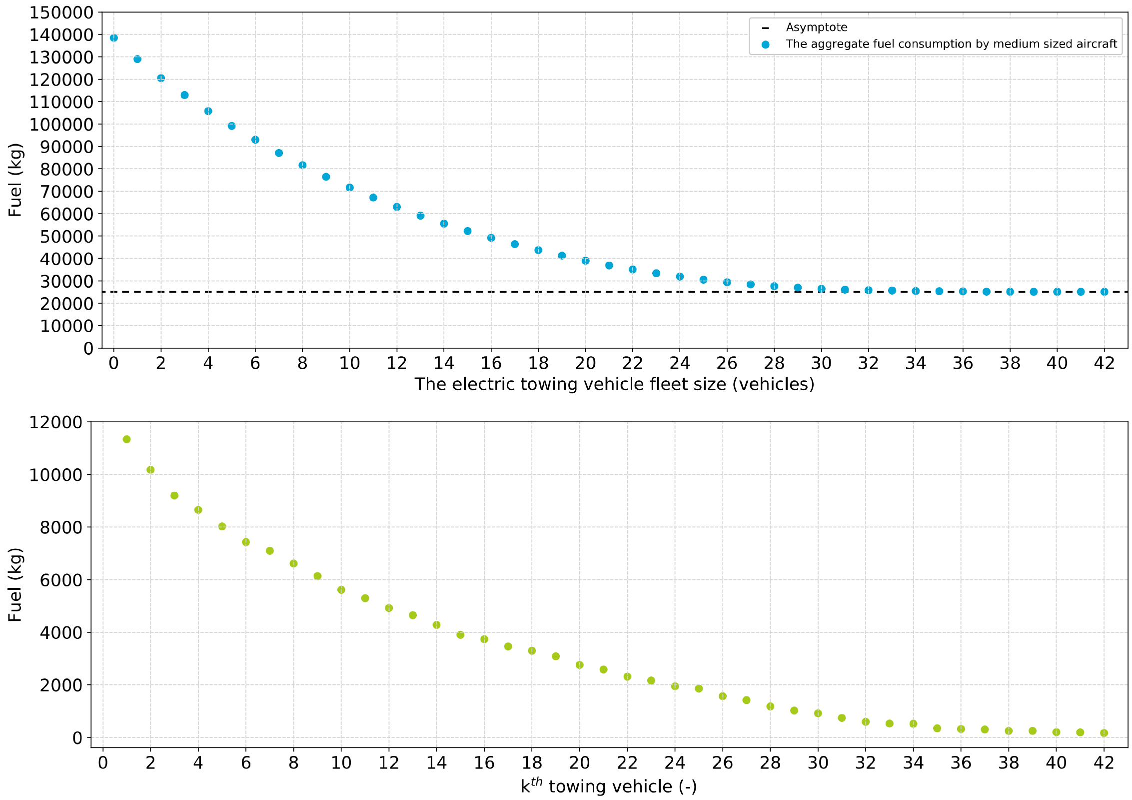

Figure 5: Fuel (top) and marginal fuel (bottom) results for medium flights at AMS

As shown in figure 6, The total fuel consumed by heavy category flights without operational towing is 52,872 kilograms of fuel. The maximum reduction in total fuel consumption is 41,377 kilograms (78%), with a fleet of twelve heavy category fully electric towing vehicles. Electrically towing all flights will cost approximately 19,460 kWh of energy. Approximately 50% fuel can be saved by deploying three towing vehicles, which will require around 11,879 kWh of energy. Approximately 75% fuel can be saved by deploying eight towing vehicles, which will cost around 18,818 kWh of energy. As with themedium category towing vehicles, the law of diminishing marginal utility applies. The marginal utility of the first heavy towing vehicle is 10,746 kilograms of fuel reduction.

All 27 super heavy category flights together consume 11,767 kilograms of fuel without electric towing. The maximum possible fuel reduction is 10,196 kilograms (86%), requiring four super heavy category towing vehicles. Again, the effectiveness of every additional towing vehicle decreases due to the law of diminishing marginal utility.

The maximum amount of energy required to tow all super heavy flights is approximately 4,260 kWh.

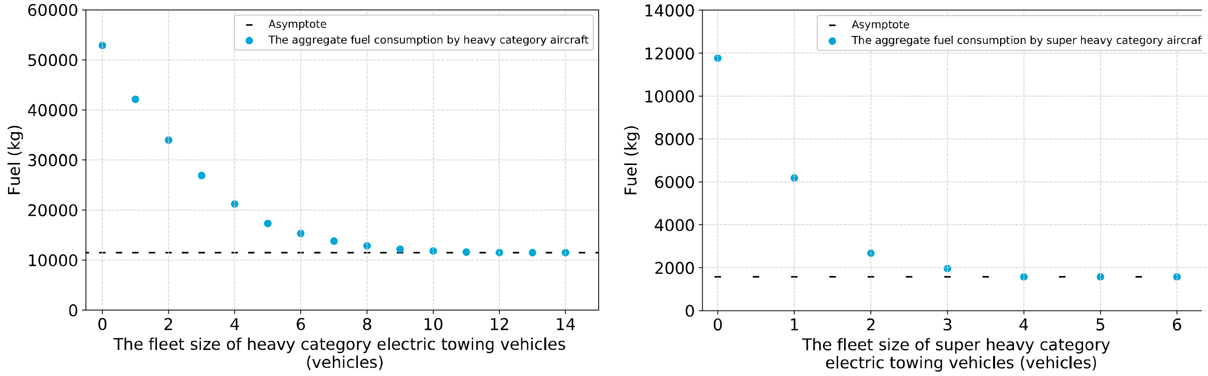

Figure 6: Fuel results for heavy (top) and super heavy (bottom) results at AMS

VI.Conclusions

At Rotterdam-the Hague Airport, the total fuel consumption per day can be reduced by at least 65% (1,548 kg). This will cost approximately 1,1MWh of power without losses due to charging. At Amsterdam Airport Schiphol, the total fuel consumption per day can be reduced by at least 82% (192,600 kg). This will cost approximately 90.4 MWh of power without losses due to charging.

The largest fuel reduction potential at Schiphol is by towing the medium category aircraft due to the large number of medium category flights. By towing all the medium category flights, 60% less fuel will be consumed at Schiphol.

The effectiveness of the fully electric towing vehicles is higher at Amsterdam Airport Schiphol than at Rotterdam-the Hague Airport. This is due to the on average longer taxi routes at Schiphol in combination with more flights, resulting in a higher utilization for the towing vehicles. When looking at Schiphol alone, the largest fuel reduction potential is with the medium category vehicles, followed by the heavy category vehicles, as there is more fuel to be saved.

The marginal utility of fully electric towing vehicles diminishes exponentially with increasing fleet size. The cost of the vehicles would thus have a large influence on how may vehicles could be profitably used.

VII.Recommendations

The ground movement models can be improved for the conventional taxiing movements. Instead of assuming a constant acceleration of 0.7 m/2, the thrust can be determined from the thrust setting and engine thrust rating. Also, the kinematics can be simulated over multiple links at a time if the links are oriented in the same direction, instead of simulating per link separately. The simulations of sharp turns can be improved, instead of using time and energy penalties.

The vehicle routing problems can be improved by keeping track of the battery life during operations. If the problem is split in multiple parts, the results of one part should be integrated into the next part. Include the effects of traffic and delays in the model.

The runtimes for the current model are significant. Should this pose a problem, a simpler assignment model, which does not look at time needed to travel between flights, could give realistic enough results without the long runtimes.

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