Potential Impact of Operational Towing on Aircraft Emissions

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by

Megan Segeren

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Megan Segeren
Delft, November 2022

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Nomenclature

Part I: Scientific Paper

Airports

AMS	Amsterdam Schiphol Airport
ARN	Stockholm Arlanda Airport
ATH	Athens International Airport
AYT	Istanbul Antalya Airport
BCN	Barcelona El Prat Airport
BRU	Brussels Airport
CDG	Paris Charles de Gaulle Airport
CPH	Copenhagen Airport
DUB	Dublin Airport
DUS	Dusseldorf International Airport
FCO	Rome Leonardo da Vinci International Airport
FRA	Frankfurt Airport
HEL	Helsinki Airport
ISL	Itanbul Ataturk Airport
LGW	London Gatwick Airport
LHR	London Heathrow Airport
LIS	Lisbon Humberto Delgado Airport
MAD	Madrid-Barajas Airport
MAN	Manchester Airport
MUC	Munich Airport
MXP	Milan Malpensa Airport
ORY	Paris Orly Airport
OSL	Oslo Airport
PMI	Palma de Mallorca Airport
SAW	Istanbul Sabiha Gokcen International Airport
STN	London Stansted Airport
TXL	Berlin-Tegel Airport
VIE	Vienna International Airport
WAW	Warsaw Chopin Airport
ZRH	Zurich Airport

Acronyms

APU	Auxiliary Power Unit
CNG	Compressed Natural Gas
GSE	Ground Service Equipment
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LTO	Landing Take-Off Cycle
NB	Narrowbody
OAG	Official Airline Guide
OEM	Original Equipment Manufacturer
SET	Single-Engine Taxiing
STA	Scheduled Time of Arrival
STD	Scheduled Time of Departure
TAT	Turn Around Time
UHCs	Unburned Hydrocarbons
USD	United States Dollar
WB	Widebody

Chemical Formulae

CO	Carbon Dioxide
CO_2	Carbon Monoxide
HC	Hydro Carbons
NO_x	Nitrogen Oxides; Nitric Oxide (NO) + Nitrogen Dioxide (NO_2)

Sets

V	Set of towing vehicles, v
F	Set of flights, f
T	Set of finite time-steps, t

Subsets

V_f	Subset of vehicles in V, compatible with flight f
F_{vt}	Subset of flights in F compatible with vehicle v, at time-step t

Decision Variables

p_{vt}	Continuous decision variable: Fuel of vehicle v at time-step t [kg]
r_{vt}	Continuous decision variable: fuel vehicle v refuels at time-step t [kg] or [kWh]
x_{vf}	Binary decision variable: 1 if vehicle v tows flight f ; 0 otherwise
y_f	Binary decision variable: 1 if flight f taxis itself; 0 otherwise
z_{vt}	Binary decision variable: 1 if vehicle v is refuelling at timestep t; 0 otherwise

Parameters

$C_{SET_f}^{IN}$	Inbound SET taxi fuel [kg]
$C_{SET_f}^{OUT}$	Outbound SET taxi fuel [kg]
$C_{taxi_f}^{IN}$	Inbound conventional taxi fuel [kg]
$C_{taxi_f}^{OUT}$	Outbound conventional taxi fuel [kg]
$C_{tow_{vf}^{IN}}$	Inbound towing fuel [kg]
$C_{tow_{vf}}$	Outbound towing fuel [kg]
$E_{p_{AC}}$	Emissions of pollutant p by aircraft [g]

Parameters Continued

$EI_{p_{AC}}$	Emissions index of pollutant p for the aircraft [g/kg]
EI_{p_V}	Emissions index of pollutant p for the vehicle [g/kg]
$FF_{AC_{conv}}$	Fuel flow of aircraft during conventional taxiing [kg/min]
$FF_{AC_{SET}}$	Fuel flow of aircraft during SET [kg/min]
FF_{APU}	Fuel flow of APU [kg/min]
$FF_{ENG_{idle}}$	Aircraft engine idle fuel flow [kg/sec]
$FF_{ENG_{SET}}$	Aircraft engine SET fuel flow [kg/sec]
FF_V	Vehicle fuel flow [kg/min]
$N_{ENG_{AC}}$	Number of engines on aircraft [-]
N_{ENG_V}	Number of engines on tow vehicle [-]
P_{ENG_V}	Power of tow vehicle engine [kW]

P_{max}	Fuel/Energy capacity of a vehicle [kg] or [kWh]
Q_v	Maximum refuel/recharging capacity per timestep [kg] or [kWh]
SFC_{ENG_V}	Vehicle engine specific fuel consumption [kg/kWh]
STA_f	Scheduled time of arrival of flight f
STD_f	Scheduled time of departure of flight f
TAT	Vehicle turn around time
$T_{active_{AC}}$	Time that aircraft engines are active
T_{active_V}	Time that vehicle engines are active
T_{end}	Time that vehicle ends towing job
$T_{Rounded}$	Taxi time of flight rounded up to the nearest 5 minutes
T_{SET}	Time that aircraft is taxiing with reduced engines
T_{taxi_f}	Taxi time of flight f
T_{TOW}	Time that aircraft is being towed
T_{warm}	Engine warm-up time

Part II: Literature Study

Acronymns

APU	Auxiliary Power Unit
A-SMGCS	Advanced Surface Movement Guidance and Control Systems
ATC	Air-Traffic Control
CNG	Compressed Natural Gas
EEDB	Engine Emission Databank
FCP	Fleet Composition Problem
FSP	Fleet Sizing Problem
GSE	Ground Service Equipment
HNN	Hopfield Neural Network
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IPCC	International Panel of Climate Change
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LTO	Landing Take-Off Cycle
MAPF	Multi-Agent Path Finding
MHNN	Modified Hopfield Neural Network

MILP	Mixed-Integer Linear Programming
RF	Radiative Forcing
SD-VSP	Single Depot Case for the Vehicle Scheduling Problem
SESAR	Single European Sky ATM Research
SET	Single-Engine Taxiing
TNO	Netherlands Organisation for applied scientific research
VFC	Vehicle Fleet Composition
VOC	Volitile Organic Compounds
VSP	Vehicle Scheduling Problem

Chemical Formulae

CO	Carbon Monoxide
CO_2	Carbon Dioxide
CH_4	Methane
HC	Hydrocarbons
NO_x	Nitrogen Oxides
O_3	Ozone
$PM_{2.5}$	Particulate Matter 2.5 μm
PM_{10}	Particulate Matter 10 μm
SO_x	Sulfur Oxides

Introduction

The aviation industry has grown to become a crucial part of modern society by connecting businesses and people around the globe. With this, we saw exponential growth in demand, but without a suitable alternative, the industry has become the fastest-growing source of greenhouse gases in the transportation sector. The European Commission (2021), estimated that in 2017, aviation emissions in Europe accounted for 13.9% of all transport emissions and 3.8% of total carbon dioxide (CO_2) emissions . Due to pressure from policymakers as part of the European Climate Action Plan, the aviation industry has reacted by creating the Destination 2050 plan by van der Sman et al. (2020) to reduce aviation-related emissions through policy and action.

The Destination 2050 plan outlines measures that can be taken in four pillars to improve the carbon footprint of the industry. Four categories where improvements have been identified are aircraft and engine technology, air traffic management and aircraft operations, sustainable aviation fuels, and smart economic measures. In the report, improvements in Air Traffic Management (ATM) and aircraft flight and ground operations are crucial for short- to medium-term emissions reductions. Alternative taxi solutions are a key part of the action plan. Operational towing is deemed a feasible alternative to conventional taxi operations. Literature on the emissions and fuel savings of operational towing, however, has been limited to airport-specific studies. For this reason, there is a gap in the literature on the impact of operational towing on a wider European scale. In addition, research has focused on simulating a scenario where all taxi operations are replaced by operational towing. This means that the marginal savings of each vehicle cannot be researched. Because of vehicle and aircraft compatibility, a mixed operations scenario is realistic within a 15-year timeline given the budget constraints of stakeholders and the speed of technology development and certification.

The goal of this research is to estimate the emissions savings per unit of vehicle cost of implementing operational towing for commercial passenger air traffic at major European airports. This aims to find a link between towing vehicle fleet size and the maximum fuel and emissions savings potential. By finding the marginal savings of each towing vehicle, an investment cost can be linked to fuel and emissions savings. This means that upcoming technologies can be compared and stakeholders can choose the most suitable technology to fit their budget or emissions mitigation target. The objective of this research is to develop a model that can estimate the European emissions savings of operational towing per vehicle in a towing fleet. This model will estimate the maximum fuel savings per vehicle fleet size that can be obtained at 30 European airports.

The report is structured as follows. In Part I, the research paper is presented. This contains details of the research method, results, and conclusions. In Part II, the literature review is presented. In the literature review, the motivation for this research and previous literature are discussed. The literature study also includes the planning of this project. Finally, in Part III supplementary work is presented. In Appendix A, an overview of all changes to the scope of this research compared to those in the literature study can be found. In Appendix B, supplementary results for all 30 airports which could not be included in the research paper are included. In Appendix C all aircraft and engine combinations are listed. Finally, in Appendix D, the vehicle and aircraft compatibility matrix is presented.

I

Scientific Paper

Potential Impact of Operational Towing on Ground Emissions

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Abstract

In this paper, the emissions mitigation potential of implementing operational towing at major European airports is evaluated. Using mixed-integer linear programming, a scenario simulating mixed taxiing operations is used to find the relationship between fixed vehicle costs and target emission savings at an airport and European level. Using formulae derived from the ICAO Advanced Emissions Model, fuel burn and emissions are calculated for conventional taxiing, single-engine taxiing (SET), and hybrid and electric operational towing. An assignment optimization model is used to assign vehicles in a vehicle fleet to flights; yielding the minimum fuel to cover a flight schedule with mixed taxiing operations. As the number of vehicles in the fleet increases, the saving potential for each additional vehicle is calculated, linking fuel and emission savings with vehicle costs. Two scenarios are compared; Scenario 1 with hybrid towing vehicles and Scenario 2 with electric towing vehicles. Applying this method to 30 case-study airports, a maximum jet fuel reduction of 66% for hybrid towing and 57% for electric towing is calculated; outperforming SET at 29 of the 30 airports. The average taxi time and aircraft compatibility are the driving factors that influence the maximum fuel savings potential. The total average taxi minutes of compatible flights is thus the best metric to predict an airport's potential, with a coefficient of determination equal to 0.96 for hybrid towing and 0.97 for electric towing. Because of the shorter refuelling downtime, hybrid vehicles can service more jobs per day than electric vehicles. This means a smaller hybrid fleet size can achieve the same CO_2 and jet fuel savings on a European level. As the fleet size increases, the marginal savings per hybrid vehicle decrease at a higher rate than electric vehicles. This means that the maximum emissions savings potential can be a misleading metric for comparing strategies. By using this approach to link vehicle fleet size and potential savings, a more extensive trade-off of emission mitigation strategies is possible, allowing stakeholders to find the best strategy to fit a budget or emission savings target.

Keywords: Mixed Taxiing Operations, Operational Towing, Single-engine Taxiing, Emissions Mitigation, Mixed-Integer Linear Programming, Assignment Model

1 Introduction

Over the past decades, the aviation industry has grown to become a crucial part of modern society by connecting businesses and people around the globe. In response, demand grew exponentially, but without a viable alternative, the industry has become the fastest-growing source of greenhouse gases in the transportation sector. Figures published by the [European Commission, 2021] show that in 2017, the direct emissions caused by aviation accounted for 13.9% of emissions from transport and 3.8% of total carbon dioxide (CO_2) emissions in Europe. This does not consider other harmful pollutants, such as nitrogen oxides (NO_x) and unburned hydrocarbons (UHCs). Although significant industry technological improvements have been made, because of the lengthy development and certification time, the traffic growth outpaces these improvements. With the European Commission's goal of CO_2 neutrality by 2050, short- and medium-term mitigation strategies as outlined in the Destination 2050 report by [van der Sman et al., 2020] must be implemented by 2035. Aircraft Taxiing Operations are highlighted in the report as an area for improvement. Alternative taxiing strategies suggested are single-engine taxiing, operational towing, and electric taxiing. With a timeline of fewer than 15 years; airlines, airports, and aircraft manufacturers have time pressure to choose and implement new ground operations procedures. For this reason, research into the cost trade-off of emissions savings is necessary to allow stakeholders to invest their time and resources in the most effective strategy. Although the feasibility and emissions at an airport level have been researched, there is a gap in research about the emissions-related return of investment on a European scale. To fill this gap, this research will focus on how the fuel and emissions savings potential of implementing operational towing at 30 European airports changes as the investment into towing vehicles increases. To research this, a model is developed that estimates the daily European fuel and emissions savings per unit of fixed cost by finding the maximum fuel and emissions savings potential of each additional towing vehicle implemented at 30 European airports.

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This research will allow for a better comparison of mitigation strategies from a stakeholder perspective by understanding how fuel and emissions savings evolve as vehicle investment increases. The main contributions are the following. Given a flight schedule and taxi time statistics, an estimate of the fuel burn and emissions savings of any towing fleet size is possible using the tool created. With accurate input data, stakeholders such as airlines, OEMs, or airports can estimate the potential savings at any global airport. The method also allows an association between fixed and emissions savings potential. Given an emissions savings target, a stakeholder could choose the cheapest mitigation strategy to reach their target. Alternatively, given a budget, stakeholders can choose the mitigation strategy with the most impact. The method provides additional insight for a better comparison of each alternative mitigation strategy from a stakeholder perspective.

This paper is structured in the following way. First, a literature review highlighting relevant research on operational towing is found in Section 2. Next, the research methodology is presented in Section 3. This provides information about fuel consumption and emissions calculations, modelling operations, and the assignment model. In Section 4, case-study airports, and vehicle scenarios are presented. This is followed by the results of the case-study, sensitivity analysis and validation in Section 5. Finally, the conclusions and suggestions for future research are presented in Section 7.

2 Literature Review

2.1 Conventional and Single-Engine Taxiing

Emissions and fuel consumption for conventional and single-engine taxiing (SET) are needed as a baseline for this research. Three industry-standard approaches by the [International Civil Aviation Organization, 2020] are recommended; simple, advanced and sophisticated. In literature, the ICAO advanced emissions model is used as it is the most accurate emissions calculation method that does not require proprietary data. In [Kumar et al., 2008] the advanced model is used to research the emissions savings of single-engine taxiing, this approach does not consider engine warm-up times or engine thrust settings. [Guo et al., 2014] also use the ICAO advanced emissions model to compare emerging ground propulsion systems. This research compares fuel burn, NO_x, HC, and CO of conventional taxiing, single-engine taxiing, operational towing, and electric taxiing emissions at 10 US airports, a similar scope size to this research. Using the more accurate emissions approach, [Stettler et al., 2018] model emissions at London Heathrow, comparing the fuel flow, NO_x, CO and HC emissions relative to conventional taxiing. This was the first literature which used flight data recorders for accurate taxi information. The more accurate model finds that using 7% thrust over-estimate the fuel savings by around 16%. This method however requires an in-depth analysis of taxi manoeuvres. For a more accurate result, [Yim et al., 2013] applies the same method as [Kumar et al., 2008], however using a thrust setting of 10%, yielding results closer to more advanced models.

2.2 Operational Towing

2.2.1 Cost and Feasibility

As towing technology is relatively new and has not been tested on a global scale, the relevant literature on the cost and feasibility is limited. [Lukic et al., 2018] published a review of all emerging electric taxiing technologies giving detailed comparisons of the technology including the cost, readiness level and compatibility. This was followed up by [Lukic et al., 2019] where the challenges and feasibility of the systems are explored. It is concluded that the implementation cost, fuel, and time savings are important factors in the trade-off for the feasibility and applicability of the technologies, however, the exact benefits of the technologies can only be known if the scenarios are tested on a large scale, such as the simulated cost trade-off which will be explored in this thesis. The most closely related literature to the scope of this research is published by the [Division of Transportation Energy Conservation, 1980]. This is an in-depth study of operational towing performed at 20 US airports, motivated by the increase in fuel prices after airline deregulation in 1978. The literature has two objectives; outlining the feasibility of towing and determining the best airports for testing it operationally. A cost analysis is performed and concluded that with a fuel price of $1.50 per gallon, all airports were estimated to see net savings. This study compares outdated technology and traffic situations making conclusions irrelevant to the current state of the industry. Finally, [Du et al., 2016] researches the cost of towing by building a model to determine the best time to buy and sell towing vehicles. The problem is decomposed into a master and sub-problem and solved using a column generation algorithm. The master problem in the paper determines the fleet size and mix of tow vehicles by selecting the schedules while minimizing cost. The sub-problem determines what period is the best time to make such a purchase. The first part uses vehicle assignment to optimize the vehicle schedule to minimize cost.

2.2.2 Emissions Modelling

Operational towing emissions modelling is a common topic presented in literature. [Guo et al., 2014] present the expected emissions of 4 scenarios; conventional taxiing, single-engine taxiing (SET), operational towing and electric taxiing and compared their expected results at 10 US airports for fuel burn, HC, NO_x and CO. Authors [Dellaert and Hulskotte, 2017] present emissions models for the landing take-off cycle (LTO), auxiliary power units (APU), ground service equipment (GSE), fuelling and handling, tyre wear, and brake wear to estimate emissions at 18 Dutch airports. This is the first to publish emissions modelling techniques for all ground equipment. These modelling approaches will be used for modelling vehicle fuel burn and emissions. In literature by [Deonandan and Balakrishnan, 2010], the emissions performance of diesel, gasoline and compressed natural gas (CNG) towing vehicles are compared with conventional and SET at 20 US airports. Diesel tugs saw an increase in NO_x emissions, and a decrease in fuel burn, CO_2, HC and CO. This aligns with previous emissions measurements at Zurich airport presented in the work of [Schürmann et al., 2007]. Gasoline tugs saw an increase in CO and HC emissions while having a decrease in all other emissions and CNG saw an increase in all emissions. This is interesting as it was the first paper to compare the emissions of different tow vehicle types for implementing operational towing. In all literature, the focus is on the comparison of fuel burn, CO_2, CO, HC and NO_x emissions. There is a gap in research about the emissions of a mixed-operations approach and emissions when vehicle compatibility is taken into consideration.

2.2.3 Optimization Models

Of the literature on optimizing operational towing, objectives are categorized into literature that solves routing problems and literature that solves capacity problems. For example, in the work from [Soltani et al., 2020], mixed-integer linear programming is used to route tow-trucks to aircraft, including a pick-up time, drop-off time and the set of taxiways to complete the taxing operations. One of the main contributions to literature is the collision avoidance by using routing constraints. This is the first paper to explore a mixed fleet of towing and conventional taxiing. Information used in the model is highly airport specific, and in much more detail than should be used in this thesis. Literature with a broader view is seen in the work of [Du et al., 2014]. The authors also use mixed-integer programming this time with a column generation heuristic solution procedure to solve a vehicle routing problem while minimizing travel time and operational cost. The algorithm is applied to major European airports. This literature solves a different objective but is an example of the level of detail per airport that is realistic for the scope of the thesis. Authors [Morris et al., 2016] build a model for minimizing travel time minimizing delays and maximizing throughput. This work is mainly focused on capacity issues at airports. Similarly, authors [Zaninotto et al., 2019] focus on capacity-related issues by building a model which minimizes the number of conflicts. Their approach uses agent-based modelling and is thus not an optimization problem. In the published literature, there is no research into the optimized assignment of vehicles for minimizing the amount of fuel used where vehicle compatibility is taken into account. Additionally, the literature focuses on airport-specific operations by mapping detailed towing routes to optimize distance-based problems. Models are not built to be easily adapted for a large scale.

3 Methodology

The goal of this research is to build a tool that can relate the discrete steps in fixed costs of operational towing to fuel and emissions savings at European airports. The methodology is split into two sections; calculation of fuel consumption and emissions, and modelling the optimization problem to relate cost to fuel and emissions savings.

3.1 Calculating Fuel Consumption and Emissions

3.1.1 Calculating Aircraft Fuel Consumption and Emissions

To calculate the aircraft fuel consumption and emissions, the advanced emissions model formulation from the [International Civil Aviation Organization, 2020] Airport Air Quality Manual is used. The fuel consumption expressed in [kg/min] when an aircraft is taxiing conventionally, $FF_{AC_{conv}}$, is calculated using Equation 1. This equation uses the idle engine fuel flow, $FF_{ENG_{idle}}$, corresponding to a 7% thrust setting. A factor of 60 is used to convert the engine fuel flow from seconds to minutes.

$$FF_{AC_{conv}} = FF_{ENG_{idle}} \cdot 60 \cdot N_{ENG_{AC}} \tag{1}$$

To calculate fuel consumption while modelling single-engine taxiing (SET), an increased engine fuel flow value, $FF_{ENG_{SET}}$, is used. This is calculated using Equation 2, and corresponds to an engine thrust setting of about 10%. Unlike the name suggests, the number of engines used during SET is not always equal to one. As shown in Equation 3, the number of engines used in the calculation depends on the total number of engines on the aircraft, and if the number of engines is an even or odd number. Using the formulation in Equation 3, aircraft with two or three engines are assumed to taxi with one engine during SET. Larger aircraft with four engines such as the A340, A380 or B747 are assumed to taxi with two. A factor of 60 is used to convert the fuel flow from seconds to minutes.

$$FF_{ENG_{SET}} = FF_{ENG_{idle}} \cdot 1.5 \tag{2}$$

$$FF_{AC_{SET}} = \begin{cases} FF_{\mathrm{ENG}_{SET}} \cdot 60 \cdot \frac{N_{ENG_{AC}}}{2} & \text{, if } N_{ENG_{AC}} \text{ is even} \\ FF_{\mathrm{ENG}_{SET}} \cdot 60 \cdot \frac{(N_{ENG_{AC}}-1)}{2} & \text{, if } N_{ENG_{AC}} \text{ is odd} \end{cases} \tag{3}$$

The emissions of pollutant p from the aircraft, $E_{p_{AC}}$, are calculated in [g] using Equation 4. In this equation $EI_{p_{AC}}$ is the idle emissions index of each pollutant in [g/kg]. Depending on if an aircraft is taxiing conventionally or with reduced engines, the respective FF_{AC} is used. An overview of all variables used in the calculations are shown in Table 1.

$$E_{p_{AC}} = FF_{AC} \cdot T_{active} \cdot EI_{p_{AC}} \tag{4}$$

Table 1: Overview of variables used for aircraft fuel consumption and emissions calculations.

Parameter	**Description**	**Unit**	**Source**
$N_{ENG_{AC}}$	Number of engines on the aircraft	[-]	[International Civil Aviation Organization, 2021]
$FF_{\mathrm{ENG}_{idle}}$	Idle engine fuel flow	[kg/sec]	[International Civil Aviation Organization, 2021]
$FF_{\mathrm{ENG}_{SET}}$	SET engine fuel flow	[kg/sec]	[International Civil Aviation Organization, 2021]
$EI_{CO_{AC}}$	Emissions index of CO for the aircraft	[g/kg]	[International Civil Aviation Organization, 2021]
$EI_{NOx_{AC}}$	Emissions index of NO_x for the aircraft	[g/kg]	[International Civil Aviation Organization, 2021]
$EI_{HC_{AC}}$	Emissions index of HC for the aircraft	[g/kg]	[International Civil Aviation Organization, 2021]
$T_{active_{AC}}$	Time aircraft engine(s) are active	[min]	Estimated using methodology in Section 3.2.6 and 3.2.7

3.1.2 Calculating Hybrid Tow Vehicle Fuel Consumption and Emissions

Tow vehicle fuel consumption and emissions are calculated using an equivalent equation to the ICAO advanced approach shown in Equation 5, and Equation 6. In these equations, FF_V is the fuel burned in [kg/min], and E_{pV} is the emissions of pollutant p in [g]. Because SFC_{ENG_V} is given in [g/kWh], a factor of $\frac{1}{60}$ is used to convert from hours to minutes and $\frac{1}{1000}$ is used to convert from grams to kilograms. An overview of the variables used in the calculations are presented in Table 2.

$$FF_V = \mathrm{P}_{ENG_V} \cdot \mathrm{N}_{ENG_V} \cdot \mathrm{SFC}_{ENG_V} \cdot \frac{1}{60} \cdot \frac{1}{1000} \tag{5}$$

$$E_{pV} = FF_V \cdot T_{active_V} \cdot EI_{pV} \tag{6}$$

Table 2: Overview of variables used for aircraft fuel burn and emissions calculations.

Parameter	**Description**	**Unit**	**Source**
P_{ENG_v}	Power of vehicle engine	[kW]	Vehicle engine manufacturer
N_{ENG_V}	Number of engines on vehicle	[-]	Vehicle manufacturer
SFC_{ENG_V}	Vehicle engine specific fuel consumption	[g/kWh]	Vehicle engine manufacturer
T_{active_V}	Time vehicle is active	[min]	Methodology in Section 3.2.6 and 3.2.7

3.1.3 Calculating Electric Vehicle Energy Consumption and Emissions

To model electric tow vehicle emissions, the required energy for each towing job is calculated in [kWh/min] based on the towing vehicle specifications. The emissions for each job are calculated in [g/kWh] based on the emissions figures of energy sources in the Netherlands published by [Otten and Afman, 2015]. All values used in the model are presented in Table 5 in Section 4.

3.1.4 Calculating APU Fuel Consumption and Emissions

To model the auxillary power unit (APU) fuel consumption, standard values for fuel flow published by [International Civil Aviation Organization, 2020] for narrow and wide-body aircraft are assumed. All values used in the model are presented in Table 5 in Section 4.

3.2 Modelling Taxi Times and Operations

To relate cost to emissions savings, an optimization model is used which relates the vehicle fleet size to a maximum potential fuel savings. The model calculates the minimum fuel used to cover a flight schedule by assigning tow vehicles to feasible flights with the highest fuel savings. By incrementally increasing the towing fleet size, the change in fuel savings can be tracked, linking the emissions and fuel savings to a fixed vehicle fleet cost.

3.2.1 Limitations of Model Input Data

The optimization model uses flight data from the OAG 2018 database [OAG Aviation Worldwide LLC, 2018]. This database provides the scheduled time of arrival and departure of aircraft rounded to the nearest 5 minutes, limiting the time-window accuracy of the model to 5 minutes. The database also includes the scheduled aircraft type, however does not include the engine type of the aircraft. Engine types for all aircraft are therefore assumed. The database also has no taxi time data for the scheduled flights. Representative taxi times for the case-study flight schedules must therefore be generated.

3.2.2 Modelling Aircraft Taxi Times

To assign taxi times to each flight, the Eurocontrol taxi time statistics are used [Eurocontrol, 2019b, Eurocontrol, 2019c]. The mean, standard deviation and median taxi-time for inbound flights are given for all airports and seasons. For outbound traffic, the distributions are also sorted into wake category type. The skewness of the dataset is calculated using Equation 7. A random Pearson distribution with the length of the number of flights is created. Each flight is assigned one element of the random Pearson distribution to represent its taxi time. This process is iterated 100 times, and the average of the iterations for each flight is assigned as the taxi time, T_{taxi_f}. For inbound traffic, $T_{taxi_f}^{IN}$ represents the time it takes between leaving the runway, and arriving at the parking position. For outbound traffic, the taxi time represents the time between leaving the parking position, and entering the runway. $T_{taxi_f}^{OUT}$ is used for calculating C_{tow} and C_{taxi} in Section 3.2.6 and 3.2.7.

$$\text{skew} = 3\left(\frac{mean - median}{STD}\right) \tag{7}$$

3.2.3 Linking Engine Data with Aircraft type

As the engine types for the aircraft are not available, an engine type for each unique aircraft type is assumed based on commonly used engines. Using the Engine Emissions Databank from [International Civil Aviation Organization, 2021], the fuel and emissions parameters shown in Table 2 in Section 3.1.1 are collected and used for calculating the fuel burn and emissions associated with each aircraft type.

3.2.4 Modelling Seasonality

As airport operations are susceptible to changes in demand based on seasonality, two flight schedules are used to model changes in seasonality. To find dates that represent the average daily traffic situation of each airport, a filtering tool is created to find dates that reflect an average day of operation. This tool filters data from the OAG 2018 database for each case-study airport to find a date of operation in the IATA Summer and Winter schedule matching the average daily movements for 2018 published by [Eurocontrol, 2019a]. The date with the closest number of movements to the actual average daily number of commercial movements is chosen. Using this method allows scaling up the results to reflect yearly fuel and emissions savings with as little bias as possible caused by demand changes.

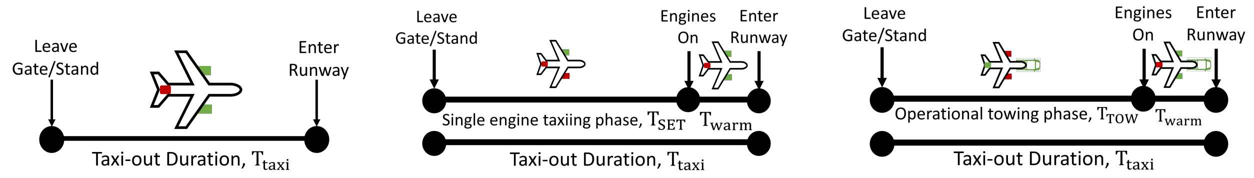
3.2.5 Modelling Time using Discrete Time Intervals

To model operational towing, discrete time intervals of 5 minutes, t, are used. This interval size is chosen to match the accuracy of the scheduled departure times (STD) and scheduled arrival times (STA) which have an accuracy of 5 minutes. By matching the interval of the input data, it is possible to reduce computing time by reducing the number of decision variables in the optimization program. An additional variable is introduced to represent taxi time rounded up to the nearest 5 minutes, $T_{Rounded}$. The cost of each job pairing is calculated using T_{taxi}, thus the introduction of $T_{Rounded}$ has no impact on the fuel burn calculations.

3.2.6 Modelling Outbound Traffic Operations

To model the fuel burn during outbound traffic operations, three assumptions are made. First, it is assumed that the taxi time, T_{taxi}^{OUT}, is the time between the aircraft leaving its gate or stand, and entering the runway.

Second, it is assumed that when aircraft engines are powered off, the use of an Auxillary Power Unit (APU) is necessary to provide power to the onboard electrical systems. Finally, it is assumed that every aircraft must have their engines powered on for a minimum time, T_{warm}, to allow their engines to warm up before take-off. As T_{warm} is an assumed value, the affect of this variable is investigated in the sensitivity analysis in Section 5.5. These assumptions are taken into account when modelling conventional taxiing, single-engine taxiing (SET) and operational towing operations.



(a) Outbound Conventional Taxiing

(b) Outbound SET

(c) Outbound Operational Towing

Figure 1: Visual of outbound operations for conventional taxiing

During conventional taxiing, fuel is only burned by the aircraft engines. This is illustrated in Figure 1(a). The fuel burn, $C^{OUT}_{taxi_f}$, is calculated using Equation 8. For SET operations, the engine warm-up time must be taken into account for the fuel burn calculation. This is illustrated in Figure 1(b). To model the fuel burn for a SET operation, $C^{OUT}_{SET_f}$, Equation 9 is used. In this equation the first term represents the portion of the operation where the aircraft taxis with a reduced number of engines. The second term represents time where all engines are turned on during T_{warm}. Finally, in outbound towing operations, fuel is burned by the towing vehicle, the APU, and the aircraft engines. For towing operations it is assumed that the vehicle engine is powered on for the entire taxi time. The aircraft APU is powered for the time between the aircraft leaving the gate or stand, and the engines being turned on. The aircraft engines are powered on at the end of a towing job during T_{warm}. This is illustrated in Figure 1(c). To calculate the fuel burn of towing operations, $C^{OUT}_{tow_{vf}}$, Equation 10 is used. The first term in the equation represents the fuel used by the towing vehicle, the second term represents the APU fuel burn, and the third term represents the aircraft engine fuel burn.

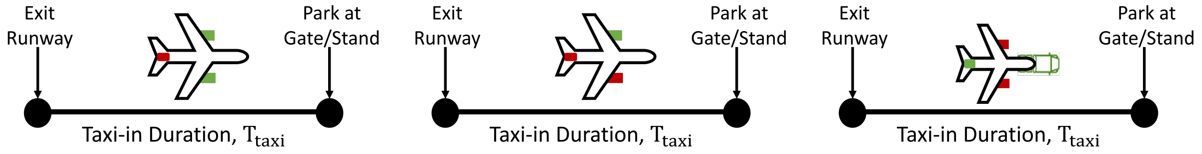
$$C^{OUT}_{taxi_f} = FF_{AC_{conv_f}} \cdot T^{OUT}_{taxi_f} \tag{8}$$

$$C^{OUT}_{SET_f} = FF_{AC_{SET_f}} \cdot \left(T^{OUT}_{taxi_f} - T_{warm}\right) + FF_{AC_{conv_f}} \cdot T_{warm} \tag{9}$$

$$C^{OUT}_{tow_{vf}} = FF_v \cdot T^{OUT}_{taxi_f} + FF_{APU} \cdot (T^{OUT}_{taxi_f} - T_{warm}) + FF_{AC_{conv_f}} \cdot T_{warm} \tag{10}$$

3.2.7 Modelling Inbound Traffic Operations

To model the fuel burn of inbound operations, the taxi time, T^{IN}_{taxi}, represents the time between the aircraft leaving the runway, and parking at the gate or stand. For inbound operation it is assumed that aircraft engines can immediately be powered down once an aircraft leaves the runway.



(a) Inbound Conventional Taxiing

(b) Inbound SET

(c) Inbound Operational Towing

Figure 2: Visual of inbound operations for conventional taxiing

For conventional taxiing the inbound fuel burn, $C^{IN}_{taxi_f}$, is calculated using Equation 11 as illustrated in Figure 2(a). For SET operations the fuel burn, $C^{IN}_{SET_f}$, is calculated using Equation 12 as illustrated in Figure 2(b). For inbound towing operations the fuel burn consists of the vehicle fuel burn and APU fuel burn as illustrated in Figure 2(b). This is calculated using Equation 13, where the first term represents the vehicle fuel burn and the second term represents the APU fuel burn.

$$C^{IN}_{taxi_f} = FF_{AC_{conv_f}} \cdot T^{IN}_{taxi_f} \tag{11}$$

$$C^{IN}_{SET_f} = FF_{AC_{SET_f}} \cdot T^{IN}_{taxi_f} \tag{12}$$

$$C^{IN}_{tow_{vf}} = FF_V \cdot T^{IN}_{taxi_f} + FF_{APU} \cdot T^{IN}_{taxi_f} \tag{13}$$

3.2.8 Modelling Vehicle Turn-around Time

To realistically model tow truck availability, a vehicle parameter representing the turn around time, TAT, is introduced. This parameter is used to block the time-steps after a towing job to give the tow vehicle time to travel between jobs. This blocked time only affects the availability of the tow truck, and is not included in the cost calculations. When a vehicle takes on a tow job, it is blocked from the STD or STA of the flight until the T_{END}, which is calculated using Equation 14. A visualization of this modelling is shown in Figure 3. A turn-around time of 10 minutes between the end of a job and starting the next job has been chosen for the base model. This reflects the worst case scenario that the tow vehicle services back-to-back flights and would need to reposition the maximum possible distance. 10 minutes has been used as this reflects the average unimpeded taxi-time of the airports. This modelling approach assumes that tow trucks would not be affected by push-back delays when repositioning between jobs.

$$T_{END} = \begin{cases} \text{STD}_f + T_{Rounded_f} + \text{TAT} & \text{if } f \text{ is an outbound flight} \\ \text{STA}_f + T_{Rounded_f} + \text{TAT} & \text{if } f \text{ is an inbound flight} \end{cases} \tag{14}$$

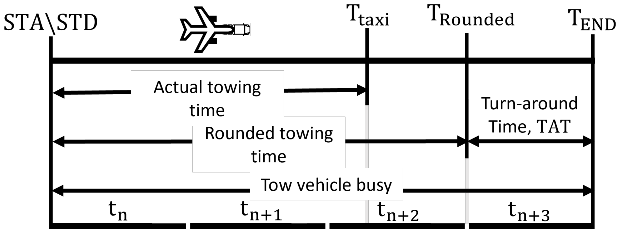


Figure 3: Rounded vehicle availability blocks

3.2.9 Modelling Tow Vehicle Refuelling and Recharging

To allow the model to be flexible for both electric and diesel powered towing vehicle, a parameter Q_v representing the maximum refuelling flow is introduced. For diesel vehicles this is expressed in [kg/min] and for electric vehicles this is expressed in [kW/min]. Refuelling and recharging is modelled in this way so vehicles can partially refuel or recharge during a time-step. For modelling refuelling in the optimization model, two additional variables and one additional parameter are used; p_{vt}, r_{vt} and P_{max}. Variable p_{vt} is the amount of fuel or kilometres left in the vehicle at time-step t. The variable, r_{vt}, is the maximum fuel that can be refilled in a time-step constrained either by the capacity of the fuel tank or refill fuel flow. Parameter P_{max} is the capacity of a vehicle; for fuel powered vehicles this is expressed in [kg] and for electric vehicles in [kWh].

3.3 Optimization Model

3.3.1 Overview of Modelling Assumptions and Simplifications

To optimize the fuel used of each fleet size, an assignment mixed-integer linear programming model is used. The following assumptions are made, based on the reasoning presented in the methodologies section.

- The assumed time to tow an aircraft is equal to the assigned taxi time.
- Each input flight schedule is discretized into time-steps of 5 minutes.
- The engine type of each aircraft is assumed based on commonly used engines for each aircraft type.
- Propeller aircraft are omitted.
- Each outbound aircraft has a fixed engine warm-up time for outbound SET and operational towing operations.
- The time between jobs for attachment and detachment of a towing vehicle, and relocating vehicles is neglected in fuel and emissions calculations.

To model a mixed-operations scenario of operational towing and conventional taxiing, a novel assignment model formulation described by Equations 15a to 15j is proposed using the sets, subsets, variables and parameters found in Table 3.

Table 3: Sets, variables and parameters used in optimization model formulation

Sets			***Sub-sets***	
V	Set of towing vehicles, v		V_f	Subset of vehicles in V, compatible with flight f
F	Set of flights, f		F_{vt}	Subset of flights in F compatible with vehicle v, active in time-step t
T	Set of finite time-steps, t			
Decision Variables			***Cost Parameter***	
x_{vf}	Binary	1 if vehicle v tows flight f; 0 otherwise	$C_{tow_{vf}}$	Cost in kg of fuel for vehicle v to tow flight f
y_f	Binary	1 if flight f taxis itself; 0 otherwise	C_{taxi_f}	Cost in kg of fuel for flight f to taxi itself
z_{vt}	Binary	1 if vehicle v is refuelling or recharging at time-step t; 0 otherwise	***Vehicle Parameter***	
p_{vt}	Continuous	Fuel [kg] vehicle v has available at the beginning of time-step t	P_{max_v}	Maximum fuel capacity [kg] of vehicle v
r_{vt}	Continuous	Fuel [kg] vehicle v refuels time-step t	Q_v	Maximum fuel [kg] that can be dispensed by fuel pump per time-step

$$\textbf{minimize} \quad \sum_{f\in F}\sum_{v\in V} C_{\text{tow}_{vf}} \cdot x_{vf} + \sum_{f\in F} C_{\text{taxi}_f} \cdot y_f \tag{15a}$$

$$\text{subject to :} \quad y_f + \sum_{v\in V_f} x_{vf} = 1 \qquad \forall\ f \in F \tag{15b}$$

$$z_{vt} + \sum_{f\in F_{v_t}} x_{vf} \leq 1 \qquad \forall\ t \in T, v \in V \tag{15c}$$

$$p_{vt} = p_{v(t-1)} + r_{vt} - \sum_{f\in F_{v_t}} C_{tow_{vf}} \cdot x_{vf} \qquad \forall\ t \in T, v \in V \tag{15d}$$

$$r_{vt} \leq Q_v \cdot z_{vt} \qquad \forall\ v \in V, t \in T \tag{15e}$$

$$x_{vf} \in \{1,0\} \qquad \forall\ v \in V, f \in F \tag{15f}$$

$$y_f \in \{1,0\} \qquad \forall\ f \in F \tag{15g}$$

$$z_{vt} \in \{1,0\} \qquad \forall\ v \in V, t \in T \tag{15h}$$

$$p_{vt_0} = P_{max_v} \qquad \forall\ v \in V \tag{15i}$$

$$0 \leq p_{vt} \leq P_{max_v} \qquad \forall\ v \in V, t \in T \tag{15j}$$

3.3.2 Objective Function

The objective function of the mixed-integer linear programming model is described in Equation 15a. This equation minimizes the total fuel used by aircraft and towing vehicles to service every flight in a given flight schedule. The first term in the objective function represents fuel used for all flights that are towed using cost matrix C_{tow}. The decision variable x_{vf} is a binary variable equal to 1 if vehicle v tows flight f and 0 otherwise. The second term of the objective function represents the fuel used for flights that taxi using cost matrix C_{taxi}. Decision variable y_f is a binary variable equal to 1 if a flight taxis itself and 0 otherwise.

3.3.3 Assignment Constraints

The assignment constraints are described by Equations 15b and 15c, and are an adaptation of the general assignment problem formulation. Equation 15b ensures all flights are serviced exactly once using either a compatible tow vehicle or by taxiing itself. Equation 15c ensures all vehicles complete no more than 1 task per time-step. A new binary decision variable z_{vt} is introduced which is equal to 1 if a vehicle is refuelling during time-step t, and 0 otherwise. By allowing the sum of this equation to equal less than 1, a tow truck may either tow a compatible flight, refuel or remain idle in a time-step.

3.3.4 Fuel Constraints

The fuel constraints are described by Equations 15d and 15e. The fuel at the end of each time-step, p_{vt}, is calculated using Equation 15d. The first term represents the available fuel or energy at the end of the previous time-step, $p_{v(t-1)}$. The second term represents the fuel that can be refilled at the time-step, r_{vt}. The third term represents the fuel used during any jobs that begin in time-step t. By formulating the equation in this way, the fuel or energy needed to cover an entire job is subtracted at the beginning the job. A vehicle can therefore only start a job if it has enough fuel to service the entire job. As explained in Section 3.2.9, r_{vt} can either be constrained by a vehicle fuel tank size, P_{max_v}, or by the maximum refuelling flow per time-step, Q_v. Due to Equation 15d, by constraining p_{vt} in Equation 15j, r_{vt} is also constrained by the fuel tank size. Finally, Equation 15e ensures that r_{vt} becomes 0 when an aircraft is not refuelling, and that it can never refuel or recharge more than the maximum fuel flow per time-step, Q_v.

3.4 Evaluating Model Results

3.4.1 Evaluation on an Airport Level

On an airport level, the focus is finding the driving characteristics that make an airport a better or worse candidate for operational towing. For each vehicle fleet size, the following parameters are collected; jet fuel used , diesel or energy used, number of flights towed, and the emissions of CO_2, CO, HC and NO_x. As the fleet size is iterated, the marginal savings of each parameter are calculated until they converge at a maximum value. The potential of each airport is evaluated for fuel and emissions savings and ranked. The correlation between characteristics including taxi time, number of flights, and traffic type and maximum fuel savings is compared. The marginal savings at each airport for all fleet sizes are used for the Europe-wide analysis.

3.4.2 Evaluation on a European-Wide Level

To evaluate the performance of operational towing on a European level, the marginal savings from all vehicles are sorted such that vehicles at airports with the highest savings are added first. Once the vehicles are sorted, the respective jet fuel used, diesel or energy used, number of flights towed, and the emissions of CO_2, CO, HC and NO_x are calculated. The results are plotted to understand how the operational towing strategies perform on a Europe-wide scale for fuel and emissions savings. This analysis assumes a scenario where there is cooperation from all European airports, and each additional vehicle in the European fleet can be assigned to any of the 30 airports.

3.4.3 Evaluating Cost of Fuel and Emissions

For the cost analysis, industry prices for 2018 taken from the EU energy price dashboard [European Commission, 2019]. For the analysis, it is assumed that the cost of all transport fuels are equal, thus the cost of diesel is the same as jet fuel. In the dashboard, prices are quoted with a maximum, average and minimum cost. The analysis is done with all three values in Table 4 for fuel and energy to understand how the prices effect the cost trade-off.

Table 4: 2018 industry fuel prices

EU Industry Price	Low	Average	High
Electricity [€/kWh]	0.06	0.11	0.18
Petroleum Products [€/L]	0.82	0.95	1.14

3.4.4 Modelling Fixed Costs

For the analysis of the hybrid and electric vehicles, several assumptions must be made about the fixed costs of the vehicles and infrastructure. In [Lukic et al., 2019], taxibot vehicles are quoted to cost between $1-3M USD. It is assumed that the fixed vehicle cost for both hybrid and electric towing vehicles are both equal at €2M. For a simplification in the model, airport infrastructure costs for additional roadways and uncoupling areas to handle the additional vehicle traffic are not taken into account in the analysis. It is assumed that the costs for both vehicle types would be in the same range as similar infrastructure would be necessary for both vehicles.

3.5 Validation

3.5.1 Fuel Burn and Emissions

To validate that the assumed parameters in the model output results representing a realistic scenario, the fuel savings potential for SET, hybrid and electric operational towing are compared with data presented in literature. As the literature published on operational towing does not take vehicle compatibility into account, the maximum fuel and emissions savings at each airport, assuming all aircraft can be towed, are compared with previously published figures. Literature using a method assuming a 7% thrust setting predict savings of of 20 to 45% using SET [Kumar et al., 2008, Deonandan and Balakrishnan, 2010]. Figures reported using more accurate modelling suggest that the 7% thrust model over-estimates fuel savings by about 16% [Ravizza et al., 2013]. Thus, the SET fuel saving should be within a range of 4-30%. In literature, when ignoring the compatibility of aircraft, using hybrid towing vehicles is estimated to reduce 25% to 85% of taxi emissions [Deonandan and Balakrishnan, 2010, Ithnan et al., 2015]. Using the modelling approach and ignoring vehicle compatibility, the average total CO_2 savings for narrow and wide body vehicles should be within this range. For electric towing vehicles, CO_2 savings are expected to be as high as 85% [van der Sman et al., 2020].

3.5.2 Estimated Taxi Times

Two days of flight schedules with actual taxi times from Milan Malpensa are used to validate that results using the generated taxi times represent a realistic scenario. The optimization model is run to cover the same flight schedule using the actual and generated taxi times for the hybrid and electric scenarios. A comparison of the generated and actual taxi times distributions is made, and the method is deemed valid if the disparity between results remains within a 5% range.

4 Description of Case-Studies

To simulate European daily traffic, the top 30 European airports based on 2018 daily aircraft movements are used as case-study airports. Actual flight data from one day of operation in the 2018 IATA Summer and Winter season are taken as input for the model. A list of all case-study airports and dates of operation can be found in Table 18 found in Appendix B. For all case-study airports, two scenarios of operational towing are taken into account simulating hybrid towing vehicles and electric towing vehicles. The parameters used in the model are shown in Table 5.

Table 5: Parameter values used in the optimization model.

Model Parameter	Description	Value	Model Parameter	Description	Value
T_{warm}	Aircraft engine warm-up time	3 [min]	$EI_{CO2_{AC}}$	Aircraft emissions index of CO_2	3160 [g/kg]
TAT	Vehicle turn around time	10 [min]	$EI_{CO2_{Ve}}$	Electric vehicle emissions index of CO_2	355 [g/kWh]
$EI_{CO2_{Vh}}$	Hybrid vehicle emissions index of CO_2	3116 [g/kg]	$EI_{NOx_{Ve}}$	Electric vehicle emissions index of NO_x	0.49 [g/kWh]
$EI_{NOx_{Vh}}$	Hybrid vehicle emissions index of NO_x	32.8 [g/kg]	$FF_{APU_{NB}}$	Narrowbody APU Fuel Consumption	1.77 [kg/min]
$EI_{HC_{Vh}}$	Hybrid vehicle emissions index of HC	3.4 [g/kg]	$FF_{APU_{WB}}$	Widebody APU Fuel Consumption	4 [kg/min]
$EI_{CO_{Vh}}$	Hybrid vehicle emissions index of CO	10.7 [g/kg]			

4.1 Scenario 1: Hybrid Towing

In Scenario 1, hybrid towing is simulated based on the data available for the Taxibot Narrowbody (NB) and Taxibot Widebody (WB) towing vehicles [Smart Airport Systems, 2020a, Smart Airport Systems, 2020b]. In the optimization program, narrowbody and widebody traffic are iterated separately as they have independent aircraft compatibility. To analyze the overall effectiveness of hybrid towing together, the vehicles are sorted in terms of their marginal savings to choose the most effective vehicle fleet mix. The corresponding vehicle data used in the simulations for both scenarios is found in Table 6, published by the vehicle and engine manufacturers [Scania CV, 2016a, Scania CV, 2016b].

Table 6: Model parameters for hybrid towing vehicles.

Vehicle	Compatible Aircraft	Engine Type	Number Engines	Specific Fuel Consumption [g/kWh]	Power [kW]
NB	A318-A321 B737-B757	Scania DC09	2	205	257
WB	A330-A380 B767-B747	Scania DC16	2	217	517

4.2 Scenario 2: Electric Towing

The second scenario simulates operational towing with the use of an electric towing vehicle based on all available data published on the Phoenix E tow vehicle by [Goldhofer, 2022]. Of this data, the compatible aircraft types, battery capacity and maximum charging speed are available. The specific energy consumption of the vehicle during towing is not publicly available, thus is assumed in the model. Using a maximum of 20 daily towing jobs at Frankfurt International Airport as published by [Lufthansa Group, 2022], an average value of 9.6 [kWh/km] is calculated, resulting in 4 [kWh/min] of towing at Phoenix E's top speed of 25 [km/h].

Table 7: Model Parameters for electric towing vehicles

Vehicle	Compatible Aircraft	Engine Type	Capacity [kWh]	Assumed Recharge Speed [kW/min]	Assumed Consumption [kWh/min]
Phoenix E	E170-195 CS100/CS300 B737- B787 A318-A350 DC-10/MD-11	AST-2E	165	2.5	4

5 Results

The results section has been split into four categories; airport savings, the effects of airport characteristics, European-wide savings, and the taxi time validation. Results comparing the fuel savings of each scenario take only the jet fuel savings into account. The emissions savings results include the emissions outputted from the aircraft, APU and towing vehicles.

5.1 Airport Results

5.1.1 Airport Jet Fuel Savings

Using the average daily jet fuel used for conventional taxiing as a baseline, the maximum average daily jet fuel saved with single-engine taxiing (SET), hybrid and electric operational towing are compared. This is presented in Figure 4. The results show that the majority of European-wide jet fuel savings can be achieved at the 10 European airports with the highest number of daily flight movements. With the exception of London Stansted Airport (STN), both the hybrid and electric case-study scenarios achieve higher jet fuel savings than SET at all airports.

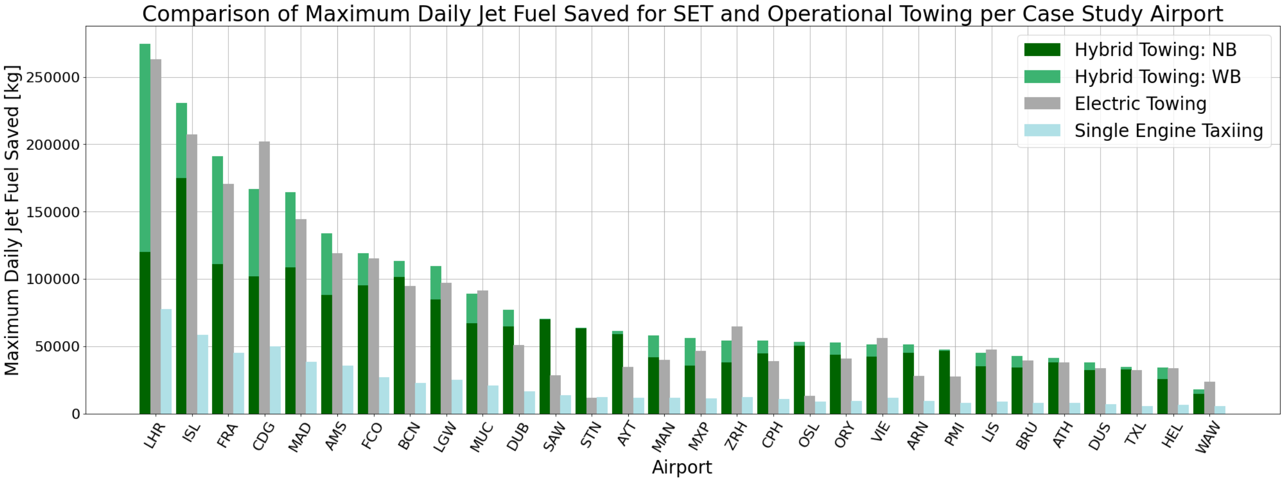


Figure 4: Jet Fuel Savings Comparison between SET, Hybrid Towing and Electric Towing at the 30 Case-Study Airports

5.1.2 Airport CO_2 Savings

The maximum daily CO_2 savings for each airport are shown in Figure 5. The calculated CO_2 emissions for both hybrid and electric towing take into account the emissions contributions from the aircraft engines, APU and towing vehicles. With the exception of London Stansted Airport (STN), both the hybrid and electric case-study scenarios achieve higher CO_2 savings than SET at all airports. Of the 30 case-study airports, the maximum daily CO_2 savings potential is higher for electric towing than hybrid towing at 20 airports. Of these 20 airports, the top 10 airports with the highest number of daily movements are included.

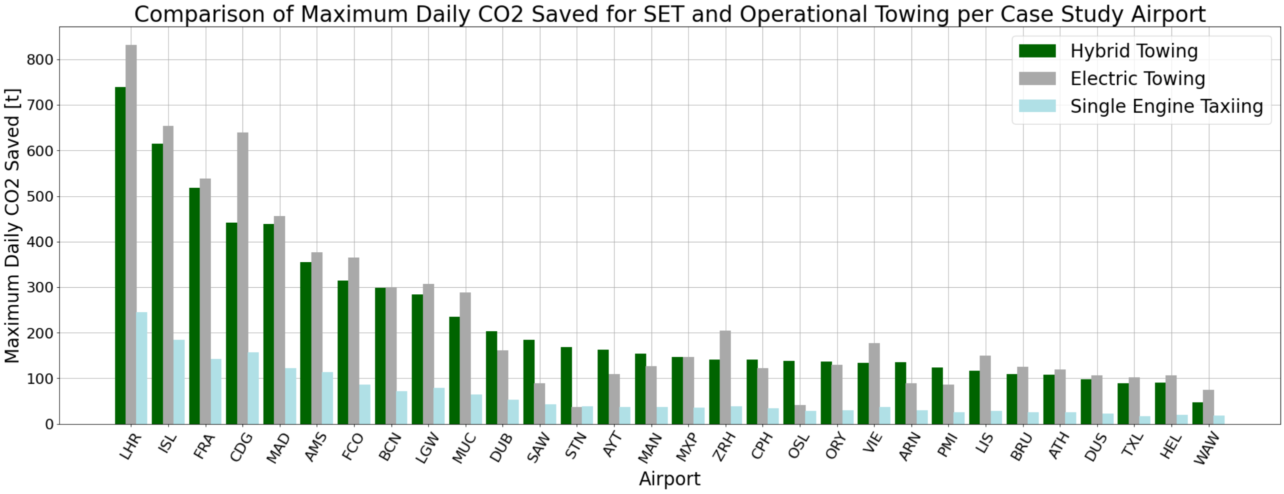


Figure 5: CO_2 Savings Comparison between SET, Hybrid Towing and Electric Towing at the 30 Case-Study Airports

5.1.3 Airport NO_x Savings

Figure 6 presents the NO_x emissions for the 30 case-study airports using hybrid towing, electric towing and single-engine taxiing. The values take into account the NO_x emissions contributions from the aircraft engines, APU and towing vehicles. At 29 of the 30 airports, the maximum potential NO_x savings are highest using electric towing. Due to the high NO_x emissions of diesel combustion at high pressures and temperatures, hybrid towing emits more NO_x at 29 of the 30 case-study airports than conventional taxiing. The savings potential for SET and electric towing are higher than hybrid towing for all 30 case-study airports.

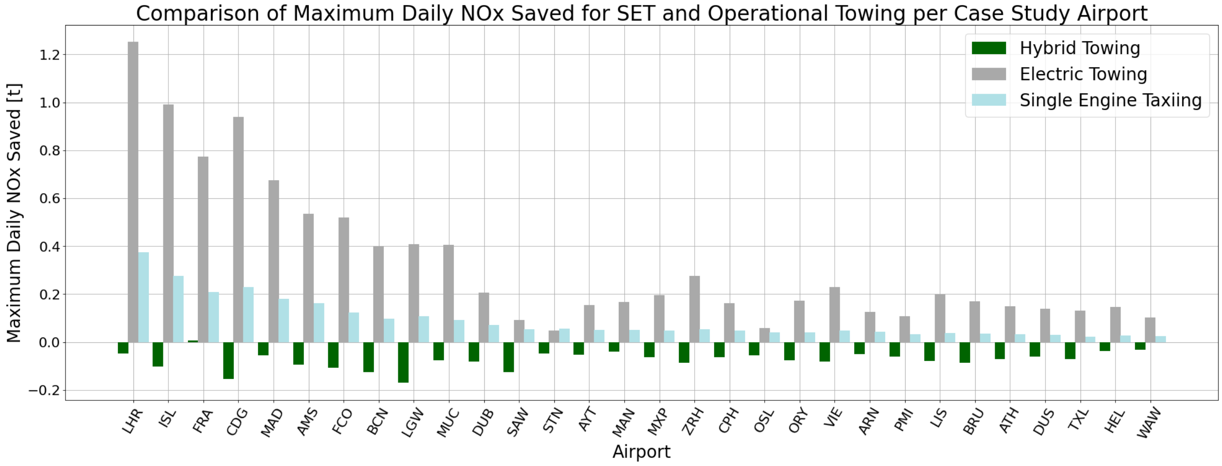


Figure 6: NO$_x$ Savings Comparison between SET, Hybrid Towing and Electric Towing at the 30 Case-Study Airports

5.2 Effect of Airport Characteristics

5.2.1 Single-Engine Taxiing

Taking conventional taxiing as a baseline, the percentage of fuel saved at the 30 case-study airports using SET ranges from 10.7% at TXL to 17.7% at LHR. This is within the reasonable range set in Section 3.5.1. As shown in Table 8, airports with the highest total taxi minutes tend to have the highest maximum fuel savings using SET. The total taxi minutes metric is defined as the product of the average taxi time of the airport and the total flights at an airport. The coefficient of determination is equal to 0.98.

Table 8: Coefficients of determination for the maximum jet fuel saved using SET

Airport Characteristic	**Coefficient of Determination ($\mathbf{R^2}$)**
Average Taxi Time	0.73
Total Flights	0.78
Total Taxi Minutes	**0.98**

5.2.2 Scenario 1: Hybrid Towing

Taking conventional taxiing as a baseline, the percentage of fuel saved at the 30 case-study airports using hybrid operational towing ranges from 41% at WAW to 78% at STN. The airport with the highest maximum daily jet fuel savings is LHR with 2.74×10^5 [kg] saved, and WAW with the lowest at 1.81×10^4 [kg] saved. When tow compatibility is not taken into account, narrowbody vehicles have an average CO_2 savings of 66% and widebody vehicles have an average CO_2 savings of 43%. This is in line with the estimates in literature used for validation of the model as explained in Section 3.5.1. As shown in Table 9, both the taxi times and number of compatible flights have an influence on the maximum daily jet fuel savings. Unlike SET operations, the fuel saved is not dependent on the total taxi minutes at an airport because not all aircraft are compatible with the hybrid towing vehicles. The total taxi minutes of compatible flights is the characteristic with the highest influence on fuel savings potential at airports with a coefficient of determination value of 0.96. This is the product of the average taxi time at an airport and the number of compatible flights in a schedule.

Table 9: Coefficients of determination for the maximum taxi fuel saved using hybrid towing

Airport Characteristic	**Coefficient of Determination ($\mathbf{R^2}$)**
Average Taxi Time	0.75
Total Flights	0.80
Compatible Flights	0.88
Compatible NB Flights	0.72
Compatible WB Flights	0.83
Total Compatible Taxi Minutes	**0.96**
Percentage of Flights Compatible	0.10

5.2.3 Scenario 2: Electric Towing

Using conventional taxiing as a baseline, the percentage of jet fuel saved at the 30 airports ranges from 14.2% at STN to 68.9% at DUS. The airport with the highest maximum daily jet fuel savings is LHR with 2.63×10^5 [kg] saved, and STN with the lowest at 1.17×10^4 [kg]. Again, the average total taxi minutes is the characteristic with the highest influence on fuel savings potential at airports. When ignoring the compatibility constraints, a maximum European savings CO_2 of 79% is estimated when the CO_2 of the energy source is also taken into account. When the energy source is not taken into account this increases to 84%. This is within the valid range from Section 3.5.1.

Table 10: Coefficients of determination for the maximum taxi fuel saved using electric towing

Airport Characteristics	**Coefficient of Determination ($\mathbf{R^2}$)**
Average Taxi Time	0.66
Total Flights	0.80
Compatible Flights	0.86
Total Compatible Taxi Minutes	**0.97**
Percentage of Flights Compatible	0.23

5.3 Savings Europe

5.3.1 Average Maximum Savings

In the case-study, a total of 22918 daily flights using jet aircraft are studied at the 30 case-study airports. The averaged daily jet fuel savings and CO_2 for SET, hybrid towing, and electric towing per flight and per airport are presented in Table 11 and NO_x results are presented in Table 12. When comparing hybrid and electric towing on a European-wide scale, hybrid towing yields higher jet fuel savings and CO_2 savings however emits higher NO_x emissions than conventional taxiing, single-engine taxiing and electric towing.

Table 11: Maximum fuel and CO_2 emissions savings comparisons

Jet Fuel Savings	**Baseline: SET**	**Scenario 1: Hybrid**	**Scenario 2: Electric**
Total [kg]	597,827	2,597,678	2,259,494
[kg]/Flight	26	113	99
[kg]/Airport	24,909	86,589	75,316

CO2 Savings	**Baseline: SET**	**Scenario 1: Hybrid**	**Scenario 2: Electric**
Total [kg]	1,889,267	6,863,436	6,813,162
[kg]/Flight	82.4	299	297
[kg]/Airport	62,975	228,781	227,105

Table 12: Maximum NO_x emissions savings comparisons

NOx Savings	**Baseline: SET**	**Scenario 1: Hybrid**	**Scenario 2: Electric**
Total [kg]	2704	-2240	9598
[kg]/Flight	0.12	-0.10	0.42
[kg]/Airport	90	-75	320

5.3.2 Europe-wide Jet Fuel Savings

A comparison of the average daily jet fuel savings as the European fleet size increases is found in Figure 7. This figure shows two points of interest. First, the point where the jet fuel saved using operational towing exceeds that of SET. Second, when the savings of operational towing converge at the maximum fuel savings. Looking at jet fuel savings, all fleet sizes of hybrid towing yield higher maximum jet fuel savings. The fleet sizes of both scenarios for these points are found in Table 13. Not only are the required fleet sizes lower for hybrid towing, the vehicles would also need to be implemented at fewer airports to exceed SET savings.

Table 13: Fleet size to achieve SET and maximum savings

Jet Fuel Savings	**Min Fleet for SET Savings**	**Number of Airports**	**Min Fleet for Max Savings**	**Number of Airports**	**Best Choice Between**
Scenario 1: Hybrid	57	15	978	30	>57 Vehicles
Scenario 2: Electric	85	23	900	30	-

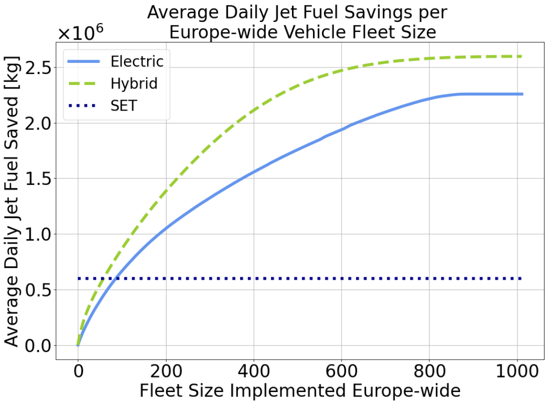


Figure 7: Comparison of European-wide Average Daily Jet Fuel Savings vs. Vehicle Fleet Size

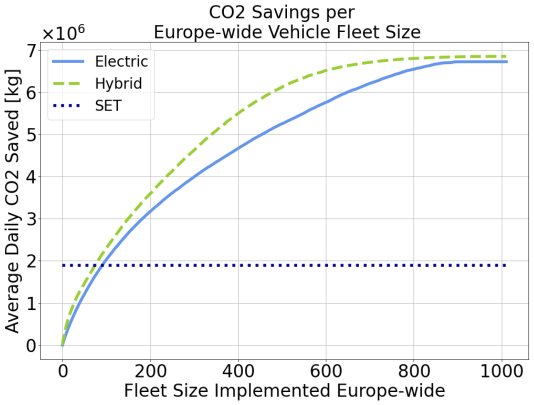


Figure 8: Comparison of European-wide Average Daily CO_2 Savings vs. Vehicle Fleet Size

5.3.3 Europe-wide CO_2 Savings

When comparing Scenario 1 and Scenario 2 in terms of CO_2 savings as shown in Figure 8, using hybrid towing yields higher CO_2 savings for all fleet sizes. The maximum Europe wide daily savings of Scenario 1 is 50 [t] higher than Scenario 2. Although the emissions of CO_2 per kWh are much lower than emissions per kg of diesel burned, 0.355 [kg/kWh] vs. 3116 [kg/kg], this can be explained by the high jet fuel savings that can be achieved by hybrid towing due to the quicker refuelling time and compatibility of the vehicles.

Table 14: Fleet size to achieve SET and maximum savings

CO_2 Savings	Min Fleet for SET Savings	Number of Airports	Min Fleet for Max Savings	Number of Airports	Best Choice Between
Scenario 1: Hybrid	74	15	978	30	>74 Vehicles
Scenario 2: Electric	91	23	900	30	-

5.3.4 Europe-wide NO_x Savings

When comparing NO_x savings of hybrid and electric towing, electric towing outperforms for all fleet sizes. As seen in Figure 9, Scenario 1 only has net positive NO_x emissions savings for a fleet size less than 178 vehicles, and never exceeds the NO_x savings of SET. Scenario 2 yields positive net NO_x savings for all fleet sizes. To exceed the NO_x savings of SET, a minimum fleet size of 72 vehicles is necessary.

Table 15: Fleet size to achieve SET and maximum savings

NO_x Savings	Min Fleet for SET Savings	Number of Airports	Min Fleet for Max Savings	Number of Airports	Best Choice Between
Scenario 1: Hybrid	-	-	34	11	Yields Positive Savings $<$ 174 Vehicles
Scenario 2: Electric	72	21	900	30	>72 Vehicles

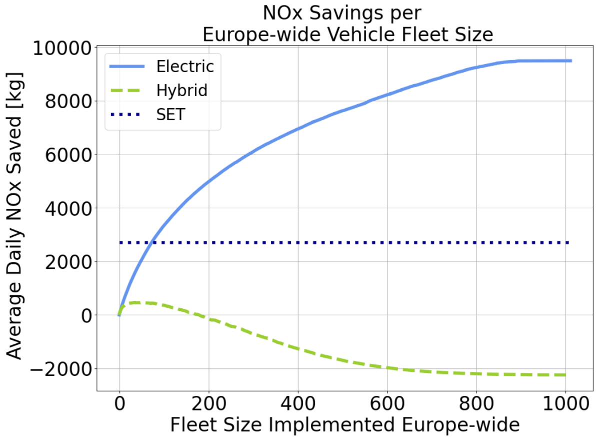


Figure 9: Comparison of European-wide Average Daily NO_x Savings vs. Vehicle Fleet Size

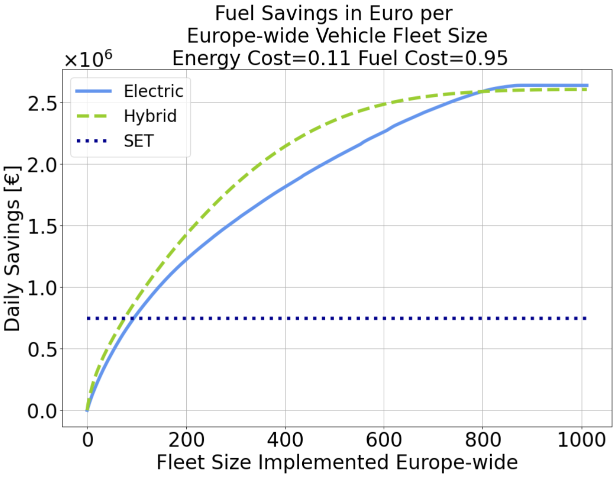


Figure 10: Fuel Related Savings in Euros

5.3.5 Cost of Implementation

For all combinations of fuel and energy prices from Table 4 in Section 3.4.3, the maximum European savings can be achieved using electric vehicles. However, due to the initially high marginal savings, hybrid vehicles have higher savings for most vehicle fleet sizes. The fleet size requirement for electric vehicles to exceed hybrid savings is shown in Table 16. An example of the relationship between savings and vehicle fleet sizes is shown in Figure 10 using the average European energy and fuel prices. For both scenarios, the maximum fuel related daily savings exceeds €2M euros per day.

Table 16: Minimum electric vehicle fleet size to exceed hybrid vehicle savings

Electricity Prices [€/kWh] Fuel Prices [€/L]	**0.06**	**0.11**	**0.18**
0.82	783	807	863
0.95	780	800	837
1.14	777	792	818

5.4 Validation of Generated Taxi Times

A comparison of the generated and actual taxi times distributions can be seen in Figure 11. The real distribution has 10 outlier flights with taxi times between 25 and 59 minutes. The real distribution also has a lower median and a lower minimum. The effect of these differences on the model results are shown below.

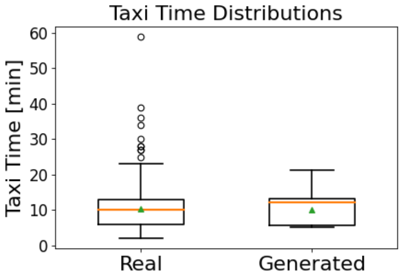


Figure 11: Difference in the Real and Generated Taxi Time Distributions

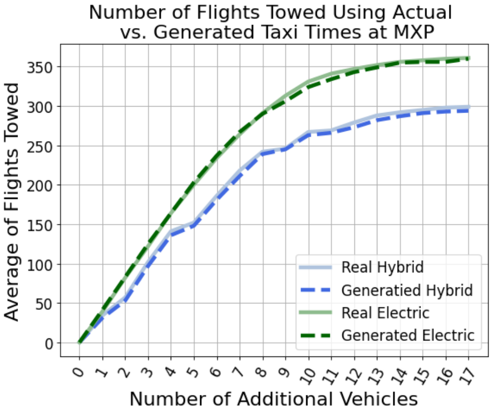


Figure 12: Difference Between the Number of Aircraft Towed Using Real and Generated Taxi Times

5.4.1 Effect on Number of Flights Towed

As shown in Figure 12, the number of vehicles towed per vehicle fleet size for both the hybrid and electric towing vehicles is not affected by the difference in generated vs. real taxi times. It can be concluded that assumed taxi times can be used to simulate a realistic number of flights towed.

5.4.2 Effect on Fuel Savings

The fuel savings using real and generated taxi times are presented in Figure 13 for hybrid, and Figure 14 for electric towing vehicles. In both situations, the real taxi times yield higher savings than the generated taxi times. This can be explained by the following. First, the generated taxi times for inbound traffic are not sorted by wake category. In the real taxi time data, large aircraft tend to have higher taxi times, and also higher potential savings when compared to the generated taxi data. Thus, the real data yields marginally higher fuel savings for inbound traffic. Secondly, the real data contains 10 outliers with flights that have a taxi time between 25 and 59 minutes. As more vehicles are added to the fleet, the outlier flights can be towed, explaining why the savings differences grow as the fleet size increases. Due to vehicle compatibility, the electric towing fleet is more affected by the outlier flights. Due to the disparities with inbound traffic and outliers in the real data-set, the baseline fuel used for conventional taxiing is also higher for the real data set. This results in a 9.8% difference in fuel savings for hybrid vehicles and 11.1% difference in fuel savings for electric vehicles when expressed in litres saved. When comparing the percent saved, the real taxi times were 1.8% higher for hybrid towing and 2.5% higher for electric vehicles. Given that the margins remain within 2.5% for both hybrid and electric simulations, it can be said that the relative fuel saved expressed in percentage from the generated data-set is a good representation of reality.

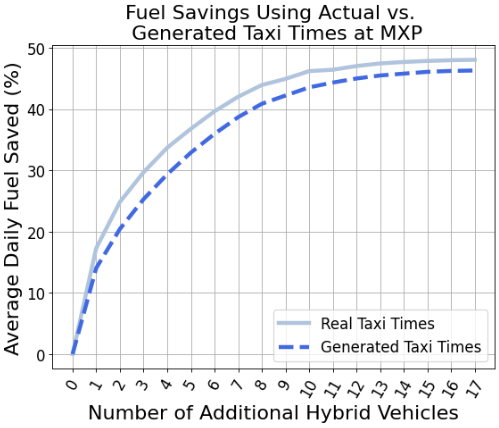


Figure 13: Average Daily Fuel Saved for Hybrid Vehicles Using the Real vs. Generated Taxi Time Distribution

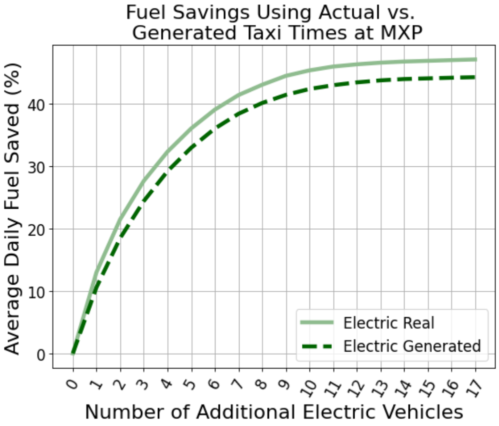


Figure 14: Average Daily Fuel Saved for Hybrid Vehicles Using the Real vs. Generated Taxi Time Distribution

5.5 Effect of Assumed Parameters

5.5.1 Effect of T_{warm}

T_{warm} is assumed in the model to match values used in literature by [Deonandan and Balakrishnan, 2010, Wollenheit and Mühlhausen, 2013]. To understand the effect that the assumption has on the results of the optimization model, a sensitivity analysis is performed on the case-study airports. The original value of 3 minutes is varied from 2 to 7 minutes. T_{warm} is found to have a direct effect on the maximum savings per vehicle fleet iteration. For narrow body traffic, every additional minute to warm aircraft engines results in an average of 5.7 kg of extra fuel burned per narrow-body aircraft towed. For wide-body traffic, every additional minute results in an average of 14.9 kg of extra fuel burned per wide-body aircraft towed. The value of T_{warm} has no effect on the number of vehicles needed to achieve maximum savings.

5.5.2 Effect of TAT

The TAT between jobs is assumed as 10 minutes for the model. As the simulation is formulated in terms of 5 minute blocks, the original TAT of 10 minutes is varied from values between 5 minutes and 20 minutes. After performing a sensitivity analysis on 10 airports, it is found that the TAT does not have any affect on the maximum average daily fuel or emissions savings at an airport. The vehicle TAT affects the marginal savings of each vehicle and thus the number of vehicles necessary to reach a certain savings. The degree that a change in TAT affects the marginal savings is airport specific, and there is no clear correlation with any of the studied airport characteristics to predict how it will effect the airport iterative results.

5.5.3 Effect of Energy Consumption

For Scenario 2, a value for the energy used in [kWh/km] is assumed for the tow vehicle. This value has an effect on the emissions savings for Scenario 2. Compared to other electric vehicles with a high towing capacity, the assumed value of 9.6 kWh/km is a relatively high value. In comparison, a Volvo freight truck has a consumption of 1.1kWh/km, however the truck has a towing capacity 8.8 times lower [Volvo Trucks, 2022]. As the number of towing jobs per day is constrained, the fuel savings are independent of the assumed value. The emissions savings of Scenario 2, however are directly related to this value. As the assumed value is relatively high, the effect of using a lower value is tested. This results in CO_2 savings for electric vehicles exceeding the value calculated for hybrid vehicles.

6 Discussion of Results

In previous literature, emission mitigation strategies are compared based on the maximum fuel or emission savings potential, with the assumption that all aircraft are operationally towed. The method of this research simulates a mixed-operations scenario, where aircraft could be towed or taxi conventionally. By using this approach, the potential of any vehicle fleet size at any airport can be estimated. In the results, it is found that the strategy that delivers the highest maximum savings potential, is not always the most cost effective strategy for all fuel or emission savings targets. This is because the marginal savings of each vehicle depends on the vehicle type. In the scenarios simulated, hybrid vehicles have a much higher initial savings potential than electric vehicles, but the savings of hybrid vehicles decrease more rapidly than electric vehicles as the fleet size increases. This finding shows that the maximum potential savings previously used in literature is not a good metric to compare strategies for all emission savings targets. By comparing the maximum potential as fleet size increases, the strategy that performs best within a stakeholder's budget or emission savings target can be chosen.

In the results, it is found that the fuel and emissions savings potential of a vehicle fleet is higher when applied across Europe than when based at one airport. This is because vehicles are assigned to flights with the highest fuel savings potential in a schedule. As vehicle fleet size increases, the marginal savings for each additional vehicle decreases. On a European level, this means that implementing smaller vehicle fleets at many airports would require a smaller total vehicle budget to achieve the same emissions savings.

The accuracy of input data is the main limitation of this research. Given the quality of publicly available data, it is not possible to produce estimations of fuel and emissions savings that represent the current situation in Europe. The main issues in the input data are the following. First, the analysis is done with data from 2018. Due to the Covid-19 pandemic, many heavy aircraft have been retired, and more fuel efficient aircraft have been introduced. This means the aircraft used in the case-study may not reflect the traffic situation of 2022. In addition, assumptions for the vehicle data are made for the simulations. For this reason, the estimated fuel and emissions savings may not reflect the actual potential of the the towing vehicles simulated in the research. Finally, engine pairings for each aircraft were assumed. Although common engine types are chosen, airlines have the freedom to choose the engine types used on their aircraft. For this reason, the aircraft and engine pairings may not reflect the current situation.

7 Conclusions and Recommendations

The goal of this research was to evaluate the relationship between fixed vehicle costs and the fuel and emissions savings potential of operational towing in Europe. In the case-study, two scenarios of operational towing are compared; hybrid and electric operational towing. The strategies are modelled and compared at 30 European airports. It is found that by implementing operational towing at airports in Europe, significant jet fuel and emission savings can be made. Because of the lower downtime required to refuel, and higher compatibility with aircraft, the hybrid vehicles in the simulation outperform electric vehicles for jet fuel and CO_2 emission savings. Electric vehicles, however, perform better than hybrid vehicles when comparing the NO_x savings for all fleet sizes. It is found that the total taxi minutes of compatible flights is the airport characteristic with the most direct influence on the performance of operational towing. This is defined as the product of the average taxi time at an airport and the number of compatible flights.

A main finding in the research is that the fuel and emissions savings potential of a vehicle fleet is higher when applied across Europe than when the same fleet size would be based at one airport. This is because the marginal savings per vehicle decrease as fleet size increases. When implementing operational towing on a large scale, investment in airport infrastructures, such as roadways and ground traffic management, is necessary. To compare the cost effectiveness of many vehicles at one airport versus a few vehicles at many airports, infrastructure costs must also be taken into account. Future research into the required infrastructure at an airport as fleet size increases should be done. Research should focus on determining how large a vehicle fleet can be so that the current airport infrastructure can support operational towing without major changes. It should also focus on how the requirements for airport infrastructure change as fleet size increases. If small fleet sizes could be implemented at airports without requiring radical changes to infrastructure or ATC technology, this this would allow the industry to maximize emissions savings in the short-term.

In addition to this, the study found using maximum savings potential of an airport is not a comprehensive enough metric to make informed decisions about the most appropriate mitigation strategy for every budget or emissions reduction target. Because of differences in aircraft compatibility and refuelling or recharging times, the change in marginal savings as vehicle fleet size increases is not the same for all vehicle types. For stakeholders, this means that mitigation strategies should not be compared based on maximum potential, but based on a fleet size that fits their constraints or requirements. For example strategies should be compared to fit the vehicle budget, target fuel or emissions savings, or the timeline for paying-off the vehicle investment with the jet fuel saved.

In this research it has been demonstrated that evaluating the change in fuel and emissions savings potential as fleet size increase provides a more complete overview of the potential of operational towing than previous methods. Future work should focus on a more detailed estimate of the required infrastructure at each airport, and on improving the quality of input data. To make more accurate estimations, data must be shared between airports, airlines, and aircraft and vehicle manufacturers. By inputting accurate vehicle data from vehicle manufacturers, accurate engine pairings from aircraft manufacturers and airlines, and reliable taxi time data from airports and airlines, a more realistic trade-off can be achieved between operational towing technologies. These improvements would allow stakeholders to choose the most cost-effective strategy to fit their budget or emission savings targets as operational towing gets implemented into daily airport operations.

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Appendices

A Appendix A: Breakdown of Maximum Fuel and Emissions Savings in Europe

Figures in Table 17 present a more detailed overview of the Europe-wide maximum fuel and emissions savings, to those presented in Section 5.3.1.

Table 17: Comparison of Europe-wide maximum daily fuel used and maximum daily savings for all operations strategies

Average Daily Values	**Conventional Taxiing Baseline**	**SET**			**Hybrid Towing**			**Electric Towing**		
		Used	**Saved**	**% Saved**	**Used**	**Saved**	**% Saved**	**Used**	**Saved**	**% Saved**
Jet Fuel [L]	4.93e6	4.18e6	7.47e5	15.1	1.68e6	3.25e6	65.9	2.11e6	2.82e6	57.3
Combined Fuel [L]	4.93e6	4.18e6	7.47e5	15.1	2.19e6	2.74e6	55.7	2.11e6	2.82e6	57.3
Diesel Used [L]	0	0	0	0	5.03e5	-5.03e5	-	0	0	0
Energy Used [kWh]	0	0	0	0	0	0	0	6.95e5	-6.95e5	-
CO2 [t]	1.25e4	1.06e4	1.89e3	15.2	5.60e3	6.86e3	55.0	5.65e3	6.81e3	55.7
CO [t]	100	85.3	15.2	15.1	42.2	58.3	58.0	40.2	60.3	60.0
NOx [t]	17.8	15.1	2.70	15.2	20.0	-2.24	-12.6	8.2	9.60	54.0
HC [t]	8.86	7.5	1.35	15.3	5.4	3.43	38.7	3.9	5.00	56.5

B Appendix B: Case-Study Airports and Dates of Operation

In Table 18 the list of all case-study airports and the chosen dates of operation are presented. These dates determine the input used in the optimization model.

Table 18: Case-study Airports and Dates of Operation

Airport	**2018 Average Daily Movements**	**Winter Schedule Date**	**Number Flights**	**Summer Schedule Date**	**Number Flights**
AMS	1401	14/02/2018	1396	02/05/2018	1399
ARN	668	02/02/2018	667	16/09/2018	671
ATH	579	02/02/2018	581	07/10/2018	573
AYT	510	08/02/2018	493	31/05/2018	511
BCN	920	08/03/2018	922	11/10/2018	919
BRU	630	14/02/2018	627	24/06/2018	632
CDG	1337	26/01/2018	1336	05/08/2018	1337
CPH	729	02/03/2018	727	10/08/2018	729
DUB	637	14/03/2018	636	05/05/2018	640
DUS	598	16/02/2018	601	07/06/2018	598
FCO	843	09/02/2018	848	13/10/2018	856
FRA	1403	24/03/2018	1402	11/10/2018	1406
HEL	527	26/01/2018	528	23/06/2018	526
IST	1250	27/01/2018	1256	11/10/2018	1257
LGW	778	14/02/2018	768	21/04/2018	777
LHR	1309	17/01/2018	1308	01/04/2018	1312
LIS	596	20/01/2018	599	06/10/2018	599
MAD	1122	06/02/2018	1123	01/04/2018	1123
MAN	551	15/03/2018	550	26/05/2018	554
MUC	1125	06/03/2018	1122	19/11/2018	1128
MXP	533	12/11/2018	536	31/03/2018	534
ORY	637	25/02/2018	640	14/04/2018	647
OSL	705	14/12/2018	708	15/07/2018	708
PMI	603	26/03/2018	602	17/04/2018	607
SAW	619	17/01/2018	621	30/10/2018	624
STN	548	08/02/2018	546	20/04/2018	550
TXL	508	29/01/2018	509	01/07/2018	502
VIE	702	02/02/2018	703	10/04/2018	705
WAW	513	21/03/2018	516	24/04/2018	512
ZRH	744	08/02/2018	745	19/04/2018	743

II

Literature Study

previously graded under AE4020

1

Aviation Climate Effects and Mitigation

In this chapter, the current state and future goals of aircraft emissions are covered. This chapter focuses on aircraft emissions as a whole, ground specific emissions and how they can be modelled, and current and future plans by governments to mitigate climate change impacts caused by aviation. This chapter aims to answer the following questions:

- What is radiative forcing? What aviation related emissions cause radiative forcing?
- Which of these emissions are emitted while the aircraft is on the ground?
- What research has been done into modelling ground emissions?
- What is the composition of aircraft emissions? (ie. highest emitting aircraft, airports, operation type)

1.1. Emission and Climate Effects of Aviation

To develop an understanding of how operational measures can impact aircraft emissions, an overview of the emissions emitted by the aviation industry and why they are harmful will be investigated. This is followed by a more detailed look into the emissions caused during ground operations and taxiing. It is important to note that the topic of noise emissions is out of the scope of this assignment, thus although an important aspect of sustainability in aviation, it will not be explored in this report.

1.1.1. Aviation Emissions Overview

Radiative forcing according to the International Panel of Climate Change (IPCC) is "the change in the net, downward minus upward, radiative flux (expressed in Wm^{-2} due to a change in an external driver of climate change" Matthews et al. (2021). In non-technical terms, emissions with positive radiative forcing are drivers of climate change which increases the chance of extreme weather events. Not only is the aviation industry contributing to climate change, it is also directly effected by it with temperature changes, precipitation, storm-patterns and sea level changes van der Sman et al. (2020). The aviation industry is responsible for emitting harmful substances which induce radiative forcing, and subsequently effect the Earth's climate and air quality. The emissions emitted are namely carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_x), hydrocarbons (HC), methane (CH_4), carbon monoxide (CO), sulfur oxides (SO_x) and particulate matter ($PM_{2.5}$ and PM_{10}), each of which have their dangers and contribute to radiative forcing Office of Environment and Energy (2015). In Figure 1.1, a schema adapted from Lee et al. (2009); Prather et al. (1999); Wuebbles et al. (2007) shows the principle emissions from aviation operations and shows the processes that lead to radiative forcing.

Not only does the commercial aviation industry contribute to about 2.4% of global CO_2 emissions, the non-CO_2 effects such as warming induced by aircraft contrails and other pollutants, make the aviation industry responsible for approximately 5% of the climate radiative forcing.[1] While the emissions of automobiles, electricity, industrial and agricultural sectors currently exceed passenger air travel with respect to their climate change impact; the aviation industry, despite major improvements in the last 60 years is still the fastest growing sector with respect to individual emissions. It has been forecasted that emissions could triple by 2050 in comparison to the 2015 values given the projected growth of the industry Overton (2019).This is a concern for the future, thus policies and government projects in Europe are being funded to tackle this issue.

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[1] `https://ourworldindata.org/co2-emissions-from-aviation`

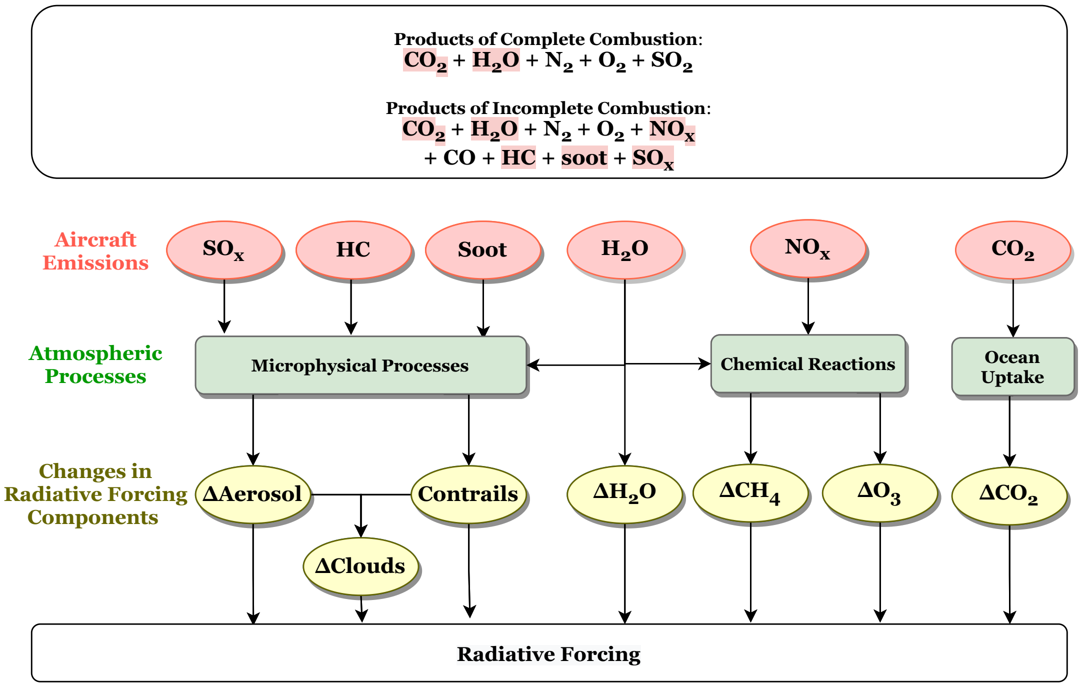

Figure 1.1: Schema adapted from figures in Lee et al. (2009); Prather et al. (1999); Wuebbles et al. (2007) showing a simple overview of aircraft emissions and the processes they go through to contribute to ratiative forcing.

The main components of aviation that contribute to radiative forcing are the following, where positive RF indicates a net warming effect and a negative RF indicates a net cooling effect:

- **CO_2 :** The direct emission of CO_2 through combustion changes the concentration of CO_2 in the atmosphere. CO_2 has a net warming effect (positive RF) as it is a greenhouse gas, trapping the heat of the earth in the atmosphere Gunnar et al. (2014); Lee et al. (2021). [2]
- **NO_x :** The emission of NO_x causes a net warming effect. This is the sum of;

  1. Photo-chemical changes leading to production of the short-term tropospheric ozone, O_3 (warming effect)
  2. Decreasing the lifetime and abundance of methane, CH_4 (cooling effect)
  3. Long-term decrease in ozone due to CH_4 reduction (cooling effect).

  When added together, NO_x still causes a net warming effect, thus positive radiative forcing Myhre et al. (2011); Lee et al. (2009, 2021).
- **H_2O :** Water vapour acts as a greenhouse gas by absorbing the longwave radiation and radiates it back to the Earth's surface causing a warming effect (positive RF). It also is a precursor to aerosols, cloud and contrail formationGunnar et al. (2014).[3]
- **Persistent Linear Contrails:** Contrails, trap terrestrial radiation (net warming) and reflect solar radiation (net cooling). Due to the day and night cycle, contrails trap more heat than

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[2] https://www.epa.gov/ghgemissions/overview-greenhouse-gases

[3] `https://climatechangeconnection.org/science/what-about-water-vapour/`

they reflect meaning that contrails have a net warming effect, and thus positive radiative forcing Lee et al. (2009); Sanz-Morère et al. (2020); Vedantham (1999); Mee (1999); Boucher et al. (2013); Lee et al. (2021).

- **Aviation Induced Cloudiness:** In many recently cited papers Boucher et al. (2013); Lee et al. (2009, 2021) clouds have been named potentially positive RF, however more research is being done into their exact contribution to radiative forcing.
- **SO_4^{2-} Particles:** The production of sulfate aerosols from aviation have a negative radiative forcing effect by scattering short wave radiation, and by increasing the reflectivity of low altitude clouds Prather et al. (1999); Lee et al. (2021).
- **Soot Particles:** Soot particles emitted by aviation absorb solar radiation and influence cloud processes such as ice cloud formation. The sum of these effects cause a net warming effect (positive rafative forcing) Lee et al. (2021); Boucher et al. (2013); Gunnar et al. (2014); Bond et al. (2013).

1.1.2. Ground Specific Emissions

In this thesis, the focus is on emissions during the LTO cycle, specifically during taxiing. It has been estimated that in Europe, taxiing accounts for 10-30% of all flight time Deonandan and Balakrishnan (2010). Due to congestion caused by the increasing number of aircraft movements, taxi times are projected to increase, causing a larger contribution from taxiing to the total LTO emissions. It was estimated that in short/medium haul operations of a A320, aproximately 5-10% of the total flight fuel is burned Deonandan and Balakrishnan (2010). At airports, the LTO operations are a major source of pollution, and have been estimated to contribute to 12% of NO_x emissions, 90% of CO_2 emissions and 91% of HC emissions locally Stettler et al. (2011). In this section, an overview of the emissions during this phase of operations are explored.

When aircraft wheels are on the ground, engines operate at their lowest combustion efficiency, leading to incomplete combustion. This means that pollutants such as CO and HC's are a concern. Due to low engine temperature, there are low amounts of NO_x emitted Schürmann et al. (2007); Office of Environment and Energy (2015). As opposed to other pollutants where only 10% of emissions are emitted during the LTO cycle and the remaining 90% above 3000 ft, roughly 30% of the emitted CO and HC's are emitted during the LTO cycle, directly affecting the local air quality Office of Environment and Energy (2015). Not only do aircraft contribute to this, but ground support vehicles also contribute such as shuttle buses for transporting passengers and crew, ground support equipment (GSE) for servicing the aircraft, and other sources such as the auxiliary power unit (APU).

In a study to analyze the impact of emissions at Zurich Airport conducted in 2004, Schürmann et al. (2007), open path devices were used to analyze the real in-use emissions of NO, NO_2 , CO and CO_2 during aircraft idling. In the study, the mixing ratios of volatile organic compounds (VOC) were also obtained by collecting air samples. To understand the effects of both ground equipment and aircraft, the study took measurements both at pushback areas and in taxiways. It was found that NO concentrations were highly dominated by the ground support vehicles, and CO concentrations were dependant on aircraft movements, however also heavily dependant on the aircraft engine type. It was found that NO_x concentrations at the airport were dominated by background levels and had no clear dependence on aircraft activities. The CO measured at the airport showed significant short-term peaks from each aircraft movement. The study found up to $50\,\mathrm{g kg^{-1}}$ variability per engine type, reported to be caused by varying engine thrust settings. It is noted that the higher thrust needed to begin taxiing leads to lower CO emissions, which is in line with other literature. An important takeaway from this study is that the main improvements that could be expected from aircraft towing would be in the local CO measurements, however, due to the diesel engines of current ground equipment, the use of diesel powered towing vehicles for operational towing would cause an increase in local NO_2 measurements. This is an important consideration for the thesis that should be addressed in the analysis phase.

1.2. Modelling Ground Emissions

In literature there are many methods used to calculate aircraft ground emissions. Due to single-engine taxiing being a widely covered topic in literature, modelling of taxi emissions has been done repeatedly, however with slight variations and varying results. The literature focuses on making conclusions that are specific to an airport, thus making the scope different than this thesis which should have a more general model which can be used at multiple airports to make conclusions about how operational towing could impact ground related emissions.

In Guo et al. (2014a), fuel consumption and pollutant emissions were estimated using the International Civil Aviation Organisation (ICAO) Engine Emission Databank (EEDB).[4] The authors use airport specific taxi times, a thrust setting of 7% and assumed secondary engines were not used during taxiing to calculate NO_x emissions. In Kumar et al. (2008), NO_x emissions were calculated using the activity schedule data and assumptions such as constant fuel flow rates and taxi emission indices per unique aircraft type. In Deonandan and Balakrishnan (2010), the CO_2 and HC emissions were estimated using a more generalized approach also assuming 7% engine thrust, with non-airport specific data. Other interesting literature on the topic of ground emissions is Guo et al. (2014a), where a comparison between different methods of mitigation techniques are explored.

In the Netherlands, a standard for civil aviation has been published by the Netherlands Organisation for applied scientific research (TNO) to model the following emissions 6 types of ground emissions; 1) aircraft, 2) aircraft auxillary power units (APU), 3) ground service equipment (GSE) , 4) fuelling and fuel handling, 5) tyre wear, 6) brake wear Dellaert and Hulskotte (2017). It is assumed that the greatest changes in emissions due to towing will be seen in aircraft and ground service equipment emissions, so for the sake of this literature review, only the formulae for aircraft emissions and ground service equipment will be presented. All further information can be found in Dellaert and Hulskotte (2017). The following equations were used to model the aircraft and ground service equipment emissions:

1. **Aircraft Emissions**

$$\text{Emission}_{\,y} = \sum_{p,m,f} \text{LTO}_{p,m} \cdot \text{N}_p \cdot \text{FUEL}_{m,f} \cdot \text{TIM}_{p,f} \cdot \text{EF}_{m,f} \tag{1.1}$$

where:

- $\text{Emission}_{\,y}$ = Emission of a specific substance in a specific year; (kg/year)
- $\text{LTO}_{\text{p,m}}$ = Number of LTO cycles per aircraft type (p) with engine type (m) per year; (1/year)
- N_{p} = Number of engines per aircraft (p)
- $\text{FUEL}_{\text{m,f}}$ = Fuel consumption of engine (m) in flight mode (f); (kg/s)
- $\text{TIM}_{\text{p,f}}$ = Duration of flight mode (f) for aircraft (p); (s)
- $\text{EF}_{\text{m,f}}$ = Emission factor of engine (m) per quantity of fuel in flight mode (f); (kg/kg)

This method can be found in Van Baaren (2019) where it is used as a baseline to explore the feasibility of fully electric aircraft towing systems, and in Kesgin (2006) for estimating aircraft landing and take-off (LTO) emissions at Turkish airports. This method has also been published in 2021 by the Netherlands Environmental Assessment Agency as the method for calculating aircraft emissionsGeilenkirchen et al. (2021).

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[4] `https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank`

2. **Ground Support Equipment Emissions**

$$\text{Emission}_{y} = \text{MTOW}_{\text{total}} \cdot \text{Fuel}_{GSE} \cdot \text{Density}_{\text{diesel}} \cdot \text{IEF}_{GSE} \tag{1.2}$$

where:

- Emission $_y$ = Emission of a specific substance in a specific year; (kg/year)
- $\text{MTOW}_{\text{total}}$ = Total summed MTOW per airport; (tonne/year)
- FUEL_{GSE} = Fuel consumption of GSE; (I/tonne MTOW)
- Density diesel = Density of diesel (0.84); (kg/I)
- IEF_{GSE} = Implied emission factor of GSE per quantity of fuel; (kg/kg)

In this equation the ground service equipment emissions are calculated based on the aircraft maximum take-off weight (MTOW). Ground service equipment covers towing tractors, de-icing equipment, stairs and belts, loaders and transporters, water and service trucks, cars, vans and busses all of which typically run on diesel fuel. This formula would need to be adapted if used in order to account for the extra kilometres of towing that a tractor must do.

In Guo et al. (2014a) models for emissions for 4 scenarios are covered: 1) Conventional Taxiing, 2) Single-Engine Taxiing, 3) Operational Towing and 4) On-board Aircraft Ground Propulsion Systems (APU powered). For the sake of the thesis only the first 3 equations from Guo et al. (2014a) for modelling will be explored in this literature review.

1. **Conventional Taxiing**
The following equation for fuel burn of taxiing during a flight is used:

$$F_i = \sum_m (T_{im} \cdot 60) \cdot N_i \cdot FF_{im} \tag{1.3}$$

and the subsequent emissions of the flight are calculated by:

$$E_{ij} = \sum_m (T_{im} \cdot 60) \cdot N_i \cdot FF_{im} \cdot EI_{ijm} \tag{1.4}$$

where:

- F_i = fuel burn during taxiing of flight i; (kg)
- E_{ij} = The emissions from flight i for each pollutant j; (g)
- T_{im} = time-in-mode for mode m for flight i (e.g., taxi-in and taxi-out); (minutes)
- N_i = number of engines used on flight i
- FF_{im} = fuel flow index in mode m for each engine used on flight i; (kg/s)
- EI_{ijm} = is the emission index for pollutant j from each engine on flight i calculated for every mode, m (e.g., NOx, CO or HC during taxi-in mode or taxi-out mode) ; (g/kg fuel)

2. **Single-Engine Taxiing Taxiing**
The following equation for fuel burn of single engine taxiing during a flight is used:

$$F_i^{\text{single}} = \sum_m (T_{im} \cdot 60) \cdot (N_i/2) \cdot FF_{im} \tag{1.5}$$

and the subsequent emissions of the flight are calculated by:

$$E_i^{\text{single}} = \sum_m (T_{im} \cdot 60) \cdot (N_i/2) \cdot FF_{im} \cdot EI_{ijm} \tag{1.6}$$

where:

- F_i = fuel burn during taxiing of flight i; (kg)
- E_{ij} = The emissions from flight i for each pollutant j; (g)
- T_{im} = time-in-mode for mode m for flight i (e.g., taxi-in and taxi-out); (minutes)
- N_i = number of engines used on flight i
- FF_{im} = fuel flow index in mode m for each engine used on flight i; (kg/s)
- EI_{ijm} = is the emission index for pollutant j from each engine on flight i calculated for every mode, m (e.g., NOx, CO or HC during taxi-in mode or taxi-out mode) ; (g/kg fuel)

To use this equation it is assumed that an aircraft with 2 engines uses 1 during single engine taxiing, and an aircraft with 4 engines uses 2. These formulae could be adapted to allow for taxiing with 1 engine for every aircraft if that were necessary.

3. **Operational Towing**
The following equations for fuel consumption of operational towing during a flight:

$$F_i^t = \sum_m (T_{im} \cdot 60) * \mathrm{BHP} \cdot LF \cdot FF_{im}^t \tag{1.7}$$

and emissions of the towing vehicle:

$$E_{ij}^t = \sum_m (T_{im} * 60) * \mathrm{BHP} * LF * EI_{ij}^t \tag{1.8}$$

can be used for operational towing. where:

- F_i^t = fuel consumption of each tow vehicle type, t, towing vehicle during towing of flight i; (kg)
- E_{ij}^t = The emissions from flight i for each pollutant j from towing vehicle type, t ; (g)
- FF_{im}^t = fuel flow index in mode m for each engine used on flight i; (kg/BHP-sec)
- BHP is the average rated brake horsepower of the tow vehicle; (BHP)
- LF is the load factor utilized in the operation
- EI_{ij}^t = is the emission index for pollutant j from each specific engine-fuel type of vehicle t; (g/kg fuel)

It is important to note that during operational towing, emissions will come from the tow vehicle being used and it depends on the energy source type and the amount of horsepower necessary.

Several other models have been used for a basis of environmental impact for literature regarding non-conventional towing methods, which will further be discussed in Chapter 2.

1.3. Composition of CO_2 in Aviation

Many, if not all literature on single-engine taxiing and operational towing focus on airport specific improvements. This however, does not give an understanding of the potential impact as a whole, as airport operations look very different from one airport to the next given the types of routes, aircraft, and number of movements. As the thesis model should be general enough to be applied to a variety of airports, the case-study should be made using data that can represent emissions at various airports. For this reason, a look into where the most emissions are emitted, by what type of aircraft we can find a better representation of the global market. Since CO emissions, the emissions on the ground that are linked closest air quality changes caused by towing, are directly related to CO_2 burn we will use global CO_2 information to define the scope of the thesis.

In a report published by the International Council on Clean Transportation (ICCT), an overview of the composition of the global inventory of CO_2 emissions was made for the years of 2013, 2018 and 2019 Brandon Graver (2020). Of the total aviation CO_2 emissions, approximately 85% of the emissions were produced by passenger flights as shown in Figure 1.2 adapted from data published in Brandon Graver (2020). Between 2013 and 2019 this value rose by 33% to 785 million tonnes of CO_2. In the same time, the number of flight departures increased by 22% and the revenue passenger kilometers (RPKs) increased by 50%. This means that despite improvements in fuel efficiency, traffic grew nearly 4 times faster. Similar figures were also noted in Office of Environment and Energy (2015) and Overton (2019). In the report, CO_2 emissions per aircraft in each of the categories are also presented.

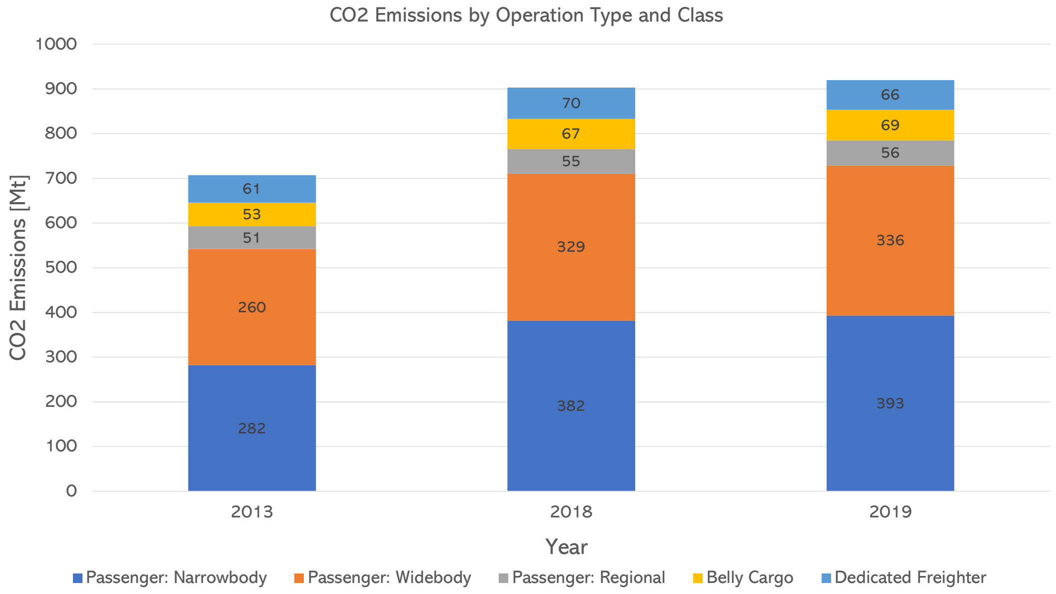

Figure 1.2: Composition of CO_2 by operations and aircraft class in 2013, 2018 and 2019 with data taken from Brandon Graver (2020).

In the same report, an overview of CO_2 emissions per aircraft type and per airport is presented among other information. This information is important, as a schedule will be built around aircraft and airport information for the model in the thesis. As the savings per airport and aircraft are of interest, these are interesting to keep in mind when choosing a sample and while analyzing data. In Table 1.1 the top 3 aircraft per aircraft type are presented using data from Brandon Graver (2020). Of these aircraft many are older, but still frequently used aircraft. Due to the pandemic, many airlines have chosen to retire older wide-body aircraft such as the A380-800, thus a significant change would be expected from the 2019 values to the present day emissions. Additionally, the top 10 airports with the most emissions are presented in Table 1.2. Exact values were not presented in Brandon Graver (2020), thus values have been rounded to the nearest 0.5 [Mt]. This information is interesting for choosing the airports for the case study of the thesis. Although one would likely choose the airports based on the number of movements, it is also possible to choose airports based on their current CO_2 emissions for the optimization model.

Table 1.1: Comparison of the CO_2 emissions of the top 3 emitting aircraft per aircraft type.

Regional			Narrowbody			Widebody		
Aircraft	**Seats per Flight**	**CO_2 Emissions (2019) [Mt]**	**Aircraft**	**Seats per Flight**	**CO_2 Emissions (2019) [Mt]**	**Aircraft**	**Seats per Flight**	**CO_2 Emissions (2019) [Mt]**
Embraer E190	100	9.54	**Boeing 737-800**	174	116	**Boeing 777-300/ -300ER**	353	77
Embraer E175	77	6.94	**Airbus A320**	169	114	**Airbus A330-300**	298	40.6
Canadair CRJ900	80	6.40	**Airbus A321**	196	48.4	**Airbus A380-800**	500	34.3

Table 1.2: Airports with the highest CO_2 emissions.

Total		International		Domestic	
Airport	**Estimated CO_2 [Mt]**	**Airport**	**Estimated CO_2 [Mt]**	**Airport**	**Estimated CO_2 [Mt]**
Dubai (DXB)	>16	Dubai (DXB)	>16	Los Angeles (LAX)	6
London Heathrow (LHR)	16	London Heathrow (LHR)	16	Atlanta (ATL)	6
Los Angeles (LAX)	15	Paris Charles de Gaulle (CDG)	11	Beijing Capital (PEK)	5
New York – John F. Kennedy (JFK)	13	Singapore Changi (SIN)	11	Chicago O'Hare (ORD)	5
Paris Charles de Gaulle (CDG)	11.5	Hong Kong (HKG)	10.5	Dallas Fort Worth (DFW)	5
Beijing Capital (PEK)	11.5	Seoul Incheon (ICN)	10	Denver (DEN)	4
Hong Kong (HKG)	11	Frankfurt (FRA)	10	San Francisco (SFO)	4
Singapore Changi (SIN)	11	New York – John F. Kennedy (JFK)	10	Seattle-Tacoma (SEA)	4
Frankfurt (FRA)	10.5	Los Angeles (LAX)	9	Seattle-Tacoma (SEA)	3
Seoul Incheon (ICN)	10	Bangkok (BKK)	8	Phoenix (PHX)	3

1.4. Emissions Conclusions on Scope of Thesis

In this section, conclusions have been made with regards to emissions guided by the initial questions. In this section conclusions to these questions are made with regards to the thesis scope. These conclusions have been made with the goal in mind of creating a model that can analyze the emissions impact that operational towing has on a global scale.

Project Scope: Emissions

As seen in other research, it is possible to model pollutant emissions using emission indices and the amount of fuel used per flight. In literature it has been found that the main pollutants of concern in the vicinity of airport terminals are HC, CO and NO_x. CO can be modelled by the CO_2 emissions. Since CO and CO_2 levels are dominated by aircraft engines, and NO and NO_2 values are dominated by ground service equipment Schürmann et al. (2007), to have a meaningful analysis of the emissions, both should be analyzed, and conclusions cannot be made about one without exploring the effect of the other.

Project Scope: Sector

The scope of this project will focus on commercial passenger air transport. This choice has been made due to the fact that commercial air passenger traffic accounts for 4 times more annual CO_2 emissions than air freight transport Brandon Graver (2020).This means that in the thesis, choices with regards to schedules and aircraft type among other things should be made for optimizing commercial passenger aviation.

Project Scope: Focus Markets
The goal of the thesis is to get a global perspective on the effect of operational taxiing, thus the model must be built using representative data. To help get a global view of the impact, a selection of the busiest airports should be used with respect to domestic, international and total air traffic. When performing a sensitivity analysis, aircraft types and airports with high and low CO_2 emissions should also be explored for a better understanding of the exact emissions benefits.

2

Current and Future State of Towing

In this section, an overview of the current practices, and literature about operational towing will be discussed. According to the ICAO phase of flight definitions, taxiing is defined as "the aircraft is moving on the aerodrome surface under its own power prior to takeoff or after landing". This could be engine power or with the use of an on-board taxi system. Operational towing is defined as manoeuvring an aircraft on the ground with the power of another vehicle, for example, a tow tractorISO Central Secretary (2016). This chapter is structured as follows; in Section 2.1 the current method of ground operations with respect to towing is discussed. Then, in Section 2.2, upcoming towing and taxiing technology is presented. Then, in Section 2.3 literature specifically with reference to conventional and single engine taxiing (SET) are explored; followed by literature on electric taxiing and operational towing in Section 2.4. As the literature on operational towing is interesting for the thesis, the types of literature have been presented categorically by their general topics; cost and feasibility, emissions, and scheduling and planning.

2.1. Current Operations

Traditionally, taxiing of aircraft has always been completed using the power of an aircraft's engines, and manoeuvring of aircraft using tow tractors has been limited to 3 operations; push-back, maintenance towing, and repositioning towing Du et al. (2014). During push back and ferry operations, the vehicles will typically not exceed 10 km/h. During taxi operations where an aircraft uses its own engine power, a speed of 20-30 knots, or 37-56 km/h is normally achieved ISO Central Secretary (2016). Currently, aircraft taxiing is limited to conventional and single engine taxiing. Both of these topics will be covered in Section 2.3.

Aircraft on ground activity can be classified under 2 sections: the turnaround and Landing and Take-off Cycle (LTO). The turnaround process describes operations which prepare the aircraft for its journey from the time an aircraft is put onto chocks, until push-back, and this also includes de-icing. The landing take-off cycle, are all the aircraft movements below 3000ft with specified thrust levels and times for each portion. This means takeoff, climb, approach, and taxi/ground idle are included in the LTO cycle **?**. Aircraft ground handling, or also referred to as turnaround, is a fundamental part of commercial aircraft operations and describes all non-maintenance related operations for preparing an aircraft for flight. The turnaround process starts when the aircraft reaches the parking position after landing and the chocks are set ('on-block time'), and ends when the LTO cycle begins ('off-block time') Schultz and Fricke (2008). When an aircraft departs, there are four main steps to be completed between the gate and runway; push back, engine start, taxi out, and engine warm-up Wollenheit and Mühlhausen (2013). Since half of these procedures are part of the turnaround phase, and the other are part of the LTO phase, currently the hand-off of responsibility is when the aircraft is finished with push-back and cleared to taxi.

2.2. Current Technology in Electric Towing Systems

Due to the push for less emissions in operations, several electric taxiing systems are being explored. There are two main categories of systems; external towing systems and internal towing systems. The main difference between is that external towing systems tow the aircraft and internal systems are integrated into the wheels of the aircraft and use electric motors powered by an aircraft's APU Guo et al. (2014a). In general, towing systems that are 100% electric travel at highly reduced speeds compared to contemporary taxiing. For this reason, a hybrid solution has also been created. An overview of the electric taxi systems on the market or being developed for commercial aviation can be found in Table 2.1. Sources of the information can be found in the table.

Table 2.1: Overview of hybrid and electric taxi/towing solutions on the market or being developed for commercial passenger aviation.

	System Configuration	Driving Method	Type	Max. Speed [km/h]	Towing Capacity [t]	Max. Power [kW]	Certified	Cost [$]	Paper
TaxiBot	External	Pilot (Taxi)+ Operator (Pushback)	Hybrid	42.6	68-85 (B737, A320)	500	Yes, since 2014	1.5-3 million	Lukic et al. (2018, 2019); Guo et al. (2014a)
Mototok	External	Remote	Electric	10	86 (B737, A320)	-	No	-	Lukic et al. (2018, 2019)
Charlotte	External-Driver Required	Driver + Extra Operator	Electric	11.3 (unloaded)	116	2*26 AC motors	-	-	Lukic et al. (2018, 2019)
LEKTRO	External-Driver Required	Driver + Extra Operator	Electric	6.44	127	2*45.5 AC motors	Yes, since 1990's	From 159K	Lukic et al. (2018, 2019)
Eagle	External-Driver Required	Driver + Extra Operator	Electric	4.8	45	2*17 AC motors	-	-	Lukic et al. (2018, 2019)
Wheel-Tug	On-board (NLG)	Pilot	Electric	16.7	B737-800	N/A	In process, was expected in 2019	-	Lukic et al. (2018, 2019); Guo et al. (2014a); Hospodka (2014)
DLR	On-board (NLG)	Pilot	Electric	25	78 A320	50	No	-	Lukic et al. (2018, 2019)
Safran & Honeywell	On-board (MLG)	Pilot	Electric	37	A320	120	No, expected in 2022	-	Lukic et al. (2018, 2019); Guo et al. (2014a); Hospodka (2014)
Safran/UoN	On-board (MLG)	Pilot	Electric	37	A320 (goal)	120	No, expected in 2022	-	Lukic et al. (2018, 2019)

2.3. Literature on Modelling Conventional and Single Engine Taxiing

Conventional Taxiing is powered by the propulsion of all available aircraft engines. Single Engine Taxiing (SET) means taxiing with less than all the available engines. For a twin-engine aircraft this means taxiing with two engines, and with a four-engine aircraft it implies using 2 of the 4 available engines Kumar et al. (2008); Guo et al. (2014a). In conventional and SET, aircraft operate using their engines and landing gear brakes. This, as explained in the previous chapter on emissions causes a considerable waste of energy due to the engine's low fuel efficiency, and high brake heating Guo et al. (2014a). The emission impact of SET has been frequently presented in research. Commonly, for modelling SET, conventional taxiing is used as a baseline.

In literature, using a thrust setting of 7% is commonly used to model engine emissions during taxiing Guo et al. (2014a); Stettler et al. (2018); Kumar et al. (2008); Nikoleris et al. (2011); Ravizza et al. (2013), with the exception of in Yim et al. (2013), where a thrust level of 10% was used to model SET and compared to conventional taxiing at a thrust range of 4-7%. Modelling of emissions for conventional taxiing can be done using Equation 1.1 as used in Van Baaren (2019); Kesgin (2006); Geilenkirchen et al. (2021), or Equation 1.3 and Equation 1.4 as used in Guo et al. (2014a). The method using Equation 1.3 and Equation 1.4 uses the advanced approach to quantify aircraft engine emissions. The advanced approach is one of 3 approaches recommended by the International Civil Aviation Organization (ICAO) Kurniawan and Khardi (2011); Secretariat, International Civil Aviation Organization (2007); International Civil Aviation Organization (2008). The other 2 approaches are the simple approach and the sophisticated approach. An overview of the approaches is shown in Table 2.2. Due to the necessity of the use of proprietary data for the sophisticated approach, for the sake of the thesis, the most accurate approach that could be applied is the advanced approach.

As mentioned the emissions savings from SET has been studied quite frequently in literature. SET has also already been adopted in operation by airlines such as Iberia Airlines and Air Qatar. The main advantages mentioned being the fuel savings and emissions reductions, as well as the ease into operation (lack infrastructure and operational changes in order for it to be used in commercial aviation) Deonandan and Balakrishnan (2010); Guo et al. (2014a). Some of the disadvantages are excessive jet blast, the possibility of single engine take-off (accidentally and very unlikely), and creation of adverse thermals in the engine cycles. Furthermore, it is not operable in conditions such

Table 2.2: Overview of ICAO recommended approaches for modelling single engine taxiing.

Approach	**Level of Detail**	**Amount of Data**	**Accuracy**
Simple	Overview	Does not take into account engine types, operational modes or time in mode (time in each phase of the LTO cycle, for example taxiing).	Moderate
Advanced	Detailed	Takes into account aircraft types, emissions indices and time in mode	High
Sophisticated	Detailed	Requires use of proprietary data	Very High

as uphill slopes, slippery surfaces, or when de-icing is required Guo et al. (2014b). For these reasons Air Qatar does not perform SET operations at low visibility, when wind speeds are 25 knots or over, and when a 180-degree turn or greater is needed to park the aircraft.[1] An overview of some of the literature about SET is shown in Table 2.3. In the table, a brief explanation of the methodology, the sample size of the case study and the findings are presented. The methodology in the literature will be used for the development of SET model for the thesis which will be used as a baseline for analyzing the effectiveness of operational towing.

Table 2.3: Overview of literature about single-engine taxiing emissions.

Liter-ature	**Methodology**	**Case Study**	**Findings**
Guo et al. (2014a)	Using ICAO Advanced Approach with thrust of 7% and 0% with taxi times specific to the particular airports	10 U.S. airports with data from 2012	Compared fuel burn and emissions of HC, CO and NO_x and found up to 50% reduction in fuel burn and NO_x emissions
Kumar et al. (2008)	Assuming thrust of 7% and 0% for taxi times and assuming aircraft trajectory, constant fuel flow, and EI per aircraft type	Orlando International Airport and NewYork LaGuardia Airport	Potential reduction of 26% and 45% respectively
Deonandan and Balakrishnan (2010)	Combination of flight data, airline fleet data and aircraft engine emissions and fuel data	General overview of top 20 American airports	General overview of the potential savings at each airport
Yim et al. (2013)	Using assumptions about fuel consumption and pollutant emissions authors Compared emissions with 10% thrust during SET on half the engines, comparedto 4-7% on all engines during conventional taxiing.	20 busiest airports in the UK	SET can save 12 early deaths in the UK
Nikoleris et al. (2011)	Used varying thrust setting values to calculate fuel consumption and NO_x emissions also analyzing turns and acceleration and braking.	Dallas Fort Worth Airport	The assumption of constant speed over estimates fuel reductions by 16% at the case study airport
Ravizza et al. (2013)	Assumptions of the taxi duration and average thrust setting using same methodology as Nikoleris Nikoleris et al. (2011)	Zurich Airport	
Khadilkar and Balakrishnan (2012)	Used FDR data withestimated taxi times,braking, turning, and accelerating	Global Airports	Taxi time was the most significant contributer to the pollutant emissions
Koudis et al. (2017)	Same methodology as Khadilkar Khadilkar and Balakrishnan (2012) to optimize aircraft take-off operations by using optimized thrust settings	London Heathrow	13% fuel reduction, 35% NOx reduction, 58% BC reduction

2.4. Literature on External Operational Towing and Electric Taxiing

Operational towing is when a conventional diesel, hybrid or electric vehicle tows an aircraft on the aerodrome surface prior to take-off or after landing in replacement of the conventional taxiing flight phase. Electric taxiing replaces conventional taxiing by using an electrically powered motor which draws energy from the aircraft's APU and is attached to a landing gear. Operational towing is an attractive option to replace taxiing as tow trucks can be adapted for a relatively low cost when compared to aircraft to operate on renewable energy sources. Operational towing, in literature also referred to as "dispatch towing", has been used at some airports in the US, however, for reasons such as landing gear fatigue life, infrastructure, and increase in traffic on the tarmac as further elaborated in Chapter 3 all being reasons that it has not yet been used widespread. APU driven wheel systems have been held back because of the APU modifications that the systems would need. Due to the high power required, a heavier system would need to be adapted into the plane, causing extra fuel during the en-route phase Guo et al. (2014a). Both operational towing and electric taxiing are subjects that have been explored in literature. There are main topics explored in literature; feasibility, emission reduction potential and scheduling or planning.

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[1] `https://www.nlr.org/areas-of-change/increasing-single-engine-taxi-operations-taxi-inboard-engines-4-engine`

Cost and Feasibility

In a 1980 study Division of Transportation Energy Conservation (1980), a cost benefit analysis of operational (extended) towing at 20 study airports was performed. Estimates were made of the benefit of the then-current towing equipment and the proposed towing equipment. The estimates of the benefits are based of (1) the fleet mix at the airport, (2) emission rates for aircraft, towing vehicles and APU systems and (3) aircraft engine shutdown times. In this study, to estimate the impact of taxiing using towing vehicles, an estimate of the average engine shutdown time was used. Engine shutdown time was defined as the time where the engine is not turned on, while the aircraft is being manoeuvred. The following assumptions in the model were made:

1. The incoming aircraft would taxi to a hook-up area using its own power and then continue to the gate by the means of the tow vehicle.
2. Outgoing aircraft would be towed to a disconnection area where its idle time and engine warm-up would be completed.

The average taxi time for each airport was computed by taking the average distances and taxi speeds at each airport, and idle times (time between taxiing to runway and waiting to take-off) are estimated. This study is very closely related to the scope of this thesis as it performs a cost benefit analysis at airports using a more zoomed out approach (ie. estimated times and distances), and also determines the number of tow vehicles necessary for operational towing. This study is not relevant for the present day as the data, airports and capacity from 1980 are no longer relevant, however, it can be seen as a relevant reference for the level of accuracy that could be used in the thesis.

In Du et al. (2016), a model is built to optimize cost and fleet composition of towing vehicles ignoring routing, however with the main goal of finding the cost optimal time to buy and sell tow trucks, Using a Column Generation Heuristic solution procedure which is explained later in section 4.6, the problem is decomposed into a master and sub-problem, and a feasible column is generated. The master problem in the paper determines the fleet size and mix of tow vehicles by selecting the schedules while minimizing cost. Only feasible schedules for each tow truck are considered, and columns are added iteratively. The sub-problem determines what period is the best time to make such a purchase. In the case of this thesis, as it will not be airport dependant, the second sub-problem of the paper is not relevant to the scope of this assignment . The main problem, however looking at optimizing the tractor fleet given and estimating the number of towing jobs possible is relevant to the thesis, albeit on a much lower level of accuracy.

Emissions

Further literature that have covered the emissions of operational taxiing more recently can also be found in Guo et al. (2014a) and Dellaert and Hulskotte (2017). Both papers used airport specific data from US airports to make conclusions about the potential HC, CO, and NO_x emissions savings and fuel burn savings. In Deonandan and Balakrishnan (2010), the performance of diesel, gasoline, and compressed natural gas (CNG) tugs were compared. Diesel tugs saw an increase in NO_x emissions, as expected from previous literature Schürmann et al. (2007), and a decrease in fuel burn, CO_2 equivalent, HC and CO. Gasoline tugs saw an increase in CO and Hc emissions, while having a decrease in the rest and CNG saw an increase in all emissions. In Guo et al. (2014b), using similar methodology, operational towing had emissions decreases for HC and CO and increase for NO_x as well. These papers, along with the papers on SET generally focus on a specific airport rather than a generalized global look at operational towing.

Scheduling or Planning

Many of the topics in the literature have very different scopes than this project with objectives such as minimizing delays, minimizing conflicts, or minimizing taxi length. As the scope of the thesis will focus on airport specific details, such optimizations are out of the scope of the assignment but a brief overview of the papers will follow.

Routing: In Soltani et al. (2020), multi-integer linear programming is used to route tow-trucks to aircraft, including a pick-up time, drop-off time and the set of taxiways to complete the taxing operations. One of the main contributions to literature is the collision avoidance by using routing constraints. Due to the scope of the thesis, routing constraints will likely not be included as an assumption that towing will replace taxiing for aircraft will be made, thus assuming towing and taxiing can be done simultaneously on the same taxi ways. Similarly, Du et al. (2014) also uses multi-integer programming this time with a column generation heuristic as solution procedure to solve a vehicle routing problem while minimizing travel time.
Capacity: Zaninotto et al. (2019), Sirigu et al. (2018) and Morris et al. (2016) focus on minimizing time related constraints on an airport specific level. These papers serve to solve the capacity problem. Thus, although they are also looking at the topic of towing and taxiing, their optimization problems have very different objectives compared to this assignment.

Of the literature, Soltani et al. (2020) is the closest literature to the scope of the thesis as it analyzes fuel consumption and the model offers aircraft to tow conventionally when a tow truck is not available. The main differences between this model and the scope of the thesis is that only CO_2 is analyzed. Furthermore, the paper focused on building a detailed model of one airport, rather than building a scheduling model that can analyze more airports in a more general way. Of the other papers, emissions were not part of their objectives, so they build models which are able to minimize delays, find shortest paths or minimize ATC workload. All of which are done on the scale of either airports or only in Europe.

Table 2.4: Overview of operational taxiing models in literature.

Literature	**Type**	**Topic**	**Objectives**	**% Towed**	**Case Study**	**Fleet**	**Total Problem Size (A/C)**
Division of Transportation Energy Conservation (1980)	Diesel Tow Trucks	Economic fleet planning	Minimize investment costs Maximize operational savings (Finding break even point)	Varied per airport	20 US Airports	Varied per airport	Varied per airport
Guo et al. (2014a)	TaxiBots (Hybrid)	Emission Comparison	Compare Emissions of Conventional Taxiing, SET, Operational Towing and Electric Taxiing	100% (in towing example)	10 US Airports	Varied per airport	Varied per airport
Deonandan and Balakrishnan (2010)	Diesel, CNG and Gasoline Tow Trucks	Emission Comparison	Compare Emissions of Conventional Taxiing, SET and Operational Towing	100% (in towing example)	10 US Airports	100% (in towing example)	Varied per airport
Soltani et al. (2020)	TaxiBots (Hybrid)	Route planning, Operational planning	Minimise fuel Minimise taxi delays	0%, 71%, 100%	YUL (Montreal)	12, 22	205
Zaninotto et al. (2019)	Autonomous Tow Trucks (Electric)	Route planning	Minimise taxi delays Minimise conflicts	100%	MLA (Malta)	Unlimited	36
Sirigu et al. (2018)	Autonomous Tow Trucks (Electric)	Route planning	Minimise path length Minimise computational time	100%	TRN (Torino)	-	-
Morris et al. (2016)	Autonomous Tow Trucks (Electric)	Route planning, Operational planning	Minimise travel time Minimise delays Maximise throughput	100%	-	30	30
Sirigu et al. (2016)	Autonomous Tow Trucks (Electric)	Operational Scheduling	Minimise time related cost Minimise energy cost	100%	TRN (Torino)	-	-
Okuniek and Beckmann (2017)	Taxibot (Hybrid) and Internal (Electric)	Operational Scheduling	Show correlation eTaxi and trajectorybased taxi operations	100%	-	-	-
Du et al. (2014)	Diesel Tow Trucks	Operational Scheduling	Minimise operational cost Minimise travel time	100%	Major European Airports	15	-
Du et al. (2016)	Diesel Tow Trucks	Economic Strategic Fleet Planning	Minimise acquisition cost Minimise # trucks	100%	Major European Airports	22	10, 25, 50, 75, 100

3

Practical Feasibility of Towing

Towing of aircraft from the gate to the runway and vice versa is not a new idea. The feasibility of operationally towing aircraft was already explored in the 1980's, however, as the environmental push of the industry was not yet as strong, although considerable savings were reported, there were no further operational changes made. The main focus of this chapter will be outlining the conclusions from previous field tests of towing as presented in Section 3.1; giving an overview of the safety and operational concerns laid out in literature presented in Section 3.2 and Section 3.3 respectively.

3.1. Previous Evaluations of Operational Taxiing

As mentioned before in section 2.3, operational taxiing has been tested in field tests before. In this section some of the main conclusions from the US Department of Energy Division of Transportation Energy Conservation (1980) and by Schiphol[1] will be outlined.

1980's Study

In September 1980, Peat Marwick Mitchell & Co performed an analysis on operational towing for the US Department of Energy to gain more insight into the feasibility and cost benefits of operational towing Division of Transportation Energy Conservation (1980). The study had 2 main objectives: 1) an assessment of constraints and feasibility of towing at 20 major airports and 2) Identifying best sites for a demonstration project. The analysis has a very similar scope to the thesis as it is a cost benefit analysis of operational towing, however the thesis should elaborate on the savings per flight and airport, in both fuel savings and money. This report could be a great use for verification and validation of the model.

The main conclusions outlined in the 1980's report in order to make operational towing operationally feasible are the following Division of Transportation Energy Conservation (1980):

1. There should be a designated location for connecting aircraft after landing so that subsequent incoming traffic is not affected.
2. There should be a designated disconnecting point for aircraft that are preparing for take-off. This point must accommodate several aircraft to allow for engine warm up, and allow for several orientations of the aircraft to allow for start-up in strong wind conditions.
3. There should be stations where stand-by tugs can wait for their next aircraft, charge, refuel after completing an operation. These stations should be positioned at the terminal area for tugs servicing departing aircraft, and near the exit taxiway for the tugs servicing incoming aircraft. There should be dedicated taxi or roadways for the tugs to travel between the service points and the attach/detachment points.
4. Crossing active runways during towing should be minimized.
5. Tug speeds should operate at speeds as close as possible to the current taxiing speeds of aircraft.
6. Towing should be avoided in extreme conditions such as crosswinds and extreme ice conditions.

Furthermore, the benefits and costs were explored in the report, however, these were based on values from the 1980's. In the report with rough construction costs included, it was found that the savings from operational towing are very closely related to the costs of jet fuel. The conclusion was

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[1] https://www.schiphol.nl/en/innovation/blog/sustainable-taxiing-taxibot-trial/

that at 18 of the 20 studied airports, with jet fuel costing $1.00 per gallon, a net savings would be achieved, and with a price of $1.50 per gallon, net savings would be achieved at all 20 airports.

Due to the changes in capacity, infrastructure of the study airports and inflation, this cannot be directly compared to costs in 2021.

Schiphol Taxibot

After a taxi bot trial at schiphol airport in March 2020, feasibility study of taxiing has been published in March 2021 pointing out 30 prerequisites needed in order to make towing implementation successful. The most important outlined by KLM are:

- **Operational:** The structural changes that need to be made to procedures such as checklists, communication protocols and training. Due to the new de-coupling points, this also poses new challenges for the air traffic controllers. It is expected that there will be more traffic due to the increase in the number of ground vehicles for such operations. These changes also mean that, pilots and ground staff would need to be re-trained. Although ground handling training is usually given by the airport, airlines would also have to audit the ground handling staff and training, which is another inherent cost of changing the operations.
- **Infrastructure:** Due to the changed uncoupling points when using towing, airport infrastructure will have to be upgraded to accommodate new roads. When using a combined system, this will also post considerable challenges.
- **Technical:** Looking at the TaxiBot in particular, the vehicle is currently too wide for at Schiphol, furthermore it is not currently compatible with all aircraft types.

3.2. Safety Concerns

When considering operational towing to replace taxiing, there are two main safety concerns that have been cited consistently in literature. The first is the structural integrity of the nose gear, as it will endure loads that it was not initially designed for, discussed in subsection 3.2.1. The second is who takes responsibility of controlling the aircraft during towing as discussed in subsection 3.2.2.

3.2.1. Nose Gear Failure

There are mixed opinions in literature if towing has an impact on the nose gear of the aircraft due to the additional stresses and strains. In the case of failure, as a primary component of an aircraft, this would have a serious impact on the safety. In Van Baaren (2019) using static equilibrium it was determined that towing would be feasible for the from landing gear without damage. However authors from Deonandan and Balakrishnan (2010); Guo et al. (2014b) state one of the operational problems for operational towing as the nose landing gear not being designed to withstand such loads on a regular basis citing a study by Virgin Atlantic and Boeing Transportation Research Board and National Academies of Sciences, Engineering, and Medicine (2012). Similarly, in the taxibot trials by KLM it was mentioned that due to loads on the nose landing gear that the use of conventional towing equipment would not be possible.[2] The KLM study does not provide any sources or data to back up this claim. In 1980, to understand structural effects on the nose landing gear caused by towing aircraft at take-off weight, the FAA contracted both Lockheed-California Company and Douglas Aircraft Company to conduct studies on the matter, as at the time they were the 2 large American aircraft manufacturers. In the studies, Lockheed studied the effects of towing on a L-1011 aircraft, and Douglas on the DC-9 aircraft.

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[2] `https://www.schiphol.nl/en/innovation/page/what-is-sustainable-taxiing-part-1/`

Lockheed Study

In the study conducted by Lockheed, Gamon (1980), 3 locations were used to test under operational and controlled conditions; Los Angeles International Airport, Dorval Airport, and a testing site in Palmdale California.

After analyzing and validating their analytical model, the tests were deemed to have a good correlation and the following conclusions were made:

1. The fatigue life of the L-1011 nose gear and its supporting structure would not be reduced due to the proposed towing below the design value.
2. The dynamic loads experienced during towing are extremely sensitive to the driver technique. Thus, a deviation from procedure could mean a significantly higher magnitude (3 times as large as typical dynamic load) which could reduce the fatigue life of the nose gear and the supporting structure.
3. Dynamic loading are sensitive to certain transmission characteristics of the towing vehicles, such as gear shifting.
4. There was no significant difference in the loading measured during snow and ice conditions. There were also no difficulties reported with controlling the tow vehicle in such conditions.
5. The significant dynamic loading loads which cause concern for fatigue damage are experienced mostly at the beginning and end of towing, and occasionally during gear shifts.

Douglas Study

In the Douglas study,Hoover (1980), the DC-9 aircraft's towing loads were observed at the Boston-Logan International Airport, measured under conditions that could be expected under normal service. The following conclusions were made:

1. The only significant loads experienced during maneuvers were at the start and stop portion
2. Loads due to slopes in intersections, steady-state towing, wet and rough surfaces were not significant
3. Components in the nose landing gear could be effected by towing aircraft, especially on aircraft with many flight hours already accumulated
4. Using periodic inspection, the safety of the components in the nose landing gear could be ensured, and fatigue damage could be detected. The removal and replacement of the parts would be necessary as the life limits are approached, which was estimated to be 40, 000 flights.
5. Loads could be reduced by engineering a shock absorbing device into the tow bars.

1980's study conclusions

In both tests, it was concluded that from an engineering safety standpoint, the static and dynamic loading would not degrade the safety of the nose landing gear and surrounding structure of either aircraft. For the L-1011 aircraft, all loads experienced were within the safe design load range, and the DC-9 had components that could be affected, however, with inspection carried out more frequently, and part replacement before part life limits, operations could also be carried out safely. It was also noted that high-speed towing would not be critical, however the braking and manoeuvring at these speeds could be critical Division of Transportation Energy Conservation (1980).

An additional concern that arose is the braking of the aircraft. Due to the tractor not having the capability to stop the aircraft, coordination with the pilots was necessary in order to come to a complete stop. The additional stopping and starting if in practice would need to be minimized and thus, additional training and certification of tractor drivers would be needed. This was also a concern mentioned in the KLM study.[3]

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[3] `https://www.schiphol.nl/en/innovation/page/what-is-sustainable-taxiing-part-1/`

Due to the age of the study, direct conclusions can still not be drawn for the applicability to current day aircraft safety. First of all, the aircraft and towing vehicles used for both studies are out of date and no longer used frequently in service. To give the study a present day perspective, the DC-9 aircraft is similar in size and take-off weight to the Embraer E195, a commonly used aircraft within Europe for short-haul flights by airlines such as KLM Cityhopper and Lufthansa Cityline. Their comparison is shown in Table 3.1 on page 40.[4]

Table 3.1: DC-9 vs. Embraer E195 specifications.

	McDonnell-Douglas DC-9-30	**Embraer E195**
MTOW	54,885 kgs	52,290 kgs
Length	36.37 m	38.65 m
Wing Span	28.47 m	28.72 m
Wing Area	93.00 m2	92.53 m2
Height	8.38 m	10.55 m
Number of Engines	2	2
Thrust per Engine	71 kN	89 kN
Total Thrust	142 kN	178 kN
Range	3,095 km	4,260 km
Cruise Speed	M0.77	M0.78
Capacity	104 passengers	100 passengers

Thus, the main factors with respect to the fatigue life of the nose landing gears are accelerations and deceleration, braking, damping of tow-bars, the frequency of inspection.

3.2.2. Responsibility

The second safety concern of towing aircraft is the responsibility Division of Transportation Energy Conservation (1980). This is also a concern mentioned by authors in the literature from Deonandan and Balakrishnan (2010); Ithnan et al. (2015); Guo et al. (2014b). Currently the procedure for push-back and taxiing is as follows. The commander of the aircraft (pilot, or person in charge if aircraft is not in service) gives a confirmation that the aircraft brakes have been released, giving the temporary responsibility to the push-back operator on the ramp. This means during push-back, the safe manoeuvring of the aircraft is the temporarily responsibility of the tug operator, who must follow the standard procedures. During push-back in an ATC controlled airport, the aircraft commander communicates with ATC. Once the aircraft is successfully pushed out of a gate or stand, the legal responsibility then transfers back to the flight crew during taxiing.

In the case of towing an aircraft, it is unclear who would carry the legal responsibility for safe manoeuvring. In the testing carried out in the 1980's, the technology available meant that the braking of the aircraft had to be done with the joint efforts of the pilots and the tug operator, and the ATC clearances and requests were relayed from the pilot to the tug operator. In the future, if towing were to be used operationally, one of the clearly defined divisions of responsibility below would be necessaryDivision of Transportation Energy Conservation (1980):[5]

1. **Tug operator has full control over the manoeuvres; pilot continues contact with ATC.**
   This option poses an issue due to the potential speed of relay, and misinterpretation of commands either from ATC to pilot or from pilot to tow operator.

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[4] `https://www.aviatorjoe.net/go/compare/DC-9-30/E195/`

[5] `https://www.schiphol.nl/en/innovation/blog/sustainable-taxiing-taxibot-trial/`

2. **Tug operator has full control over manoevers and contact with ATC.**
   This option is more realistic because the full responsibility for safe manoeuvring of the aircraft is placed on one person, however, as tug operators are often sub-contracted by the airlines and work for another company, this means contract negotiations, and retraining would be necessary. As the responsibility is much higher, and a high level of skill would be required for manoeuvring, airlines would likely prefer to have full control.

3. **Pilot has full control of manoeuvring and ATC contact during taxiing; tug driver has control of safely connecting, disconnecting and manoeuvring during push-back.**
   This option is the most similar to how operations are currently performed. A clear handover of control would be necessary, and strict division of responsibility. This option also requires proper towing equipment which allows the full control of the tow vehicle via the cockpit. This option with regard to legal responsibility makes the most sense, as the airlines can directly train their pilots.

3.3. Operational Concerns

Another issue when it comes to implementing towing is the infrastructural concerns. Ideally, if towing were to replace taxiing, it should not cause additional workload for the ATC, and it should also not cause congestion. The major implications discussed in the 1980 study were; 1)percentage of aircraft that could be operationally towed without incurring significant delay, 2)the need for towing operations to cross active runways, and 3)the need for constructing additional roadways and facilities. In addition to these in more recent literature the time concerns and additional infrastructure have also been discussed Deonandan and Balakrishnan (2010); Guo et al. (2014b); Transportation Research Board and National Academies of Sciences, Engineering, and Medicine (2012).

A major concern for Schiphol moving forward with sustainable taxiing is the management of ground traffic. During the tests, it became clear that due to capacity issues in current infrastructure and radio frequencies, a new planning, routing and guidance system to support ground controllers would be necessary to ensure safe operations as the number of vehicles increase. Thus, an Advanced Surface Movement Guidance and Control Systems (A-SMGCS), or a similar equivalent would become a pre-requisite for major airports is towing were to be introduced. The A-SMGCS system being developed as part of Single European Sky ATM Research (SESAR) plans to operate as navigation system for a pilot, offering the best taxiing route based on congestion, roadworks and other variables.

Currently, a question for the A-SMGCS, similarly to the taxiing, is if the system will be controlled on-board or on-ground (for taxiing the question is who will have the control of the towing vehicle). In the development of the A-SMGCS systems, there are three main possibilities for the technology de l'aviation civile internationale (2004);

- **Moving Map:** Built in aircraft navigation system integrated into the screens of the cockpit. When looking at an airport level, this option improves operations if all airlines have the technology installed in their aircraft. Since there is no standard for this on-board technology, airlines would likely not be willing to invest in installing hardware and downloading software for an airport that is not a company hub. Furthermore, since each tail number does not always service the same airports, it would be a larger investment and even less likely that airlines would ensure that each aircraft is equipped with information for all airports a plane may service. Since the investment for the airlines is so high, and the increase performance highly reliant on the percentage of planes with the technology, this is an unlikely option.
- **Follow the Greens:** Follow the Greens is a ground based system that involves green lights on taxiways guiding pilots to the runway or to their gate. The system requires lights to be installed, thus requiring a large investment to the airport infrastructure, but once installed, it

could be used by all airlines flying to an airport, thus increasing the airport efficiency. A major drawback to the system is the lead-time it would take to install such a system, as it requires major changes to taxi-ways that are already heavily trafficked.

- **Autonomous Airside Operations:** The last possibility for the A-SMGCS system would be to expand the number of autonomous vehicles servicing airports. This investment would not need to have as much lead time, as it does not require direct construction and alterations to existing taxiways.

Linking this back to sustainable taxiing, it is clear that the implementation of sustainable taxiing relies on lessening the workload of air traffic controllers, on the other hand, technology to lessen the workload of air traffic controllers could be directly implemented into the taxiing solution via autonomous towing vehicles. Given the timelines of innovating both systems, and the goals set by the EU for CO_2 reduction, both operational towing and ground movement technology should be able harmoniously be implemented into future ground operations.

4

Modelling Techniques

In this section several modelling techniques will be explored to explore their applicability to the operational towing topic. Firstly, an overview of the goal of the model is outlined in Section 4.1. Then, several techniques have been collected from papers on topics that have been directly related to operational and electric towing these can be found in Section 4.2, Section 4.3, Section 4.4 and Section 4.6.

4.1. Model Objective

As a beginning step in evaluating the modelling techniques, it is important to set a basis of what is expected of the model. This will be used as a foundation, however should not be seen as requirements, as the scope of the thesis may still change, thus to not limit the research. The objective of the model is to evaluate the economic feasibility of operational towing with a high-level estimate. This means that it should not rely on very accurate input data from a specific airport, rather it should be able to to give a high-level estimate of emissions impact using estimated data which can be refined. When explained in relation to aircraft, it means the model should be able to be precise within a few minutes. This means that operational costs can be simplified to an estimated cost per trip, and should not go in depth with penalties such as delay minutes. Given a timetable, average taxiing times and/or distances, and a given fleet mixture which can be adjusted to better represent a specific airport, the goal of the thesis is to be able to:

- Analyze the operational impact of towing
- Analyze the benefit of towing per flight and per airport
- Analyze the benefit per tow truck added
- Make an estimate on the global impact
- Assess potential costs and evaluate the saved emissions per unit costs
- Use the normal and single engine taxi as a baseline

In order to make more general conclusions, the model should use data from high, medium and low demand operations, it should be able to explore be applied to different input data to explore fleets mixes and taxi times of different airports. In the case that the model is programmed to choose the fleet mix of tow trucks, the model should be made to take into account all demands and seasonality for each market and make the most optimal choice for all situations.

Question Formulation

There are two questions that could be posed to solve this problem each leading to a different modelling approach;

1. Given a target fuel reduction, how many tow trucks are needed to service the schedule?
2. With a given number of tow trucks, what is the maximum fuel reduction possible using operational towing?

Both of these questions could be modelled and then evaluated using similar KPI's and comparisons to make concusions about operational towing. An overview of the two approaches and what they would mean for a model is shown in Table 4.1.

In the first approach, an optimization model would find the most optimal aircraft to tow within a schedule to minimize the cost of investment an airport would need to make to reach a certain given

Table 4.1: Overview of the approaches to the problem

	Question	**Input**	**Direct Output (Decision Variable)**	**Primary Objectives**
1)	If I have a fixed fuel reduction target how many tow vehicles are needed to achieve this?	Timetable Average Taxi Distance Number of flights Target fuel Reduction	Number of tow vehicles	Minimize investment cost
2)	If I have a fixed amount of tow vehicles, what is the maximum fuel reduction possible?	Timetable Average Taxi Distance Number of Flights Number of Tow Vehicles	Ratio of aircraft service	Maximize fuel reduction

fuel reduction target. As the emissions can be directly related to fuel, each flight can be seen as having a fixed fuel depending on the aircraft type and average taxi distance. Given a timetable with departure times and aircraft type, the model could find the best choice of aircraft to be towed which allow the fuel goal to be met while minimizing costs. In this formulation, the primary objective would be minimizing the cost of investment. When applying the first approach to the real world, this would be useful for airports to know how many of which type of tow vehicle they need in order to meet CO_2 reduction laws.

When looking at the second formulation of the problem, the objective is to maximize the fuel reduction possible with the given resources. Thus, given a certain number of tow vehicles which are capable of towing certain aircraft, how can the tow trucks be assigned to minimize the fuel production. Again, since each aircraft can be associated with a fixed fuel "cost" per trip, the model could assign the tow trucks to the most beneficial aircraft in order to maximize the benefits. This could be seen as a type of fleet assignment problem.

The first model would be necessary to set the baseline for each airport, as the number of tow trucks that are necessary for operations at airports is unknown. Then, the second approach could be used to evaluate the fuel reduction per extra tow truck added to the system. Then, using KPI's conclusions about operational towing could be made.

4.2. Vehicle Fleet Composition

When solving for the number of vehicles necessary in a fleet in optimization problems, a Fleet Sizing Problem (FSP), or Fleet Composition Problem (FCP) are commonly used. FSP is used for determining the number of vehicles necessary for a homogeneous fleet. FCP is used for determining the number of, and type of vehicles necessary and mix simultaneously for a heterogeneous set of vehicles Etezadi and Beasley (1983). Both types of problems are focused on matching supply and demand in a transportation problem. The main goal of such a problem is to find the number of vehicles in a fleet which can satisfy demand while avoiding high fixed costs associated with an underutilized fleet. VFC is often combined with a vehicle routing problem. An in depth literature review on this can be found in Hoff et al. (2010).

Kirby, Kirby (1959), and Wyatt Wyatt (1961) are some of the first authors who discuss the Fleet Sizing Problem (FSP) used for a homogeneous fleet. Kirby solves for the number of railway carriages using fixed costs, and Wyatt solves for barges, introducing a variable cost.

Literature that use Vehicle Fleet Composition (VFC) with a constant period (no change over time) are Gould (1969), Loxton et al. (2012), and Redmer et al. (2012) applied to road transport or general vehicles. In Gould (1969), seasonality is also addressed by allowing hire vehicles to be used at a cost. This could be applied to the towing problem, as ideally, the fleet would be big enough to see fuel savings, but the option for an aircraft to tow itself at a cost should also be present.

VFC with multiple periods are addressed in New (1975), Schick and Stroup (1981), Etezadi and Beasley (1983), Couillard and Martel (1990), Wu et al. (2005) and Burt et al. (2011) applied to both aircraft fleets and truck fleets. The models in this literature mainly focus on the timing of buying and selling of vehicles in a fleet in order to maximize profits.

When comparing the objectives and conclusions of literature covering the vehicle composition problem, it seems that similar formulation could be used to formulate the baseline of the fleet (to estimate the number of tow trucks at a given airport, normally used for push-back), however as the main objective of the thesis should still be optimizing for fuel use, thus performing a sensitivity analysis on the model by varying the fleet size would likely be a better solution to suit the objective.

4.3. Vehicle Scheduling Models

A vehicle scheduling model is a model used to allocate resources in an efficient way, commonly used for the routing, scheduling and decision support systems in transportation problems Ibarra-Rojas et al. (2015). Given the that a schedule has fixed departure and arrival times, fixed travelling times, and fixed arrival and departure points, a vehicle scheduling program (VSP) will assign vehicles to trips such that each trip is covered once, the sequence of trips is feasible, and the costs are minimized. In a VSP, costs can be divided into fixed and operational costs. Fixed costs are investment costs such as the cost of a new vehicle, infrastructure. An operational costs can represent anything that is not fixed, such as fuel or vehicle depreciation. In practical applications of a VSP model, the primary goal is usually the cost minimization of the fixed costs, and the secondary objective is minimizing operational costs Bunte and Kliewer (2009).

There are two complexities of the VSP; single-depot and multi-depot case. The single-depot problem has one depot where all vehicles depart from, and in the multi-depot case, vehicles can begin from multiple depots. There are several sub types of VSP models with variations have slightly different modelling techniques to make them applicable to certain situations. For a single depot case these are the minimal decomposition model, assignment model, and transportation model. For the multi depot cases there are single commodity models, multi commodity models and set partitioning models. Since the scope of the thesis will be to build a model for outgoing traffic, the more complex multi-depot formulation of the VSP will likely not need to be used, however a thorough overview of all types of these models can be found in Bunte and Kliewer (2009). The assignment model and transportation model are both special types of network flow models. Other types of network flow models that are not relevant to this thesis are the shortest path problem, and transshipment problem Bisschop (2006).

4.3.1. Overview of Single Depot Case Models

This subsection covers models that fall under the Single Depot Case for the Vehicle Scheduling Problem (SD-VSP). The SD-VSP can be formulated as a problem with known polynomial time algorithms. This makes it relatively "easy" to solve. The single depot case algorithms explored in this paper are the minimal decomposition model, assignment model, transportation model and the network flow model. A basic overview for quick comparison of the single depot models can be found in Table 4.2.

Minimal Decomposition Model

The minimal decomposition model is based on the Dilworth Theorem Bunte and Kliewer (2010). This theorem uses chains and anti-chains. Given a partially ordered set, P, a chain, C, is a subset of P such that any two elements are comparable. To understand this, a and b are comparable if either a ≤ b or b ≤ a, or both. An anti-chain, A, is a subset of P such that no two of its points are comparable Jukna (2011).

Given a finite partially ordered set (P,≤) where height(P) equals the maximum number of chains, and width(P) equals the maximum number of anti-chains; the Dilworth Theorem states that the number of anti-chains, width(P), is equal to the minimum size of the chain partition Dilworth

Table 4.2: Overview of single depot case models.

Model	Solves	Remarks	Applicable?
Minimum Decomposition Model	Minimum fleet size	Operational costs not included No upper bound for fleet size	Yes, for estimation of number of tow-trucks needed per airport to service push-back in conventional and SET (as baseline)
Assignment Model	Minimum cost and fleet size to fully cover a schedule	Operational costs are considered No upper bound for fleet size Exorbitant computational effort unless simplified	Yes, can be used for the estimation of total costs necessary to tow all aircraft.
Transportation Model	Minimum cost of operations	Operational costs are considered Bounded fleet size No upper bound for fleet size Exorbitant computational effort unless simplified	Yes, can be used for modelling mixed operations (towing and taxiing)

(1950); Jukna (2011). This means that the width of the sub-set is the minimum number of chains needed. When applied to the Vehicle Scheduling Problem, the number of incomparable trips in the timetable, T, is equal to the minimum number of vehicles needed to service the timetable. The following model is applied:
Maximize:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}X_{ij} \tag{4.1}$$

subject to:

$$\sum_{j} X_{ij} \leqslant 1, \quad \text{all } i = 1,2,\dots,n, \tag{4.2}$$

$$\sum_{i} X_{ij} \leqslant 1, \quad \text{all } j = 1,2,\dots,n, \tag{4.3}$$

$$X_{ij} \geqslant 0, \tag{4.4}$$

where:

$$\text{with } c_{ij} = 1 \text{ if } i\beta j \text{ otherwise } c_{ij} = -\infty \tag{4.5}$$

In Saha (1970), this model was used to schedule up to 319 trips. The paper mentions the issues of minimizing bus requirements while also minimizing crew requirements as it is difficult to prove a solution was optimal while also applying further constraints for crew requirements, such as rest periods, duration of active duty and layovers.

This model would use time-based constraints to find the minimum fleet size of tow vehicles necessary to completely service a timetable. The model, however does not take into account operational costs, so it would not choose the most cost-effective options, rather it would only find the longest sequence of aircraft a single tow vehicle could service. This model could, for example, be used by an airport to estimate the number of tow vehicles needed to fully service the airport, and it could be used to create schedule for each tow vehicle. This model would be sensitive to delays, and since there is no upper bound, would not be realistic to apply to aerospace ground operations applications for the sake of optimization. It could however, be a good solution for setting the baseline of the thesis for estimating the number of tow trucks at an airport that need to be used for push-backs.

Assignment Model

The assignment model is a special type of network flow model where tasks are assigned to assignee's. The assignee's need not be human; they can also be, for example, machines, vehicles or a production plant which are then assigned to a specific task. The assignment problem and transportation problem alike often require a very large number of constraints and variables when applied, thus costing exorbitant computational effort. Due to the structure of the models, most a_{ij} coefficients are equal to zero, thus meaning streamlined algorithms can be made to save computational effort Hillier and Lieberman (2014). The following are the assumptions that must be met for an application to be formulated as an assignment problem:

1. The number of assignees and the number of tasks are the same.
2. Each assignee is to be assigned to exactly one task.
3. Each task is to be performed by exactly one assignee.
4. There is a cost c_{ij} associated with assignee i (i 1, 2, . . . , n) performing task j (j 1, 2, . . . , n).
5. The objective is to determine how all n assignments should be made to minimize the total cost.

For the thesis, the first three assumptions are already fairly restrictive. If we consider the task to be towing a specific aircraft from point a to b, and the assignee as the tow-truck, it would be unfeasible to assume that there are an equal number of tow-trucks as aircraft that need to be towed, especially in the case that both incoming and outgoing aircraft are considered in the model. This, however, could be overcome by assigning dummy assignee's or dummy tasks.

In an assignment model, each trip is represented by an arrival and departure node connected as a bipartite structure. As opposed to the decomposition model, each arc in an assignment model has associated operational costs. In the assignment model the following symbols are used:

- i': arrival node
- i'': departure node
- a_{ij}: arc between i and j
- c_{ij}: Operational cost of arc i j
- c_v: fixed cost of a vehicle

In this model, for each a_{ij} combination where i and j are not compatible, ontop of the operational cost of travelling the arc, an additional fixed cost of a vehicle is added, as an extra vehicle would be necessary to cover the trips. The following model is applied which ensures that all supply and demand is equal to exactly 1. This means that for every i^{th} resource, there is only

Minimize:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ij} \tag{4.6}$$

subject to:

$$\sum_{j} x_{ij} = 1 \quad \forall i \in N' \tag{4.7}$$

$$\sum_{i} x_{ij} = 1 \quad \forall j \in N'' \tag{4.8}$$

$$x_{ij} \geq 0 \tag{4.9}$$

$$\tag{4.10}$$

This model could be useful to use as a part of the model as it allows for operational costs to be included. It could, however, pose issues as a maximum number of vehicles cannot be imposed with this model, which could be an important aspect when analyzing the effectiveness of a hybrid solution with only a percentage of aircraft being towed.

Transportation Model

The transportation model, like the assignment model is also a special type of network flow model. It is also known as the Quasi-Assignment Model is a linear programming model published in Gavish and Shlifer (1979). The transportation model uses "the savings method" from Clarke and Wright Clarke and Wright (1964) and Gaksell Gaskell (1967) to break down an objective function into a series of assignment problems. By using a cost matrix, with entries that are a function of the constraints, the solution gives an optimal solution. The computational time can be excessive, however, the problem can be formulated in a way that the branch and bound procedure can be eliminated making it very efficient Gavish and Schweitzer (1974); Gavish et al. (1978). It can be applied to problems related to efficient transportation routes to minimize shipping cost.

Generally, the transportation problem is formulated in terms of connecting points of supply and points of demand in a way to minimize cost, and it can be applied to numerous applications completely unrelated to transportation when formulated correctly. In the transportation model a requirements assumption needs to hold true such that the number of units being supplied by a source is equal to the demand for units received at sources, thus a total balance between supply and demand is necessary. In the case that this is not true, a dummy destination or dummy source can be added to reformulate the problem to fit the model type. Additionally, a penalty cost can be used if a trip is not served at all. In the transportation problem, depot arcs are also included with half of the associated vehicle costs assigned the arc back to the depot. The transportation model finds the path of least resistance with an origin of supply, destination, and unit of cost for shipping Bunte and Kliewer (2009). In a normal formulation, the transportation problem finds the minimal cost of connecting factories to warehouses, each of which have a certain cost and a limited supply. Through its iterations the model uses an intuitive approach using cost first. The model then matches supply and demand by assigning the lowest costs first and then assigning more expensive combinations.

This could be applied to the towing application. If each type of tow vehicle is modelled as a factory, each aircraft is modelled as a warehouse, and the fuel used to taxi or tow is the transport cost; a transportation model could assign each type of tow vehicle to the most cost efficient choices for the model. By extending the model, we could ensure that aircraft that are not compatible with a certain towing method will not be chosen.

In literature, Han et al. (2020) uses a similar technique for optimizing ferrying vehicles. This type of optimisation is very relevant to the scope of the thesis.

Additions to Vehicle Scheduling Models

Several extensions can be added to VSP by adding extra constrains to the model. Examples of all the extensions have been presented in detail in Bunte and Kliewer (2009). Additions that can be added include but are not limited to:

- Multiple vehicle types and vehicle type groups
- Time windows
    - Discrete time windows
    - Continuous time windows
- Route Constraints

When vehicle type groups are introduced, it only allows certain vehicles to service certain trips. This is a handy extension for aircraft towing, as not all aircraft can be serviced by the same type of towing equipment. Time windows allow for flexibility in the scheduling. Route constrains are things like fuel restrictions or maintenance intervals. All of these are useful to extend the models to make them more realistic for aerospace applications.

4.4. Multi-Objective Linear Programming

Multi-objective linear programming is used to find efficient and non-dominated solutions for problems with several objectives Luc (2016). This for example can be used when a manager not only wants to minimize costs, but also minimize the utilization of scarce resources. The topic of emissions in this thesis can be modelled as a multi-objective linear problem, as the goal is to find a balance between costs (fixed and operational) and emissions. Several papers have been published using multi-objective linear programming for environmental and cost studies including up to 9 objective functions.

For example, in Kok and van Oostvoorn (1986), a model with 5 objective functions was created applying the pairwise comparisons method as a tool for energy planning.

- minimization of total costs (DfI, 10^9)
- minimization of SO_2 emissions (Kton); upperbound: 350 K ton
- minimization of NO_x emissions (K ton); upperbound: 400 K ton
- minimization of Nuclear Energy (MW)
- maximization of Renewable Energy (FJ)

Another example of this in relevant literature can be found in Padrón and Guimarans (2019), where they apply multi-objective linear programming for scheduling ground handling vehicles, however this deals with the problem of ground handling in much more detail than needed in this thesis project. In Zhao et al. (2019), the literature uses multi-objective lear programming to solve 2 objectives; 1) minimize number of ferry vehicles and 2) most optimized usage of said vehicles. This is an interesting approach which could be adopted to the thesis, however, as it is not necessary to optimize the number of tow vehicles needed, rather to explore the benefits of an added towing vehicle, a multi-objective linear programming model will likely not be necessary for the thesis. Thus, due to the nature of the problem in the thesis, and the level of detail necessary in the analysis of each airport, a multi-objective program will likely not be necessary.

4.5. Multi Agent Path Finding

Multi-Agent Path Finding (MAPF) is a multi-agent planning problem in which paths are planned for agents where key constraint is to ensure that agents do not collide with one another. The benefit of multi-agent systems is that agents are autonomous and they are able to interact and communicate with one-another in order to solve problems that would be beyond the capability of one agent. Advantages of multi-agent systems are that they are robust, and fault tolerant, they are scalable and concurrent, and they are flexible and adaptable Stern et al. (2019).

Some features of modelling the system with a multi-agent path finding program is that it provides the possibility to analyze emergent behaviour, they perform well in uncertain environments, and in comparison to traditional modelling techniques they focus on behaviours and dynamics. Multi-agent systems allow for a more in depth analysis of how agents interact with their environment, and other agents. Some advantages are that they have high computational speed, they are easily scalable, and inherently flexible, and reusable. The solutions however can be sub-optimal, model development is very time-consuming.

This type of path-finding multi-agent system therefore is not suitable for this thesis assignment, as the main goal is looking for optimized solutions for a cost-benefit analysis. A MAPF program could be useful in future feasibility research into towing where the scope of the study is to understand the dynamic feasibility of operational towing at an airport level. For example, when a representative environment of an airport layout is modelled, a MAPF model would be able to show emergent behaviours with visualizations and KPIs. Conclusions about infrastructure, bottle-necks, or delays caused by towing could be made. Using batch runs, a deeper understanding about how variables such as number of tow vehicles, and number of flights of certain aircraft types effect the behaviour can also be obtained. As KPIs can be made for the system, specific values of fuel saved can also be explored, but again, the program would be designed to ensure dynamic feasibility and not cost optimization. In conclusion, due to the broader goal of this thesis research and due to the sub-optimal solution that a MAPF program would provide, this type of model will not be suitable for this thesis.

4.6. Other Types of Models in Relevant Literature

In this section, a brief overview of other models used in literature will be explored. Many do not fall under the scope of the project, however are interesting to mention.

Hopfield Neural Network

In Sirigu et al. (2018), the hopfield neural network (HNN) is used for solving a routing problem in shortest path research for autonomous taxi operations. The hopfield neural network is a type of recursive neural network which are characterized by a feedback signal. The feedback signal allows the output value to be used as an input, to obtain a more robust and faster response Ali and Kamoun (1993). In Hopfield and Tank (1985) the HNN algorithm was also applied to the travelling salesman problem for routing. Due to the amount of nodes necessary for a HNN algorithm, the computational time is significant.

Modified Hopfield Neural Network

The modified hopfield neural network (mHNN) was also compared in Sirigu et al. (2018) for solving a routing problem for autonomous taxi operations. When compared, the mHNN has a slower computational time, and delivered non-optimal solutions to the path problem. Other examples that were explored in the paper were Dijkstra's algorithm and A algorithm, both for solving the shortest path. As this is not necessary in the thesis, they will not be elaborated further.

Column Generation

Set Covering/Partitioning with Column Generation is a linear programming technique used for large linear programming models. It is commonly used for solving problems of routing and scheduling. An in depth overview of column generation in integer programming can be found in Wilhelm (2001) where literature is presented which uses the column generation technique for airline crew scheduling, vehicle routing and vehicle scheduling. A paper with relevant a scheduling algorithm with column generation applied is Ribeiro and Soumis (1994). Depending on the size of the problem, it is likely that building a model that can use column generation could be useful for the thesis. In papers on towing and electric taxiing, both Du et al. (2014) and Du et al. (2016) used this technique.

5

Research Proposal

Before the research question is formulated, a quick summary of the questions formed for the basis of this literature study will be answered. Then, the thesis research question is formulated.

5.1. Discussion on Literature Findings

The questions presented in the introduction were split into 3 categories which helped form the structure of this report. The following was found during the literature study.

- **Aircraft Emissions:**
    - **What is radiative forcing? What aviation related emissions cause radiative forcing?**
      Radiative forcing is a measure used to represent the change in energy flux in the atmosphere. Aviation main aviation related emissions that contribute to this are SO_4^{2-}, HC, soot, H_2O , NO_x and CO_2 .
    - **What aviation related emissions are relevant to ground operations?**
      The most relevant emissions in literature related to ground operations are HC, CO (CO_2) and NO_x . NO and NO_2 values are dominated by service equipment and CO and CO_2 levels are dominated by aircraft movements.
    - **How can aircraft ground emissions be modelled?**
      Several modelling techniques are commonly used for modelling ground emissions. These models rely on the use of the Engine Emission Databank (EEDB) from the International Civil Aviation Organisation (ICAO) for fuel consumption and pollutant emissions and a schedule.
    - **What is the composition of aviation related emissions (geographically, fleet, airports etc.)**
      Several airports and aircraft types have been identified as the largest contributors to aviation related CO_2 emissions. Furthermore, as commercial passenger air traffic contributes to 75% of emissions, this should be the main focus of the thesis.
- **Ground Operations:**
    - **What is the current state of ground operations? Are there any emissions reduction measures already used in operations?**
      The most commonly used mitigation technique is single-engine operations. This has already been adapted by several airlines. Furthermore, operational towing has been implemented at several airports in the United States, however due to the low speeds and other mentioned concerns, it has not been widely adapted thus far.
    - **What is the new technology in taxiing and/or towing?**
      There is a lot of new and upcoming technology regarding e-taxiing and electric operational towing. An overview is provided in Section 2.2.
    - **What are the main topics in literature regarding taxiing and towing?**
      The main topics covered in literature on electic taxiing or operational towing can be divided into 3 main categories; cost and feasibility, emissions and scheduling and planning. This thesis will make conclusions about cost and emissions by using a scheduling or planning model. Of the literature, only one study has been done with a similar objective, however the study was done in the 1980's meaning the technology and demand have evolved, leaving the conclusions in the paper not relevant to 2021.

  - **What modelling techniques do relevant literature use?**
    Many types of models were used. The papers mainly focused on minimizing conflicts, finding the shortest path or solving problems at a very detailed level. Due to the scope of the thesis, many of these models are thus not applicable to the thesis.

- **Towing Feasibility:**
  - **Is towing feasible? If so, what steps need to be done to make it operationally viable. If not, what are the concerns?**
    In literature and after field testing several concerns have been raised about operational towing. These fall into 2 main categories; safety concerns, operational concerns. It is concluded in all literature that infrastructure, responsibility and technical concerns must be addressed before operational taxiing can be widely adapted.

It has been concluded during the literature review that there is a significant gap in literature about the cost to benefit of operational towing. While significant amount of research has been done into optimizing towing and taxiing operations (path planning), and also into the emissions effects of alternative taxiing strategies, an estimate of the emissions savings per unit of cost has not been made in literature. For that reason, the goal of this thesis will be to develop a better understanding of the relationship between the costs of adding a tow truck relative to the emissions benefits. This implies understanding how the relationship changes as more percentage of an airport's traffic is towed, and understanding the point at which the amount of fuel saved does not outweigh the cost of investing in additional vehicles.

In order to do this analysis, a baseline model using conventional push-back and taxiing should be established in order to estimate a baseline number of towing vehicles required at an airport for conventional operations. Then using a fictional, but representative outbound schedule for high and low season operations at several major airports, an optimization program should schedule towing vehicles to tow outbound flights in order to minimize the total fuel used during taxiing given the number of extra fuel trucks available. The estimated emissions benefits per added tow truck can then be compared to develop an understanding of the relationship between cost of an additional tow vehicle with the potential emissions savings. This process can be repeated for several airports with different types of typical aircraft traffic and schedules in order to make an estimate of the global emissions impact of operational towing and the cost-benefit of its implementation.

5.2. Research Question:

With the literature study questions answered, and a more clear oveview of the background and scope of the thesis, the following research question for the thesis can be formed:

Research Question:
What are the estimated emissions savings per unit of cost of implementing operational towing for outbound commercial passenger air traffic at major global airports.

Supporting this main question, the following sub questions can be identified:

Research Sub-Questions:
Emissions:

- What is the average emissions impact of operational towing per flight?
- What is the average emissions impact of operational towing per airport?
- What are the emissions impacts per tow truck added?

- What are the estimated emissions savings of conventional towing when compared to conventional taxiing and single engine taxiing at major airports?
- What is the estimated maximum global impact of conventional towing?

Costs:

- What are the estimated fixed and operational costs of implementing operational towing at major airports?
- How do scheduling constraints impact the emissions savings per unit of cost?

5.3. Research Planning

In order to answer this research question and sub-questions the following work-packages must be done. These can be seen as intermediate goals to split the total thesis problem into more distinct parts. By completing these work-packages, the research should be able to progress towards answering the main research question:

1. Develop a basic model which can estimate a baseline number of tow vehicles needed to service conventional and SET operations at each airport.
2. Develop a basic model whose objective is to assign the set amount of resources (tow vehicles) to outgoing aircraft in order to minimize the amount of total fuel used in the operations.
3. Choose a sub-set of airports of different traffic types and build a representative flight schedule of both high and low season operations at each airport.
4. Run a sensitivity analysis, and see how the addition of extra constraints such as aircraft/tow vehicle compatibility, more clearly defined gate/runway combinations, and types of tow vehicles change the model outputs.
5. Analyze the relationship between emissions and additional towing vehicles per airport and make conclusions based on model KPI's about the associated costs and environmental benefits.

Table 5.1: Distribution of time per work-package.

Work-package	**Allocated Time**		
	Hours	**Days**	**Weeks**
1	120	15	3
2	200	25	5
3	120	15	3
4	280	35	7
5	280	35	7
Misc	280	35	7
Total:	1280	160	32

A more realistic time-frames of the thesis project can be seen in Table 5.1. This is based on a total of 42 ECTS credits. Given 1 ECTS credit represents about 30 hours of study, this has been rounded to 160 8-hour long days or roughly 32 weeks. Given other commitments such as my TA job, and vacations etc. a misc category has also been included into the timeline.

5.3.1. Work-Package 1: Building the Baseline Model

In this work-package the basic model will be created. This model will be used to estimate a baseline of the number of towing vehicles currently needed per airport to cover flight schedules. As this will be the first coding aspect of the thesis, it can be assumed that it may take slightly longer to build due to the learning curve. The main aspects will be:

- Formulating the model:
  - Defining model assumptions
  - Defining variables and parameters
  - Defining model objective function
  - Defining model constraints
  - Defining KPI's and necessary model outputs
- Building the model:
  - Familiarization with python and IBM for optimization problems
  - Implementing the model into python + IBM
  - Verification using unit testing and simple inputs

It is assumed that the building of this model will take roughly 3 weeks or 120 hours. This takes into account the formulation of the model and implementation and time for familiarity with the software. It is assumed that formal verification and validation and a sensitivity analysis will be performed later in the thesis.

Baseline Model:
Objective: Determine the minimum amount of tow trucks necessary to serve a schedule.
Inputs: Schedule including aircraft type.
Output: Minimum number of vehicles needed to service each aircraft in the schedule.
Model Type: This will likely be a fleet decomposition model as it should determine the minimum number of vehicles to fully cover a schedule if tow vehicles are only needed for pushback. The costs are not important in this model, as the output of this model will simply be used as a baseline of number of tow vehicles per airport.
Why? The output of this model will be used as an estimation of the number of tow trucks currently available at each airport to service conventional towing.
Allocated Time: 3 weeks, 120 hours

5.3.2. Work-Package 2: Building the Basic Version of the Towing Model

Similarly to the baseline model, the towing model will go through the same steps. It is assumed that the formulation of this model will take longer as the constraints heavily rely on how simplified the model will be. The model will likely go through iterations later in the thesis, but the goal in this step is to build a very simple version of the model which can later be refined. The following steps will be done in this work-package:

- Formulating the model:
  - Defining model assumptions
  - Defining variables and parameters
  - Defining model objective function
  - Defining model constraints

  - Defining KPI's and necessary model outputs

- Building the model:
  - Implementing the model into python + IBM
  - Verification using unit testing and by using a simplified input model (that can be solved by hand)

The model should take longer than the first work-package because it will deal with a more complex problem. For this week 5 weeks or 200 hours is set aside for this part. This takes into account extra time needed for taking assumptions into account in the constraints to build a simplified but realistic model. The model should be built and verified with unit testing and by inputting simple data. A more in depth plan for both verification and validation will be explored in this stage of the thesis as well. Once a simple model is running and verified, the next work-package can begin.

Towing Model:
Objective: Determine given the resources and operational constraints the most optimized schedule for operational towing which minimizes the total fuel of operations.
Inputs: Schedule including aircraft type, number of additional tow trucks, average tow times.
Output: Schedule with mixed towing and taxiing, total fuel used, associated costs etc.
Model Type: This will likely be formulated as a transportation model vehicle scheduling problem as it deals with a bounded vehicle fleet size, where operational and fixed costs are considered. Furthermore, the computation time can be limited by modelling the program efficiently for the taxiing aircraft.
Why? Using a model that allows for different vehicles allows for a batch run to be performed to understand the influence that the number of tow vehicles has on the emissions, and thus explore the environmental effects per unit of cost.
Allocated Time: 5 weeks, 200 hours

5.3.3. Work-Package 3: Schedule Generation

In this work-package the airports that will be used in the case-study will be chosen and representative schedules for an average day in their low and high season will be generated. During this time it will be chosen how many airports to consider, and how many days to consider in the thesis. It is expected that the maximum number of airports that will be considered is around 10, and a day schedule that represents low and high seasonality of different times of the year will be considered. This will likely be a schedule of maximum 4 days of operations. The exact number of airports and days included in the schedule will be more clear after the first and second work-package are completed.

- Choose Airports
- Research data on aircraft types, seasonality and average towing times.
- Identify which assumptions can be made for the schedule to fit in the scope of the project.
- Create a schedule which is representative of real life operations.
- Validate the fictional schedule with data available to ensure it is close enough to the real world operations (within the scope of the thesis)

It is assumed that for each airport it will take about 2 days or 24 hours to build a schedule. This will take into account peak times of day for the specific airport, and typical fleet that the airport serves, and average taxi times or distances. Currently, as I have not decided how many airports I will analyze, I am not sure if this will be done using python or a hand-made schedule. For now, 15 days or 120 hours will be allocated to the schedule planning to ensure the level of detail necessary for the thesis is obtained.

Schedule Generation:
Objective: Build a realistic schedule for the case-study airports to represent their traffic and seasonality.
Inputs: Schedule including aircraft type, average tow times.
Why? Will be used as the input data for both the baseline and towing models.
Allocated Time: 3 weeks, 120 hours

5.3.4. Work-Package 4: Building KPI's, Verification, Validation, Initial Results and Iterations of the Models

In this stage by focusing on one airport, the models will again be verified, and then they will be validated to ensure that they are realistic to the real world without too many assumptions. In this work-package, KPI's should be built to ensure that the models output useful information, and iterations to the models should be made to make them more realistic. This work package will consist of many iterations thus will likely take the most time, with the main goal of having realistic initial results by the end for at least 1 airport. Once iterations have been done, and the models are ready, the next work-package can begin which will run batch runs for varying schedules and numbers of vehicles for many schedules. This work-package can be broken up in to the following steps:

- Decide output KPIs
- Verify the models using more elaborate input data
- Validate that the models are close enough to real world activities
- Perform a sensitivity analysis by using extreme values etc.
- Obtain initial results for a set number of tow trucks at a test airport.
- Iterate the models for accuracy.

Initial Results:
Objective: Verify, validate, and perform a sensitivity analysis for one airport. Ensure the models output the necessary data, and iterate the models to better suit the real world applications.
Why? To perfect the model before running batch runs for different airports.
Allocated Time: 7 weeks, 280 hours

5.3.5. Work-package 5: Batch-Runs, Analysis and Conclusions

In this work-package an analysis of all airports will be made. This will include running batch runs for varying number of extra tow vehicles at each airport. In this step, results from each airport should be obtained, and a thorough analysis of the results should be made. Conclusions about operational towing should be made in this work-package, and also conclusions about the model. It is expected that due to running time, this will also take a long amount of time.

- Run batch runs for each airport to find the relationships and values for each KPI
- Compare the results of each airport to conventional taxiing and single engine taxiing
- Compare the airports to eachother, to make conclusions about how taxi times, aircraft types, type of demand etc influence the results.

- Make conclusions about the model performance, and about the results with respect to costs and emissions benefits.

Initial Results:
Objective: Verify, validate, and perform a sensitivity analysis for one airport. Ensure the models output the necessary data, and iterate the models to better suit the real world applications.
Why? To perfect the model before running batch runs for different airports.
Allocated Time: 7 weeks, 280 hours

5.3.6. Work-package 6: Other Tasks

During the literature study, I did not do a good job at planning for the unexpected such as appointments, mental-health days, and meetings. To ensure the thesis goes more according to schedule, I will also include other tasks that I need to do into my planning. In the thesis there will also be other tasks that need to be completed that are not directly related to the model. These include reporting, meetings, presentations and prep work.

- Reporting: This will be done as the thesis progresses, but will probably take much more time than I would expect, much like the literature study. Given this, I will set aside at least 3 weeks in the planning which are purely dedicated to reporting.

- Meetings: It is estimated that I will have at least 1 30 minute progress meeting every 2 weeks. This means in the 32 weeks, there will be roughly 16 meetings of 30 minutes. This accounts for 8 hours, or 1 day of work.

- Kick-off, Midterm and Green-Light: It is expected that I will need a week of preparation before these meetings to round up my work and prepare for these presentations/meetings. Thus 1 week will be put in the planning for preparation for the mid-term and green-light respectively.

- Other: My job as a TA involves around 14 hours of work per week. This is concentrated on Fridays until the beginning of Q2 and in the exam period. This means I will allocate 2 weeks to TA work and other obligations such as appointments, mental health days etc.

Misc:
Objective: Account for other obligations in my planning
Why? To make sure my planning is realistic enoguh to keep the thesis project running on-time.
Allocated Time: 7 weeks, 280 hours

Some special considerations that should also be taken into account for the planning are the midterm, green-light and defence and their respective deadlines. A basic overview of my planning vs. the official planning can be seen in Table 5.2 where the timeline with the work-packages is also included.

Table 5.2: Thesis planning in terms of milestones

Milestones	**Official Time-line Procedure**	**Proposed Time-line**	**Progress in Terms of Work-packages**
Kick-off	**Week 4**	**Week 0**	Begin Work-package 1
Work on Modelling & Reporting			Work-package 1-3 complete (11 weeks), misc (2 weeks) Partway through work-package 4 (2 weeks)
Midterm	**Week 18**	**Week 15**	
Submit Draft	(At least 14 days before green-light)		Work-package 4 complete (5 weeks), misc (2 weeks) progressing/closing up work-package 5 (5 weeks)
Greenlight	**Week 26**	**Week 27**	
Request Examination	(20 workdays before defence)		Finish work-package 5 (2 weeks), misc (2 weeks)
Submit Thesis	(At least 14 days before defence)		misc (1 week)
Defence	**Week 30**	**Week 32**	Defence!

5.3.7. Scope

Due to the time constraints on the thesis, the following can be said about the scope of the project.

- The focus will only be on commercial passenger air traffic at airports.
- The focus will be on out-bound taxiing operations. This of course does not fully encompass the topic of operational towing, however this allows a simplification for both schedule generation and modelling towing.
- The model should only be able to give a high-level estimate of emissions savings and costs per airport, thus costs of delays and runway traffic can be omitted, and exact taxiing times should be estimated at each airport.
- The research will consider operational towing using both diesel and electric vehicles despite the concerns of the nose gear.
- Aircraft noise will not be included in the scope. It is assumed that operational taxiing using diesel and/or electric vehicles will be quieter than the use of aircraft engines during taxiing.

It should be kept in mind that if a more detailed estimate about the cost-benefit of operational towing is to be made in the future, adjustments to the input data and model constraints can be made to better represent airport specific operations.

III

Supporting work

A

Appendix A: Changes in Thesis Scope

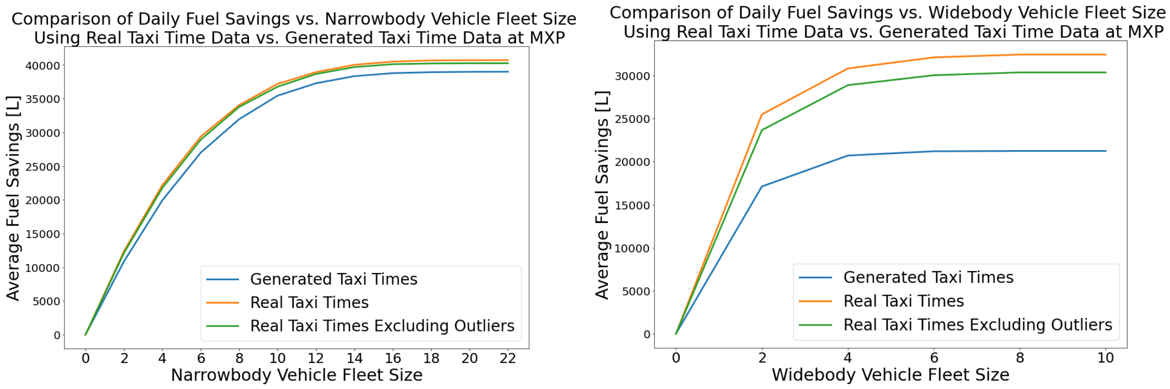
In accordance with the daily supervisor of this thesis, the scope of the project was adjusted due to the quality of available of the data and the motivation of the research. In this appendix an overview of all changes and the reasoning behind the changes are addressed, and the updated research question and sub-questions are presented.

A.1. European vs. Global airports

In the original research plan presented in the literature study in Chapter 5, the scope of the project was to focus on global airports. During the verification and validation process, it was found that the accuracy of the data sources for North American and Asian airports were not to the same standard as European Airport data. The main concerns with the data were:

- Reliability of data from the OAG 2018 database.
- Wake turbulence categorized taxi data is only available for European airports.

During verification, issues were found in the OAG 2018 data for American and Asian airports. Flights were found with the same origin and destination airport leading to the number of inbound and outbound flights being imbalanced. In a realistic scenario, since there are a fixed number of gates and stands at each airport, it is expected that these values would be similar. Given the data available, it was not possible verify which flights should be included, making the accuracy of the input data insufficient for the analysis.



(a) Narrowbody Validation Results

(b) Widebody Validation Results

Figure A.1: Taxi-time validation results for narrow and widebody vehicles using non-wake categorized outbound taxi time distributions.

During the validation process for the generated taxi times, it was concluded that in order for the results using generated taxi times to reflect a scenario using real taxi times, wake turbulence categorized data is needed. In Figure A.1, the comparison of the estimated fuel savings using actual taxi times vs. generated taxi times using non-wake categorized data at Milan Malpensa are shown. The estimated fuel savings for widebody vehicles does not reflect a realistic scenario when wake-categories are not taken into account. Since wake categorized taxi time distributions are only available for European airports, an accurate representation of widebody fuel and emissions savings is only possible for European airports. Given that the research is motivated by the CO_2 emissions savings targets for 2050 in Europe, the scope was thus re-defined to include only European airports in the case study. This change allows for more accurate results that still fit within the intended purpose of the research.

A.2. All Traffic vs. Only Outbound Traffic

In the initial research scope presented in Section 5.3.7 of the literature study, only outbound traffic operations were to be included in the analysis. This was motivated by the availability of wake-categorized taxi time distribution data for only outbound traffic. During the verification and validation process of the taxi data, it was found that using non-wake categorized data had a very small effect on the results for inbound traffic. This meant that by including inbound traffic, a more realistic estimate of the overall potential fuel and emissions savings for operational towing could be made without decreasing the quality of the results. For this reason, the scope was expanded to include inbound and outbound flights.

A.3. Vehicle Cost vs. Operations and Implementation Cost

In the initial research sub-questions presented in Section 5.2 of the literature study, sub-questions about operational and infrastructure costs were included. During the kick-off meeting, it was concluded that analyzing both the fixed and operational costs of implementing operational towing would require a detailed analysis of the current infrastructure and operations at each case-study airport. This analysis would make the scope of the thesis too large for the thesis timeline. For this reason, it was agreed that the thesis scope would focus on the marginal savings per vehicle; linking the maximum fuel and emissions savings to a vehicle fleet size.

A.4. Updated Research Question

Taking into consideration the changes in the scope of the project, the methodology of the research was created to answer the following updated research question and sub-questions.

Updated Research Question:
What are the estimated emissions savings per unit of vehicle cost of implementing operational towing for outbound commercial passenger air traffic at major European airports.

Supporting this main question, the following updated sub questions were identified:

Updated Research Sub-Questions:

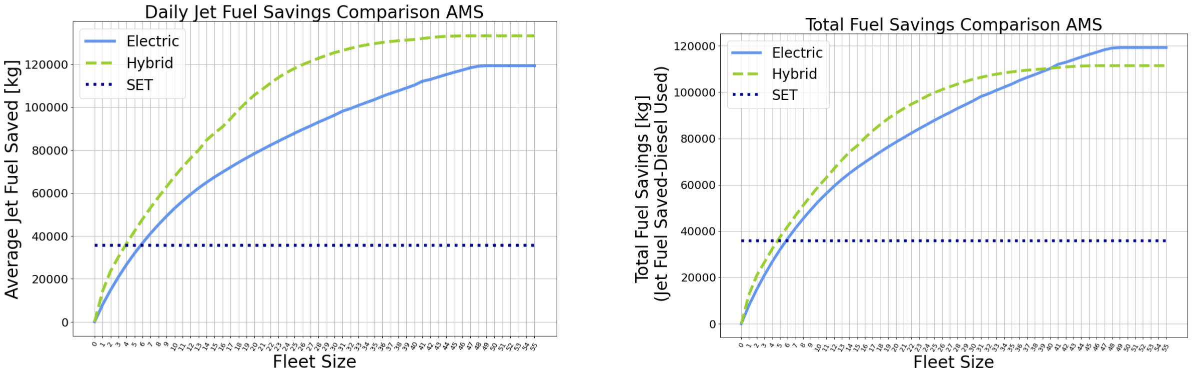
- What is the maximum daily fuel and emissions savings of implementing operational towing per flight in Europe?
- What is the maximum daily fuel and emissions savings of implementing operational towing per case study airport?
- What is the maximum daily fuel and emissions savings of implementing operational towing per flight at each case study airport?
- What is the maximum daily fuel and emissions savings per tow truck added at each airport?
- What is the maximum daily fuel and emissions savings per tow truck added Europe-wide?

B

Appendix B: Fuel and Emissions Savings per Airport

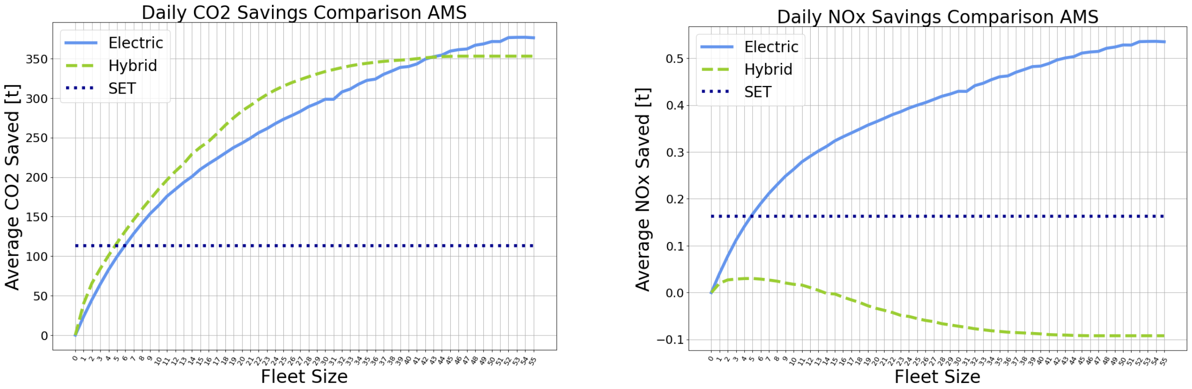
In this appendix the results from all 30 airports are presented and sorted in alphabetical order by their airport codes. As the case-study size of this thesis was so large, a summary of the maximum potential savings at each case-study airport is presented in the results section in the thesis paper. The figures presented in this appendix show the maximum fuel and emissions savings for each vehicle fleet size at each airport. This allows a comparison of technologies that is best suited for a target fuel or emissions savings goal or vehicle budget on an airport specific scale.

Amsterdam Schiphol Airport: AMS



(a) Fuel Savings Comparison AMS

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) AMS

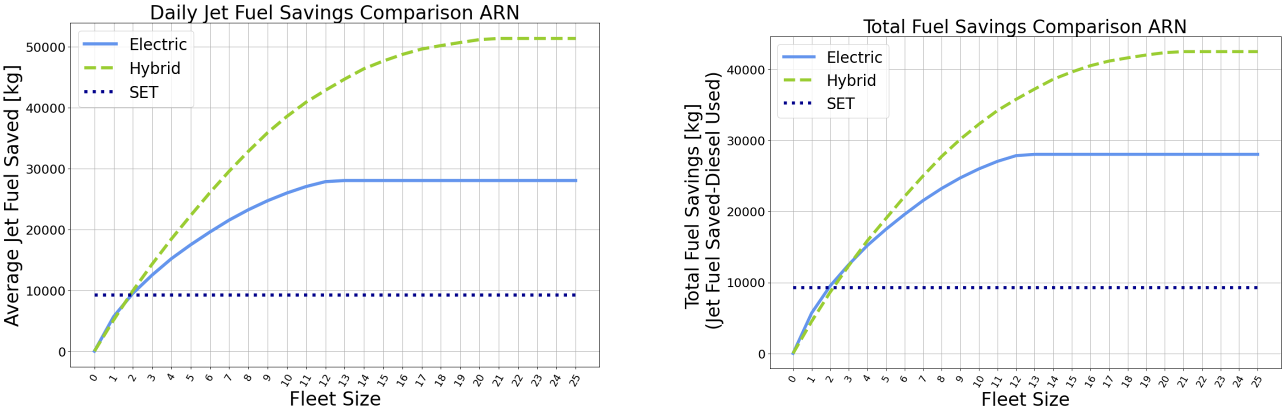


(c) CO_2 Savings Comparison AMS

(d) NO_x Savings Comparison AMS

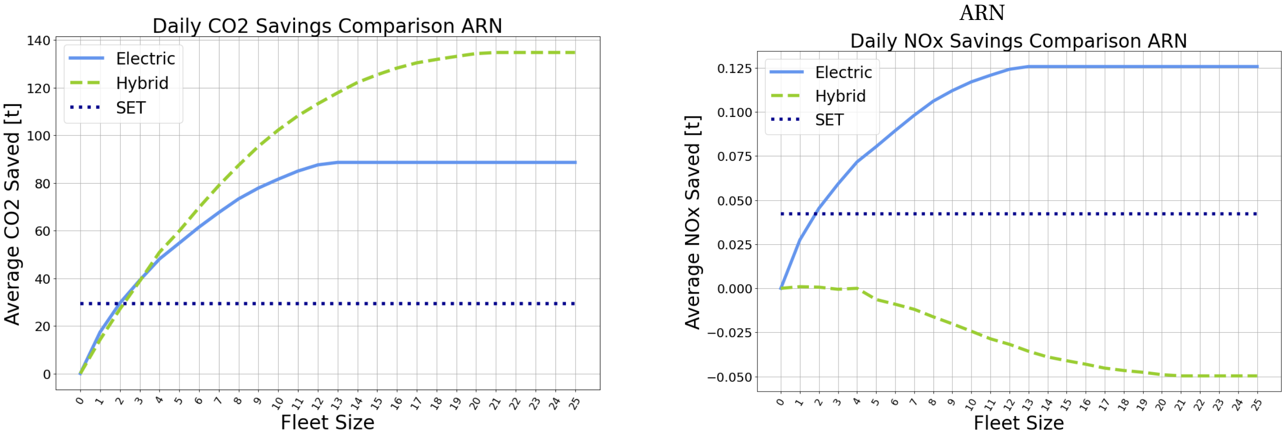
Figure B.1: Jet Fuel and Emissions Savings at AMS

Stockholm Arlanda Airport: ARN



(a) Fuel Savings Comparison ARN

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) ARN

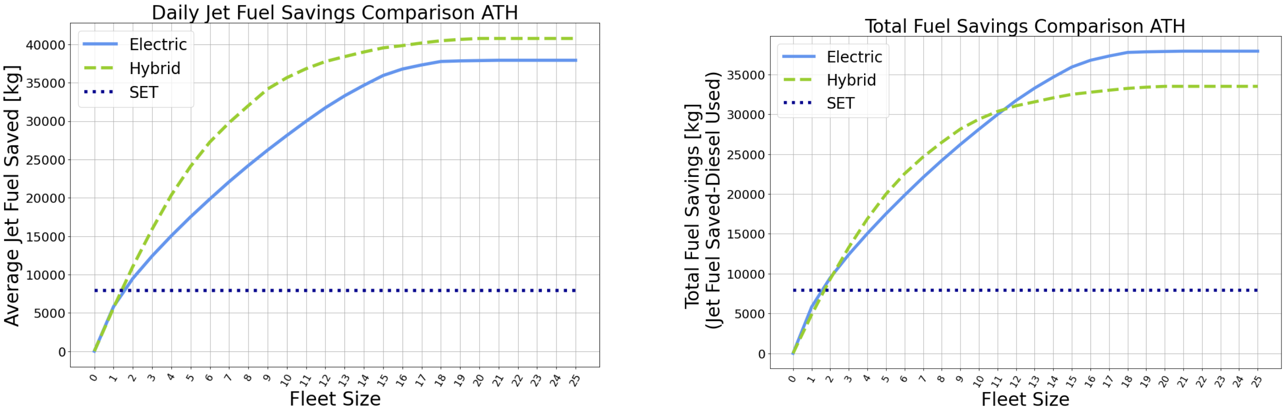


(c) CO_2 Savings Comparison ARN

(d) NO_x Savings Comparison ARN

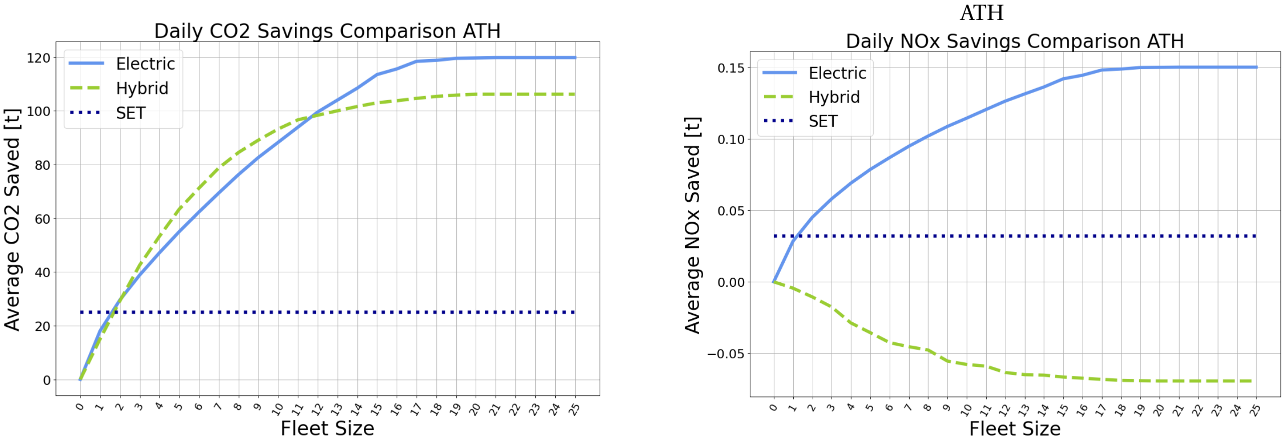
Figure B.2: Jet Fuel and Emissions Savings at ARN

Athens International Airport: ATH



(a) Fuel Savings Comparison ATH

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) ATH

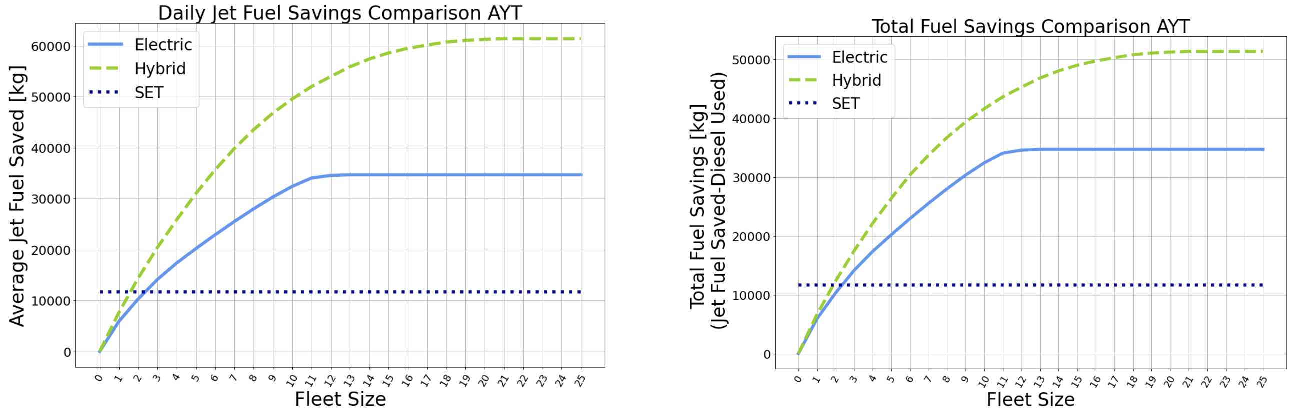


(c) CO_2 Savings Comparison ATH

(d) NO_x Savings Comparison ATH

Figure B.3: Jet Fuel and Emissions Savings at ATH

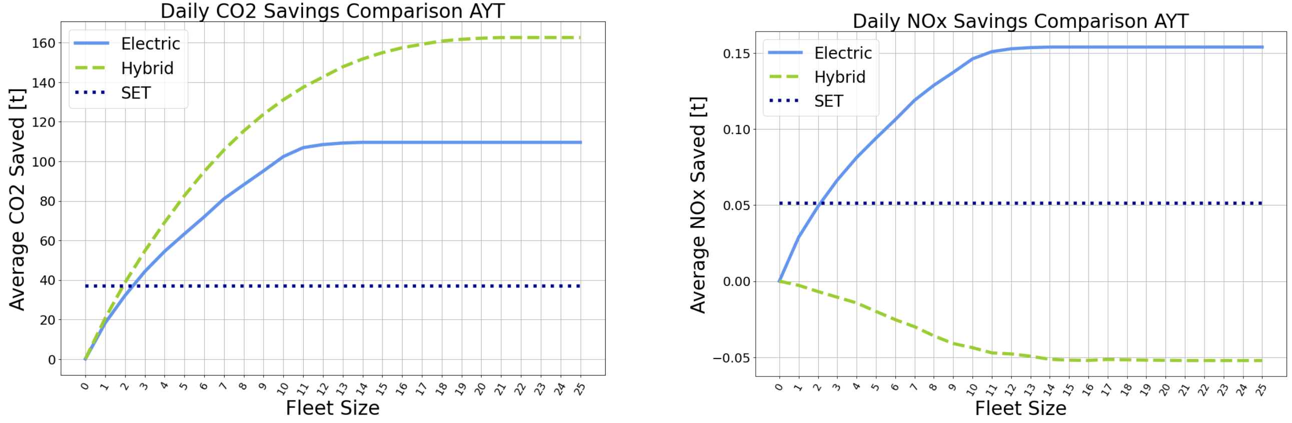
Istanbul Antalya Airport: AYT


Daily Jet Fuel Savings Comparison AYT

Total Fuel Savings Comparison AYT

(a) Fuel Savings Comparison AYT

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) AYT


Daily CO2 Savings Comparison AYT

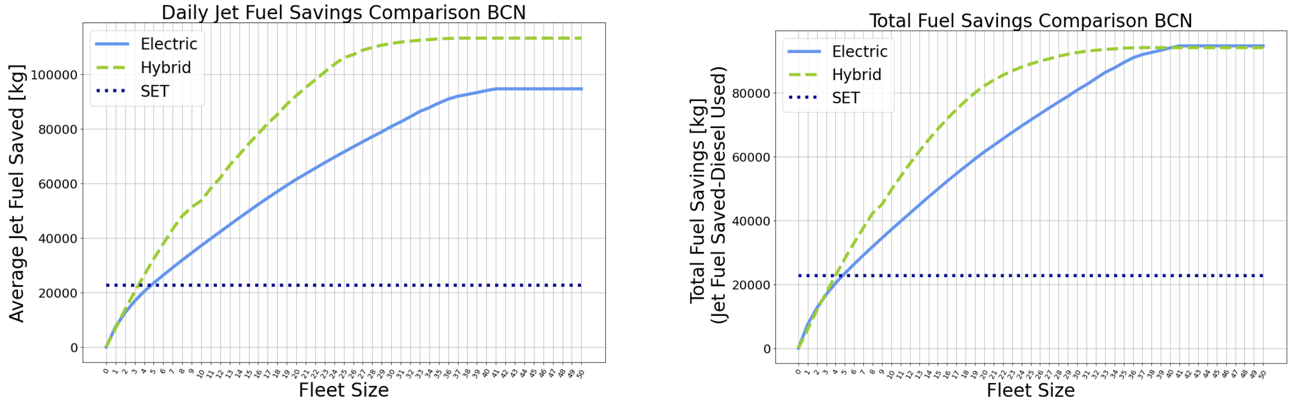
Daily NOx Savings Comparison AYT

(c) CO_2 Savings Comparison AYT

(d) NO_x Savings Comparison AYT

Figure B.4: Jet Fuel and Emissions Savings at AYT

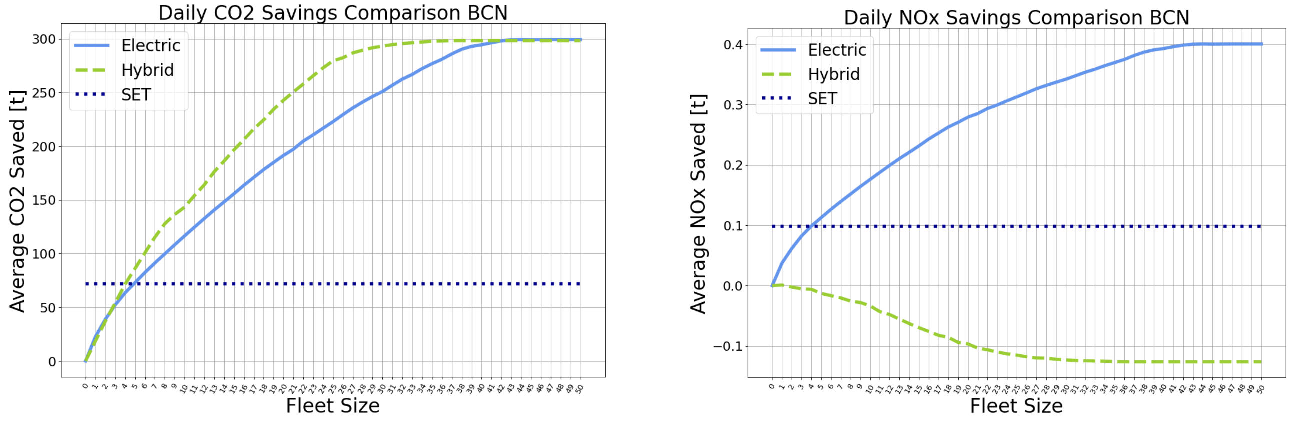
Barcelona Josep Tarradellas Barcelona-El Prat Airport: BCN


Daily Jet Fuel Savings Comparison BCN

Total Fuel Savings Comparison BCN

(a) Fuel Savings Comparison BCN

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) BCN


Daily CO2 Savings Comparison BCN

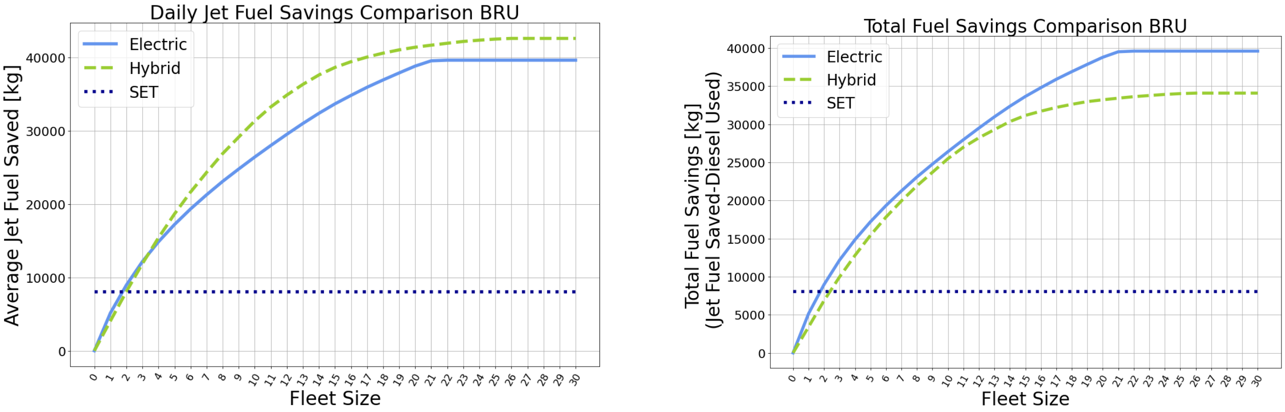
Daily NOx Savings Comparison BCN

(c) CO_2 Savings Comparison BCN

(d) NO_x Savings Comparison BCN

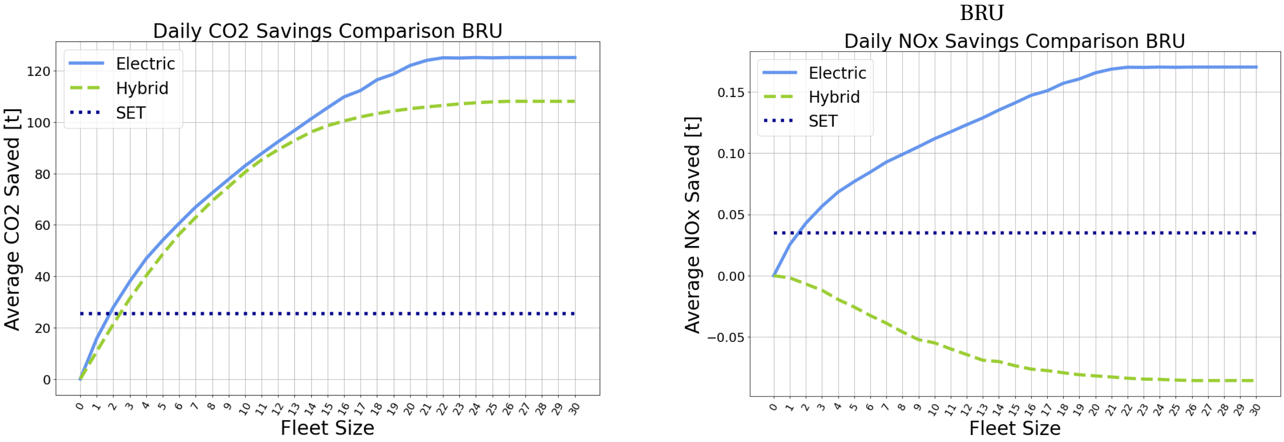
Figure B.5: Jet Fuel and Emissions Savings at BCN

Brussels Airport: BRU



(a) Fuel Savings Comparison BRU

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) BRU

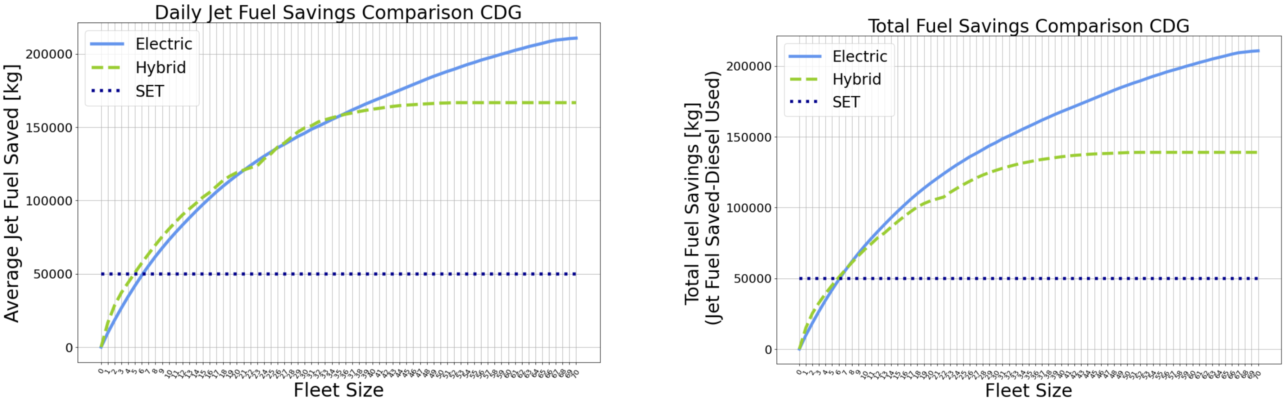


(c) CO_2 Savings Comparison BRU

(d) NO_x Savings Comparison BRU

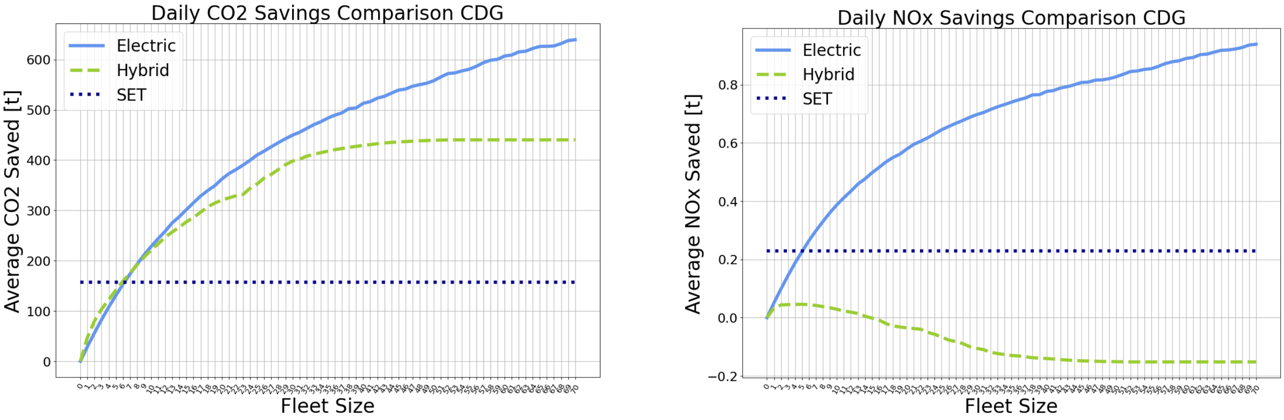
Figure B.6: Jet Fuel and Emissions Savings at BRU

Paris Charles de Gaulle Airport: CDG



(a) Fuel Savings Comparison CDG

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) CDG

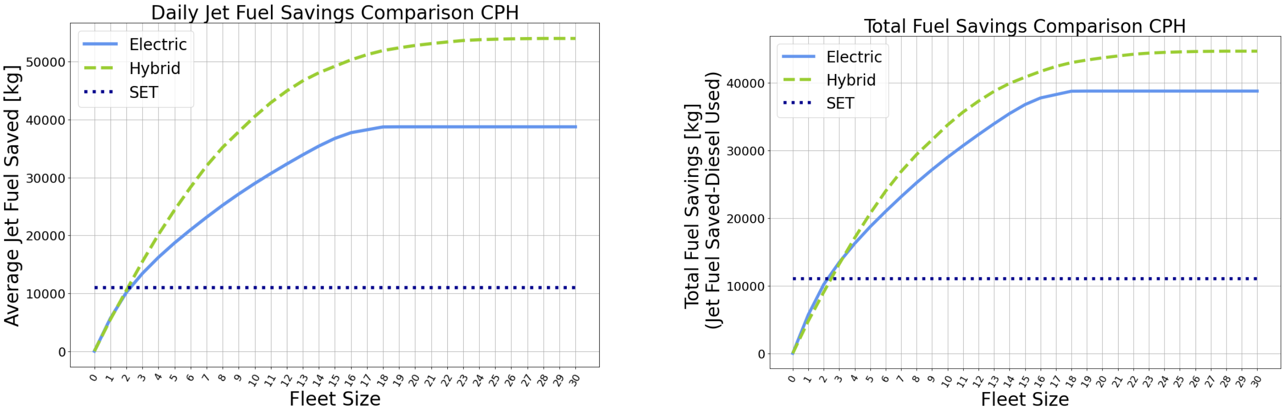


(c) CO_2 Savings Comparison CDG

(d) NO_x Savings Comparison CDG

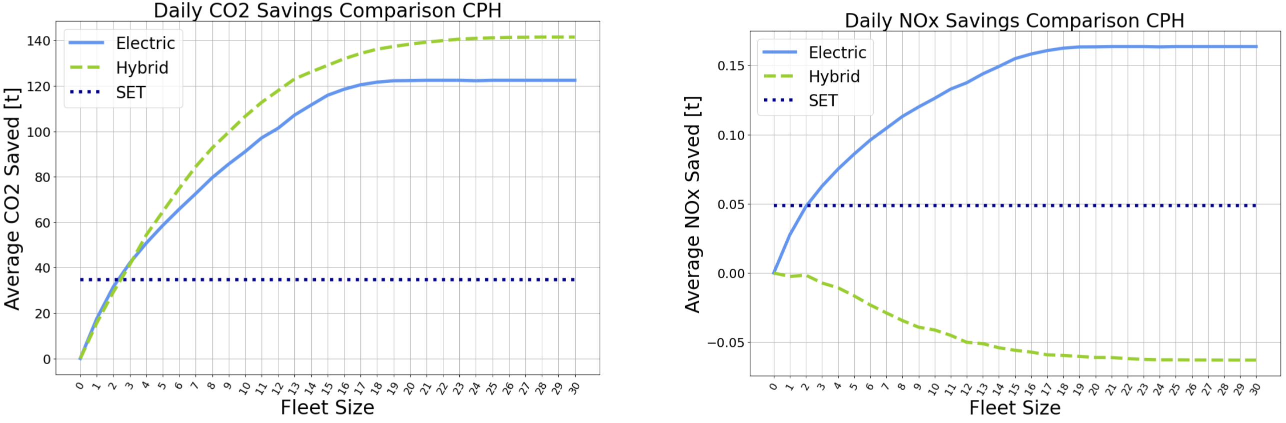
Figure B.7: Jet Fuel and Emissions Savings at CDG

Copenhagen Airport: CPH



(a) Fuel Savings Comparison CPH

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) CPH

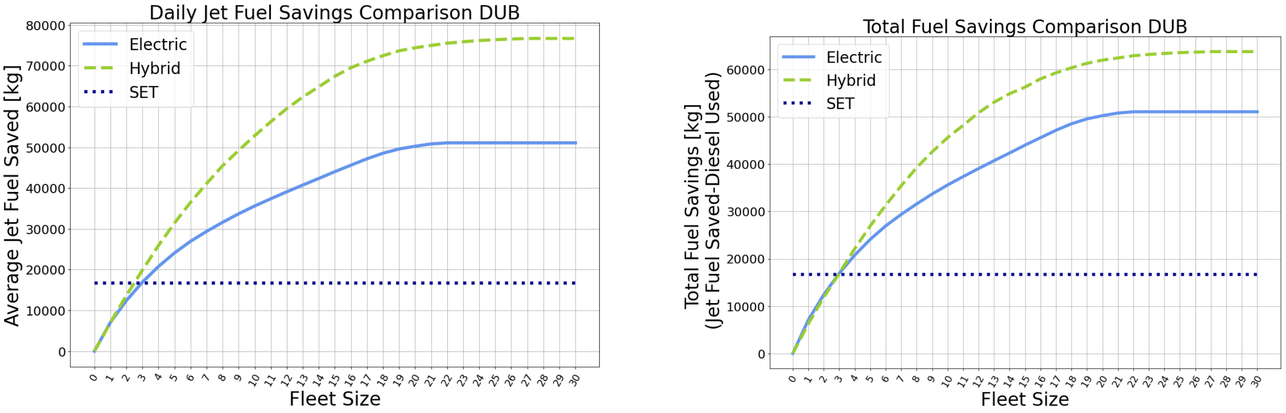


(c) CO_2 Savings Comparison CPH

(d) NO_x Savings Comparison CPH

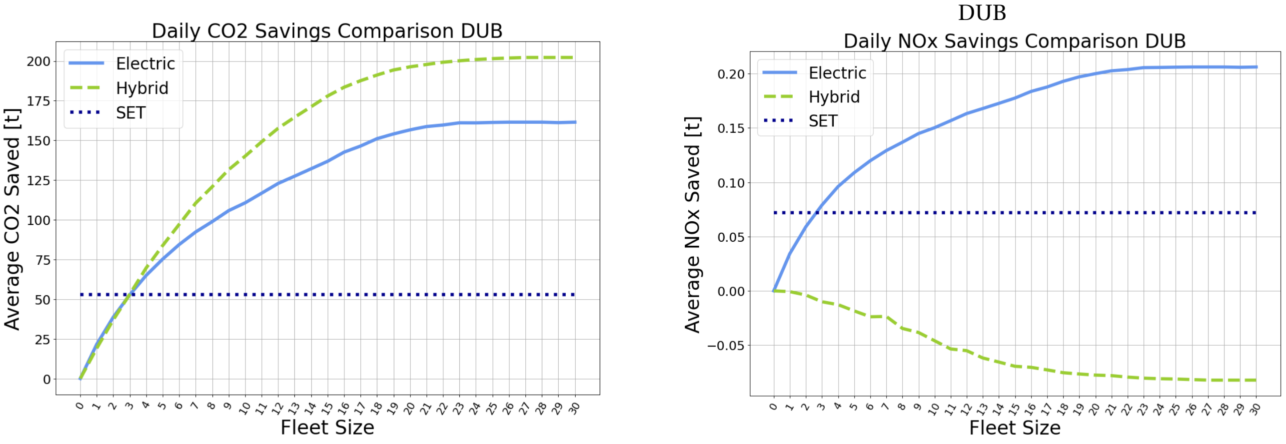
Figure B.8: Jet Fuel and Emissions Savings at CPH

Dublin Airport: DUB



(a) Fuel Savings Comparison DUB

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) DUB

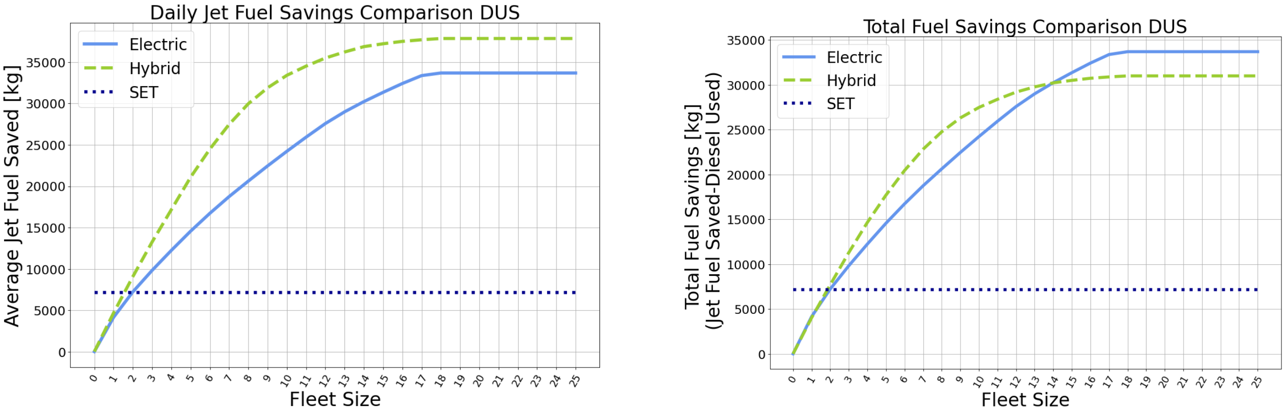


(c) CO_2 Savings Comparison DUB

(d) NO_x Savings Comparison DUB

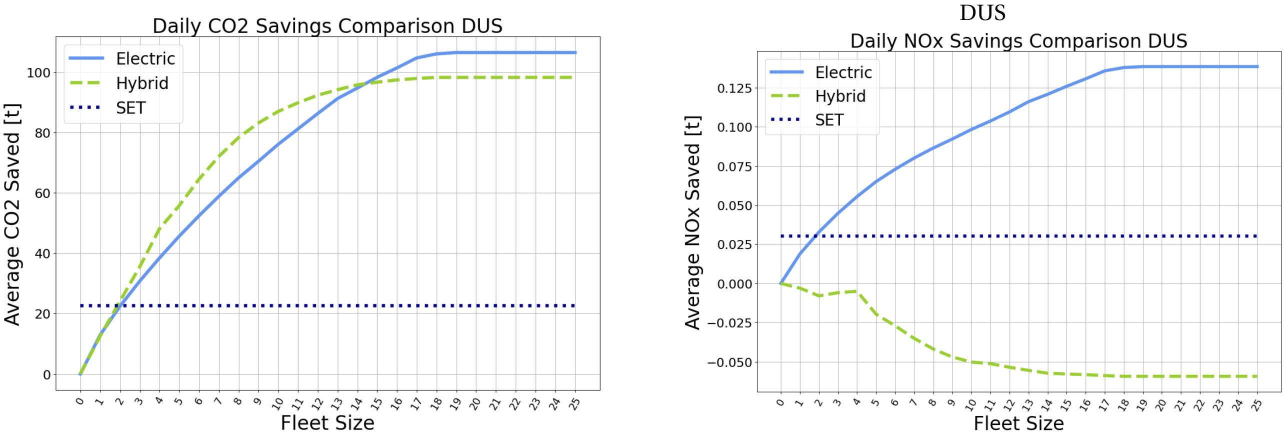
Figure B.9: Jet Fuel and Emissions Savings at DUB

Düsseldorf International Airport: DUS



(a) Fuel Savings Comparison DUS

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) DUS

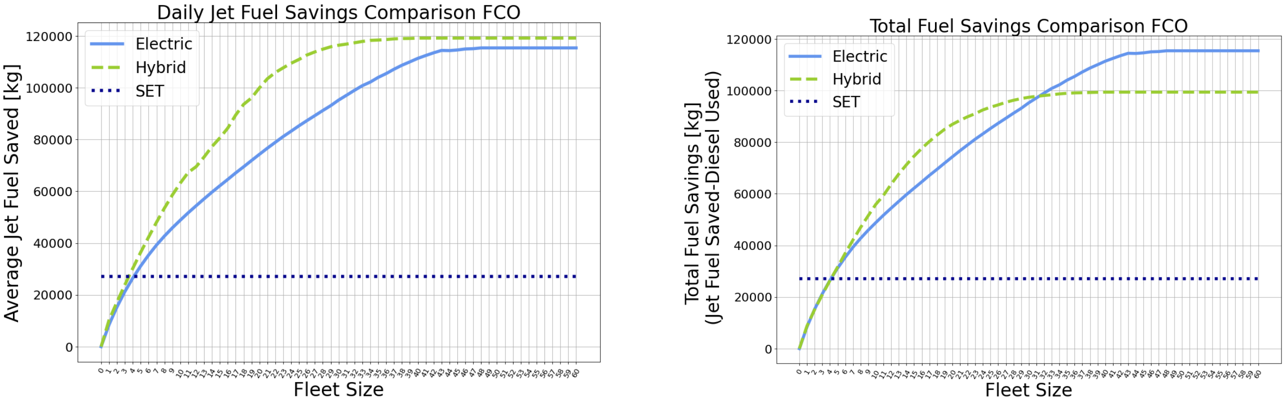


(c) CO_2 Savings Comparison DUS

(d) NO_x Savings Comparison DUS

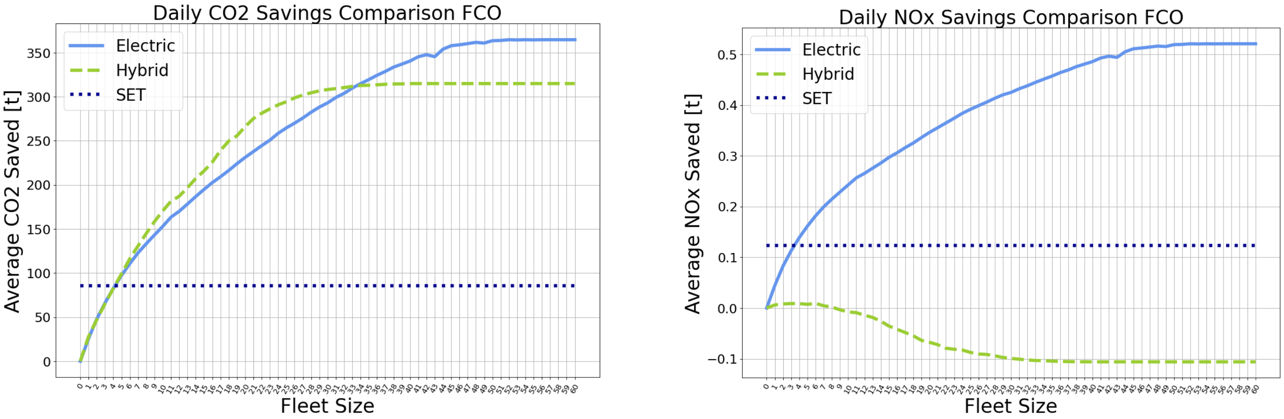
Figure B.10: Jet Fuel and Emissions Savings at DUS

Rome Leonardo da Vinci International Airport: FCO



(a) Fuel Savings Comparison FCO

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) FCO

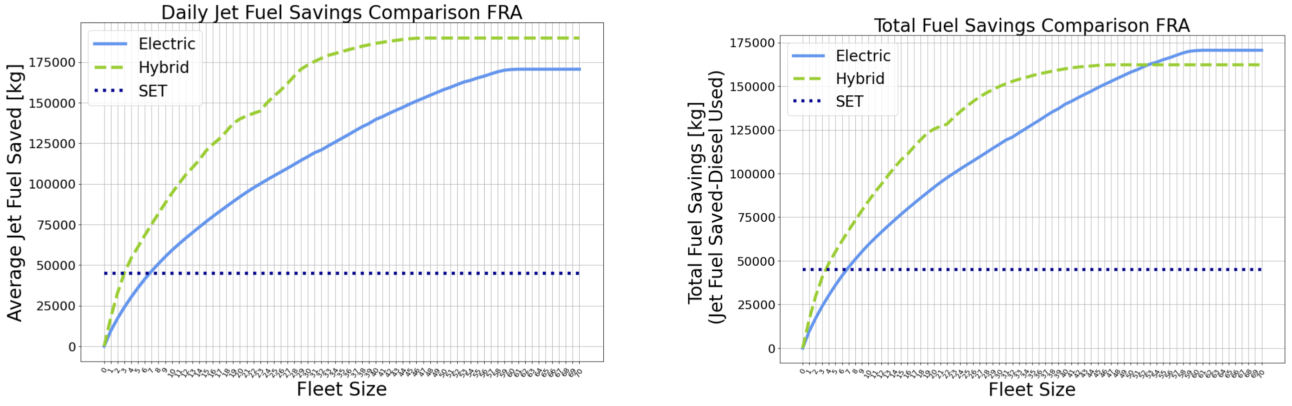


(c) CO_2 Savings Comparison FCO

(d) NO_x Savings Comparison FCO

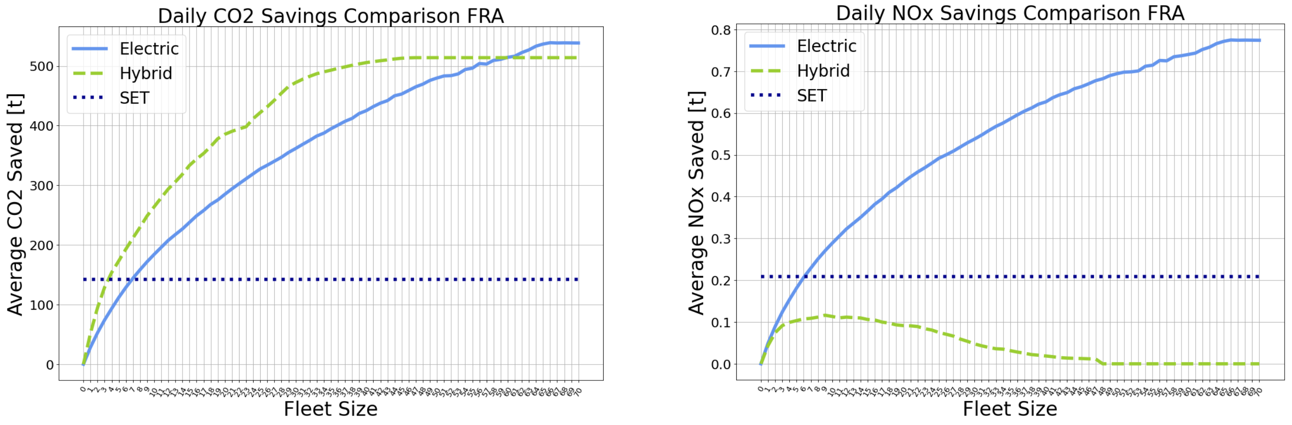
Figure B.11: Jet Fuel and Emissions Savings at FCO

Frankfurt Airport: FRA



(a) Fuel Savings Comparison FRA

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) FRA

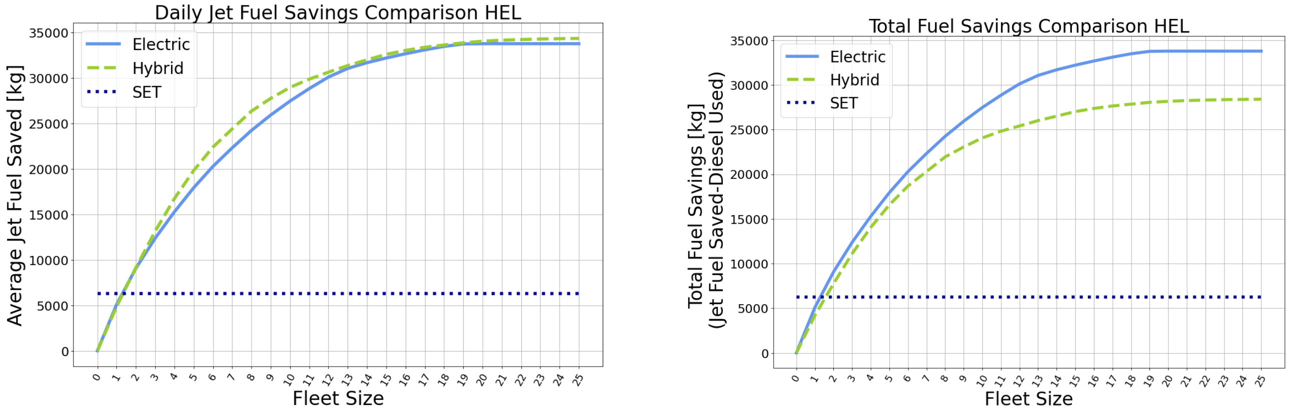


(c) CO_2 Savings Comparison FRA

(d) NO_x Savings Comparison FRA

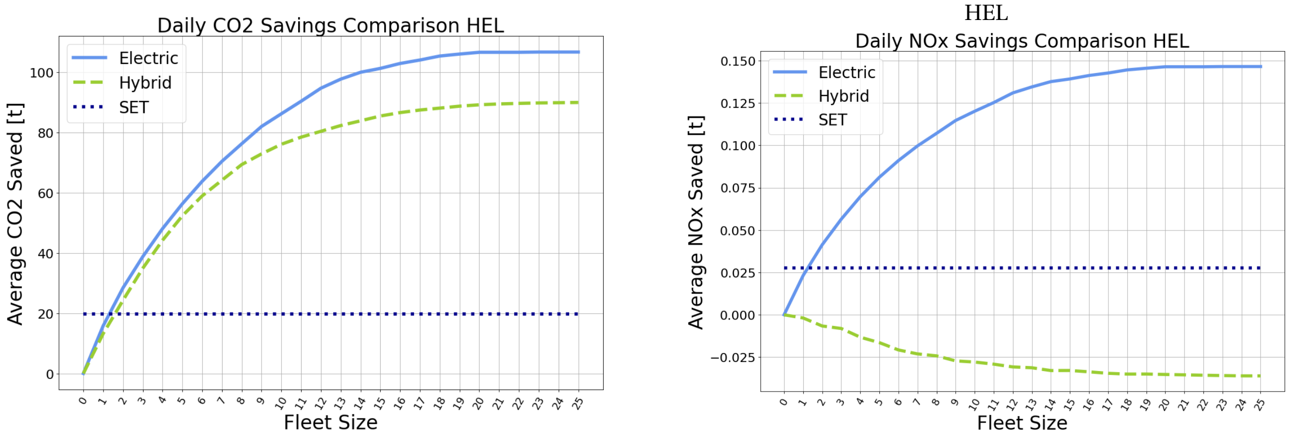
Figure B.12: Jet Fuel and Emissions Savings at FRA

Helsinki Airport: HEL



(a) Fuel Savings Comparison HEL

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) HEL

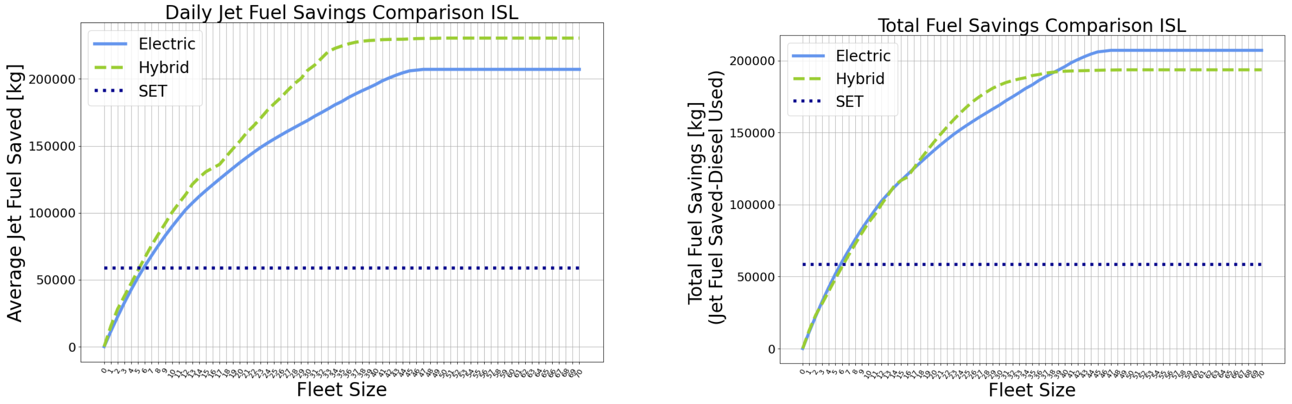


(c) CO_2 Savings Comparison HEL

(d) NO_x Savings Comparison HEL

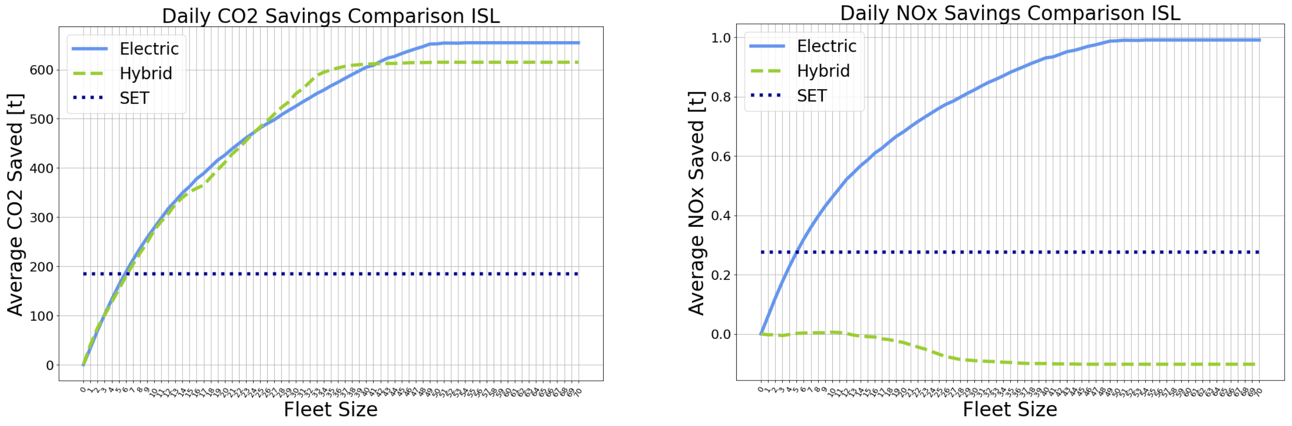
Figure B.13: Jet Fuel and Emissions Savings at HEL

Itanbul Ataturk Airport: ISL



(a) Fuel Savings Comparison ISL

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) ISL

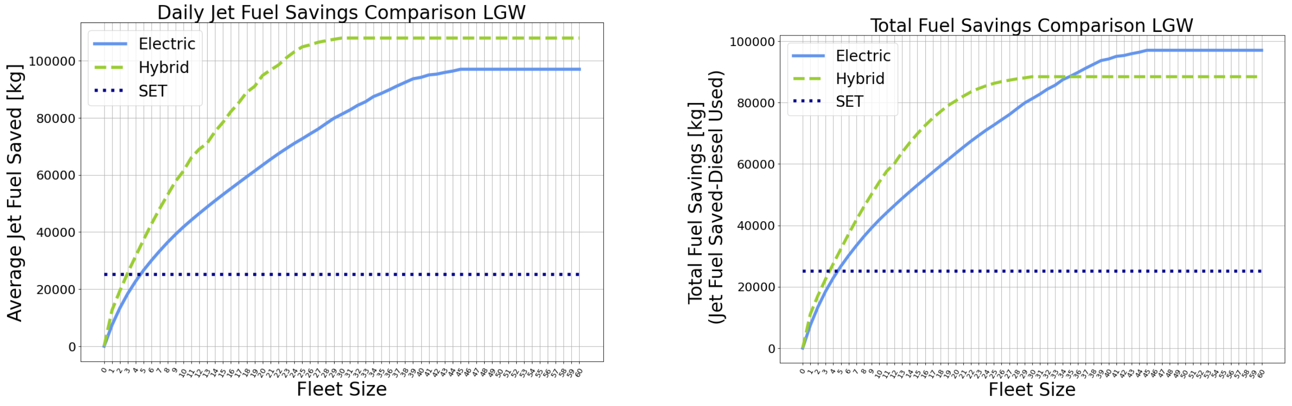


(c) CO_2 Savings Comparison ISL

(d) NO_x Savings Comparison ISL

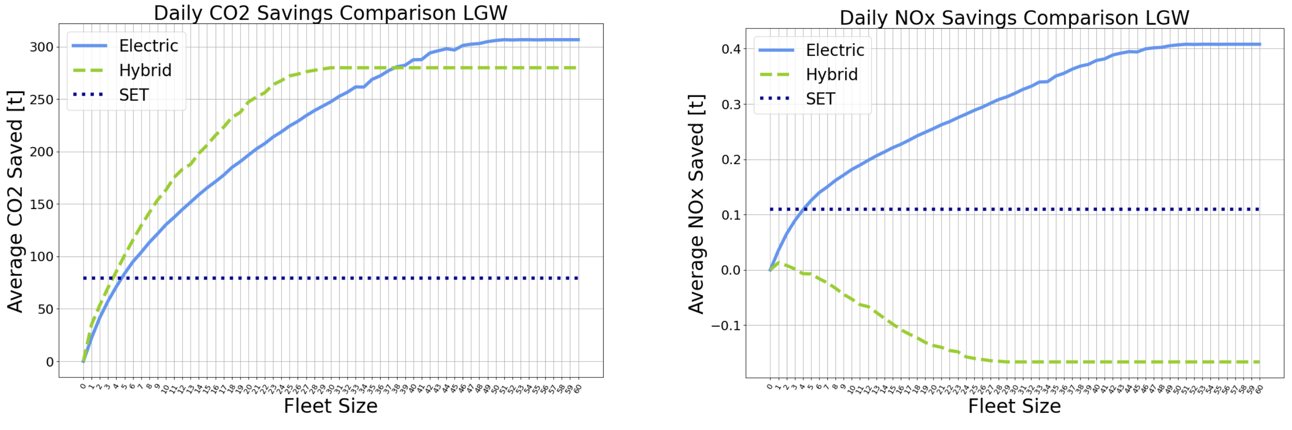
Figure B.14: Jet Fuel and Emissions Savings at ISL

London Gatwick Airport: LGW



(a) Fuel Savings Comparison LGW

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) LGW

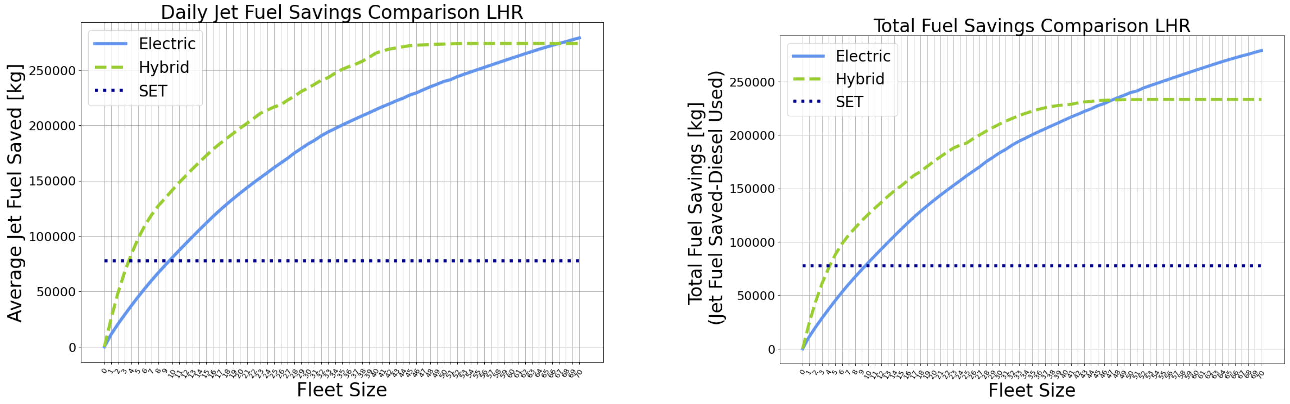


(c) CO_2 Savings Comparison LGW

(d) NO_x Savings Comparison LGW

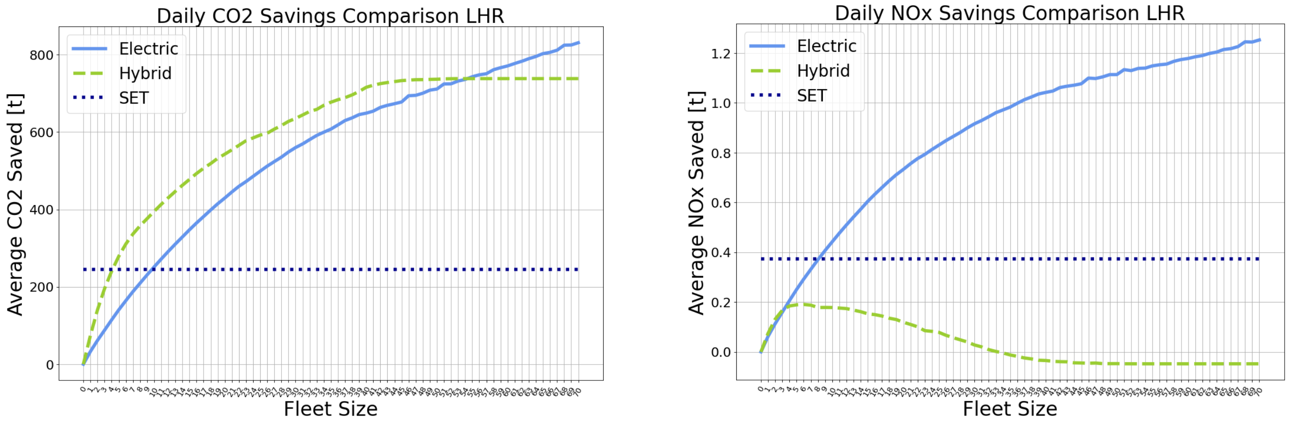
Figure B.15: Jet Fuel and Emissions Savings at LGW

London Heathrow Airport: LHR



(a) Fuel Savings Comparison LHR

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) LHR

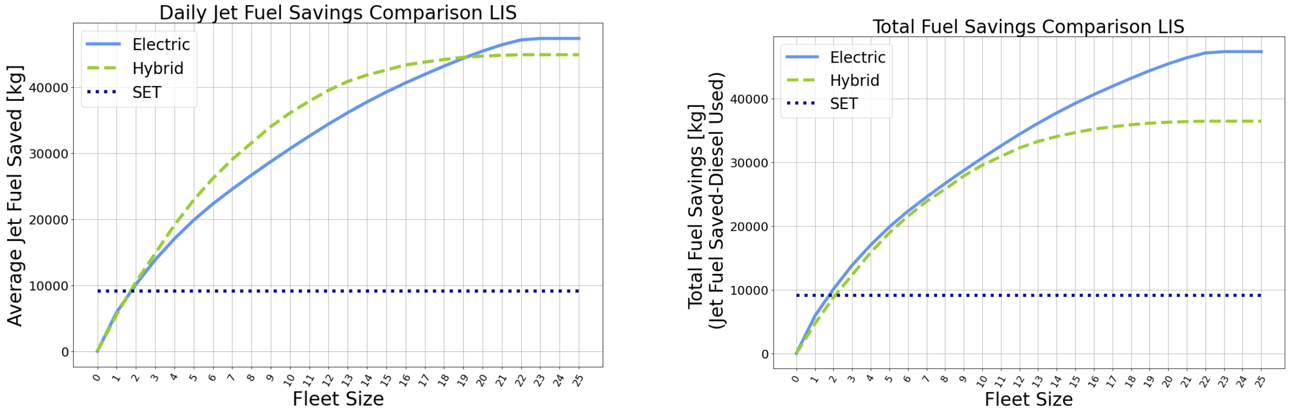


(c) CO_2 Savings Comparison LHR

(d) NO_x Savings Comparison LHR

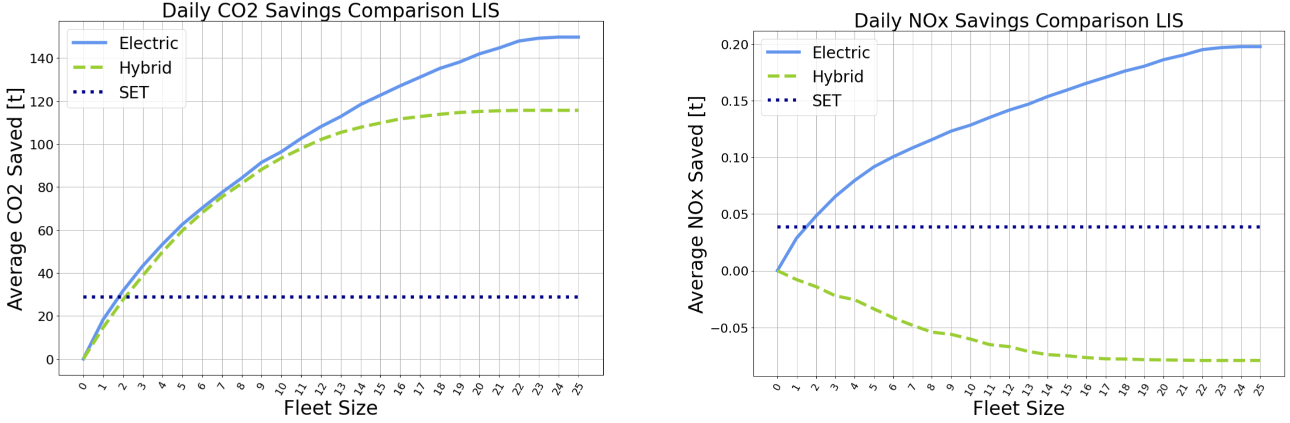
Figure B.16: Jet Fuel and Emissions Savings at LHR

Lisbon Humberto Delgado Airport: LIS



(a) Fuel Savings Comparison LIS

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) LIS

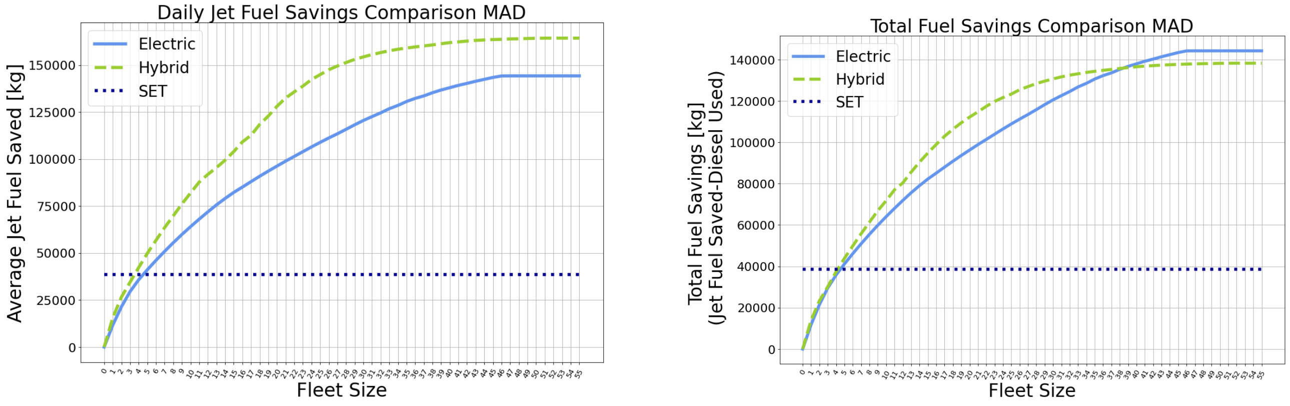


(c) CO_2 Savings Comparison LIS

(d) NO_x Savings Comparison LIS

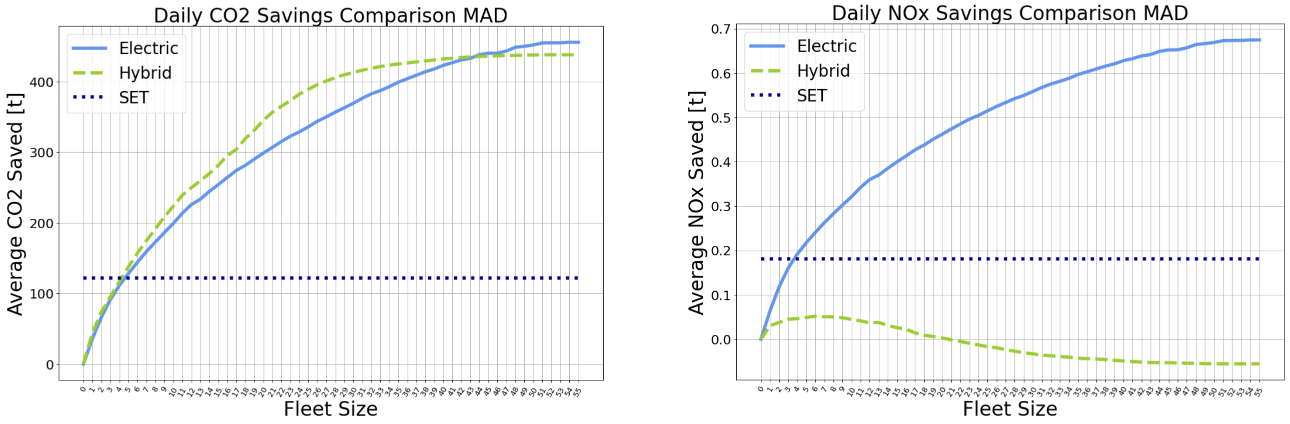
Figure B.17: Jet Fuel and Emissions Savings at LIS

Madrid-Barajas Airport: MAD



(a) Fuel Savings Comparison MAD

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) MAD

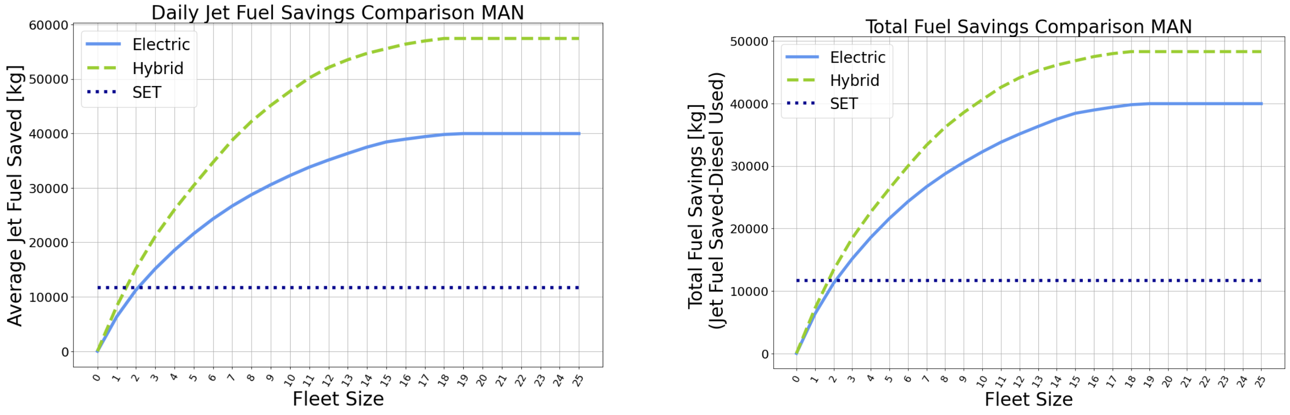


(c) CO_2 Savings Comparison MAD

(d) NO_x Savings Comparison MAD

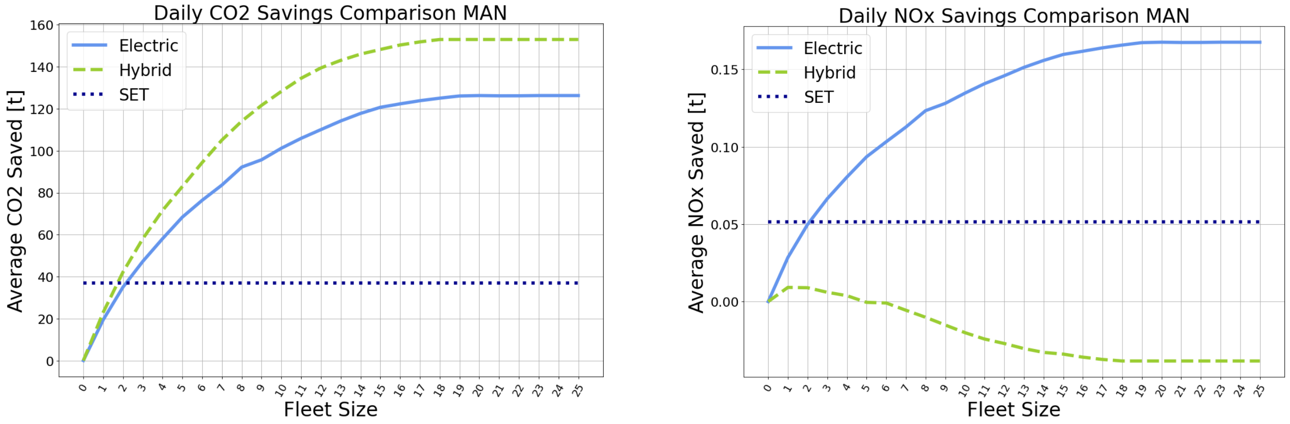
Figure B.18: Jet Fuel and Emissions Savings at MAD

Manchester Airport: MAN



(a) Fuel Savings Comparison MAN

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) MAN

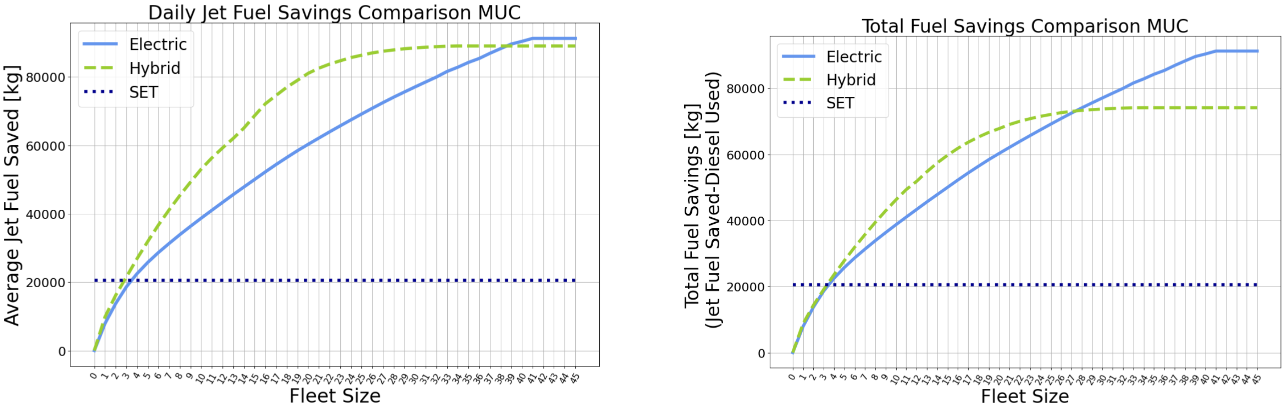


(c) CO_2 Savings Comparison MAN

(d) NO_x Savings Comparison MAN

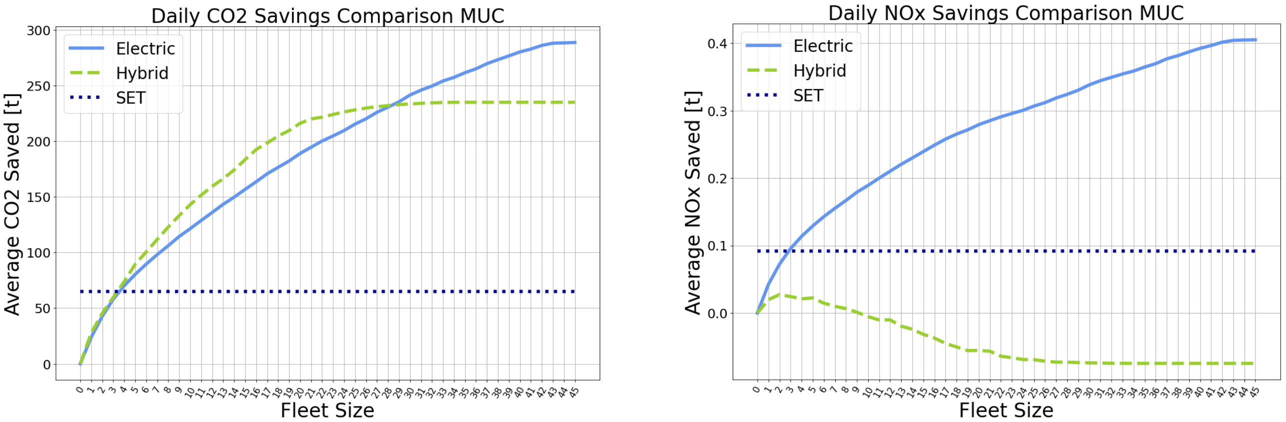
Figure B.19: Jet Fuel and Emissions Savings at MAN

Munich Airport: MUC



(a) Fuel Savings Comparison MUC

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) MUC

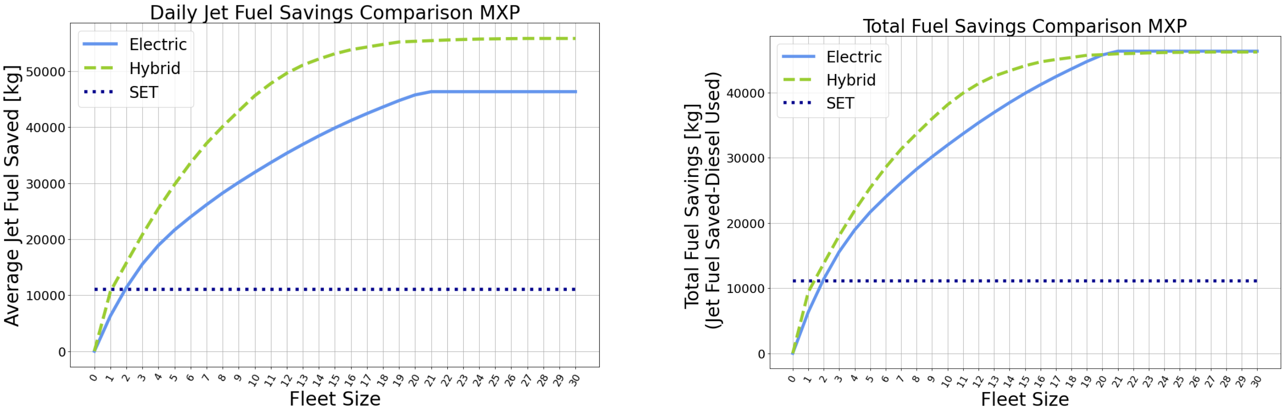


(c) CO_2 Savings Comparison MUC

(d) NO_x Savings Comparison MUC

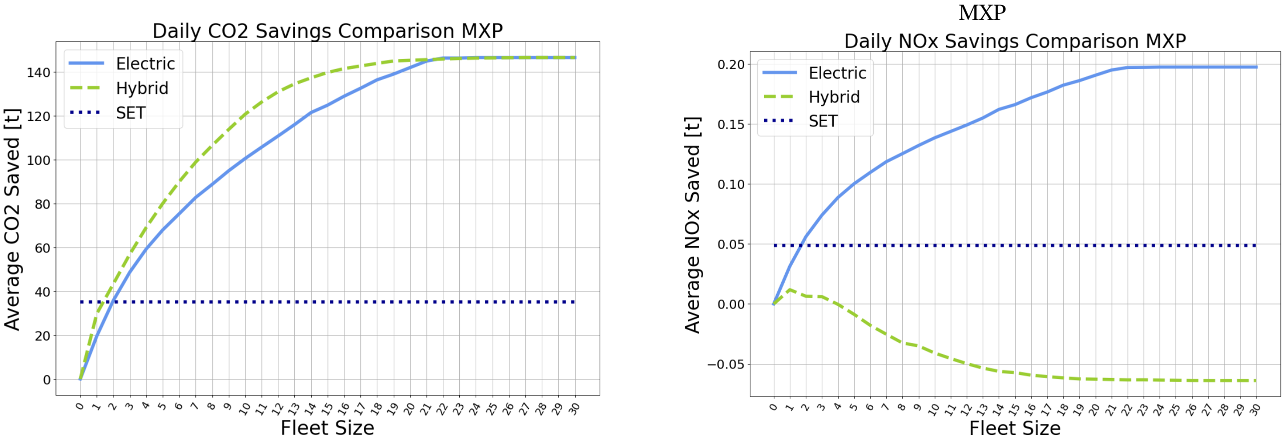
Figure B.20: Jet Fuel and Emissions Savings at MUC

Milan Malpensa Airport: MXP



(a) Fuel Savings Comparison MXP

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) MXP

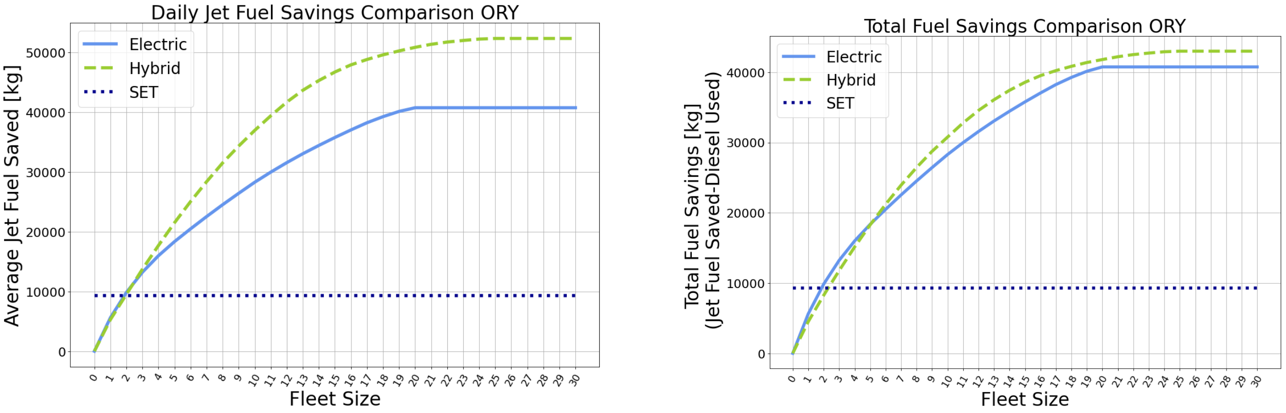


(c) CO_2 Savings Comparison MXP

(d) NO_x Savings Comparison MXP

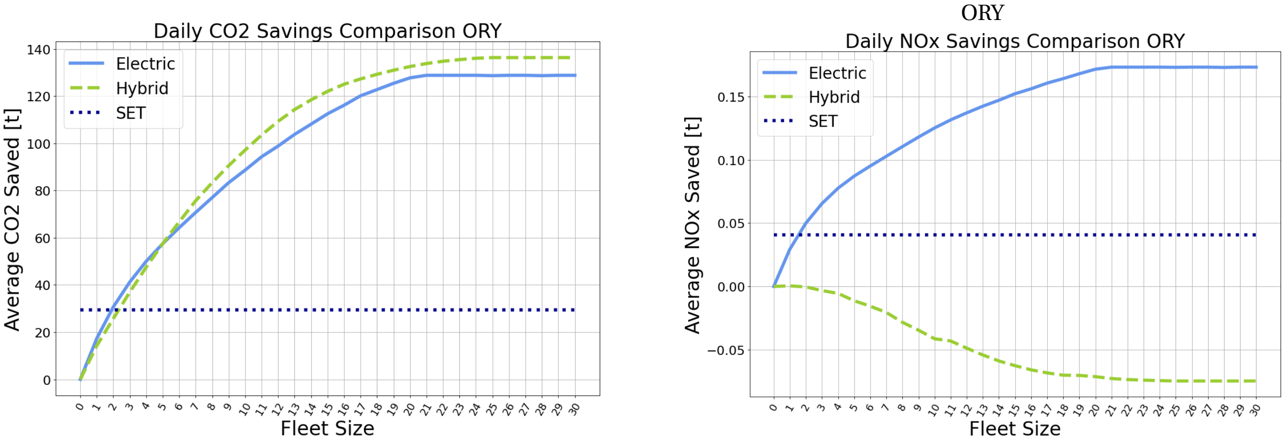
Figure B.21: Jet Fuel and Emissions Savings at MXP

Paris Orly Airport: ORY



(a) Fuel Savings Comparison ORY

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) ORY

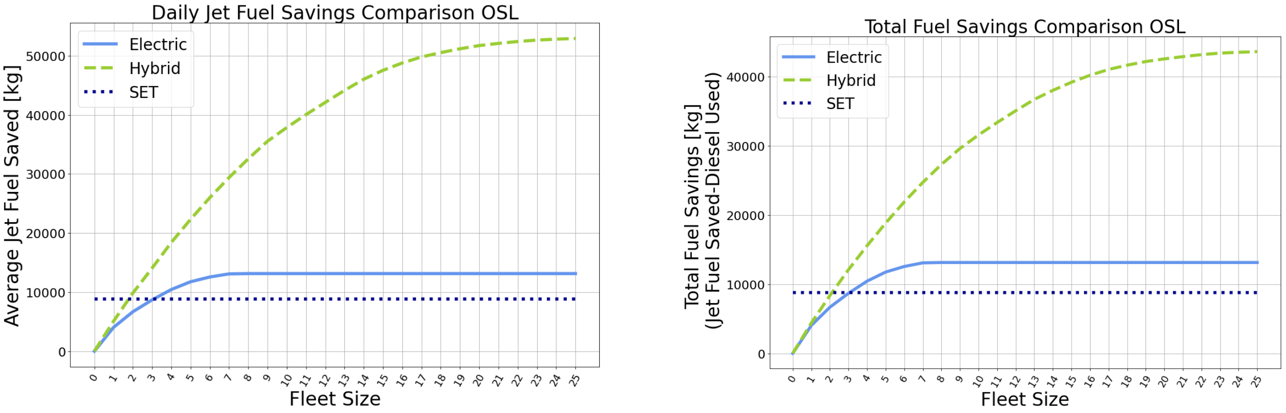


(c) CO_2 Savings Comparison ORY

(d) NO_x Savings Comparison ORY

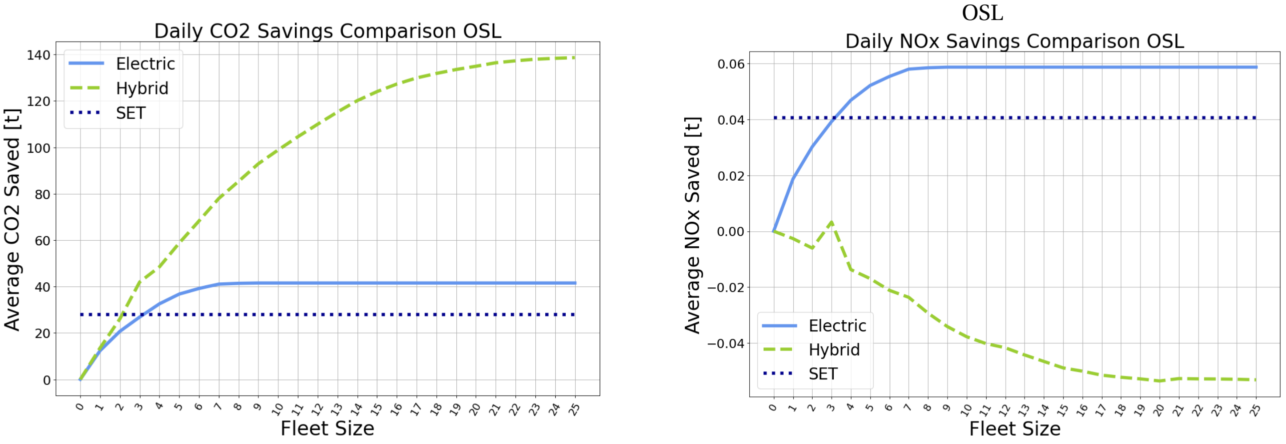
Figure B.22: Jet Fuel and Emissions Savings at ORY

Oslo Airport: OSL



(a) Fuel Savings Comparison OSL

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) OSL

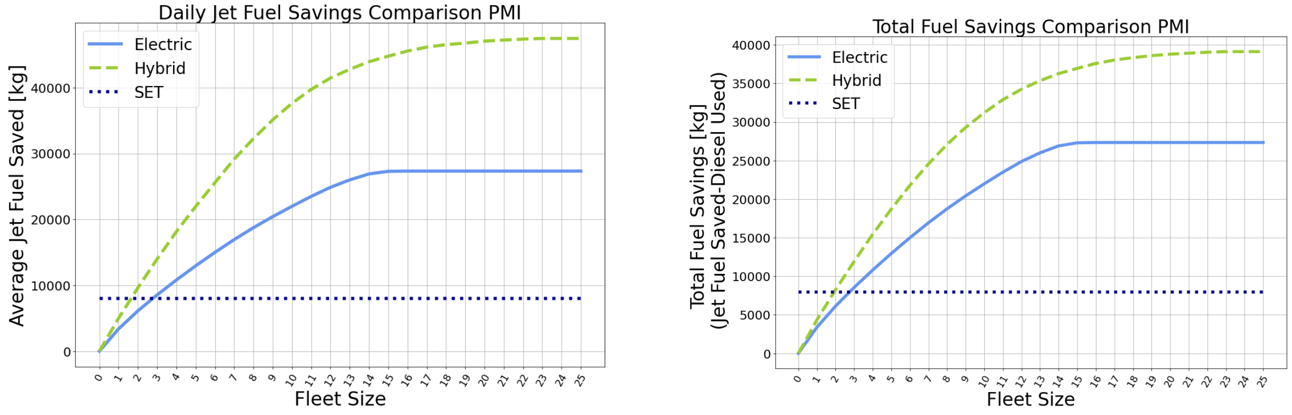


(c) CO_2 Savings Comparison OSL

(d) NO_x Savings Comparison OSL

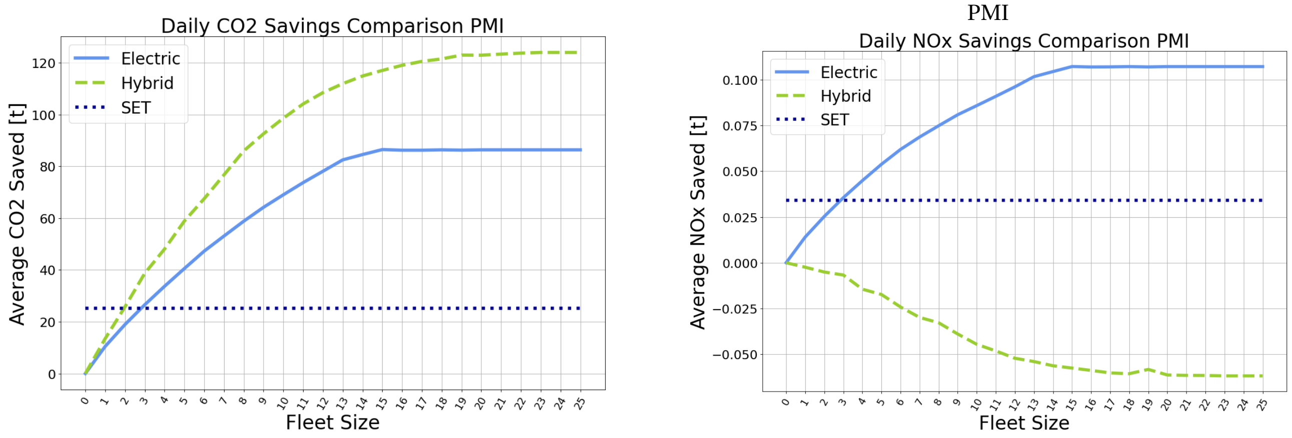
Figure B.23: Jet Fuel and Emissions Savings at OSL

Palma de Mallorca Airport: PMI



(a) Fuel Savings Comparison PMI

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) PMI

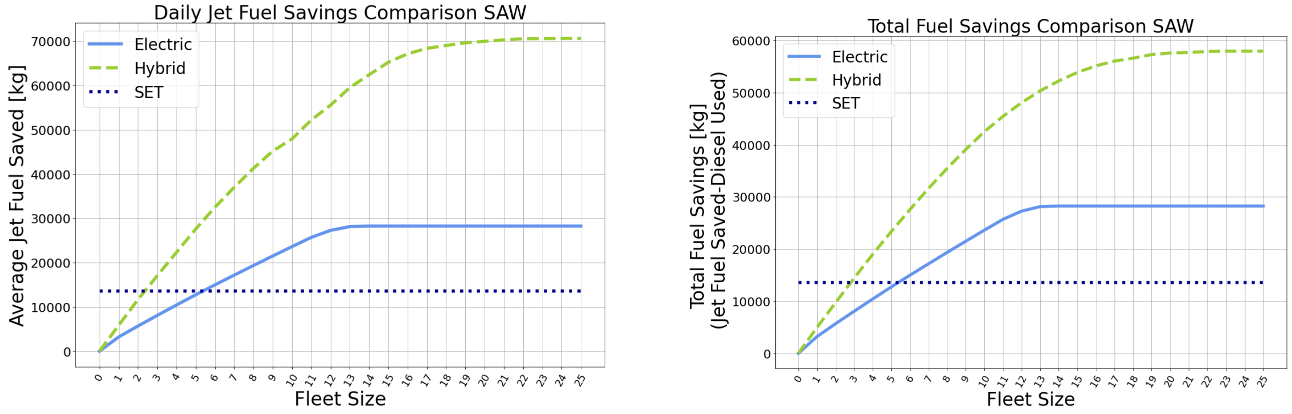


(c) CO_2 Savings Comparison PMI

(d) NO_x Savings Comparison PMI

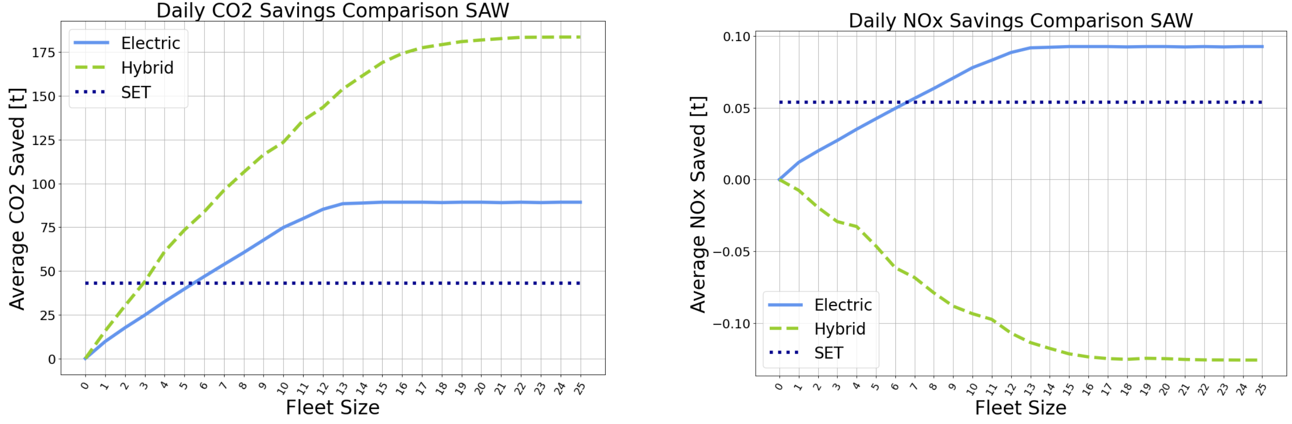
Figure B.24: Jet Fuel and Emissions Savings at PMI

Istanbul Sabiha Gokcen International Airport: SAW



(a) Fuel Savings Comparison SAW

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) SAW

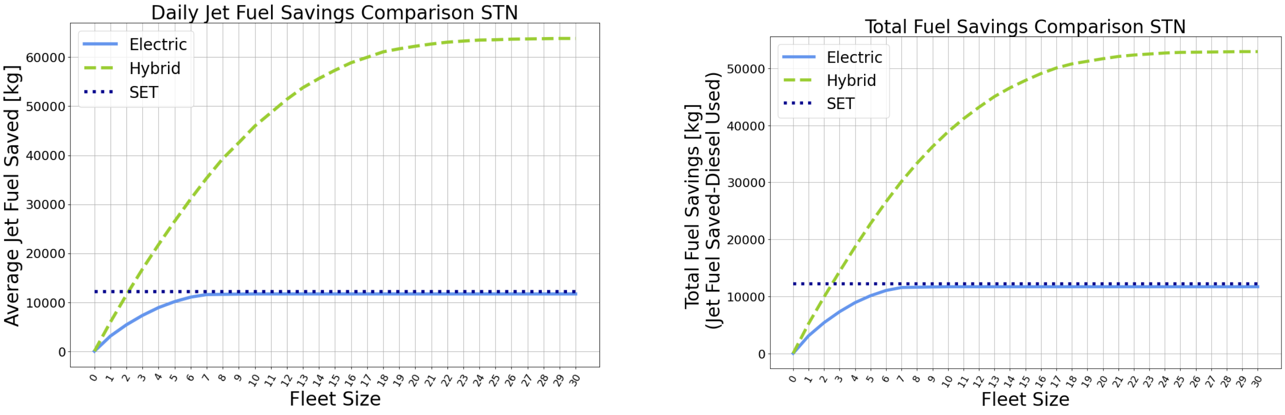


(c) CO_2 Savings Comparison SAW

(d) NO_x Savings Comparison SAW

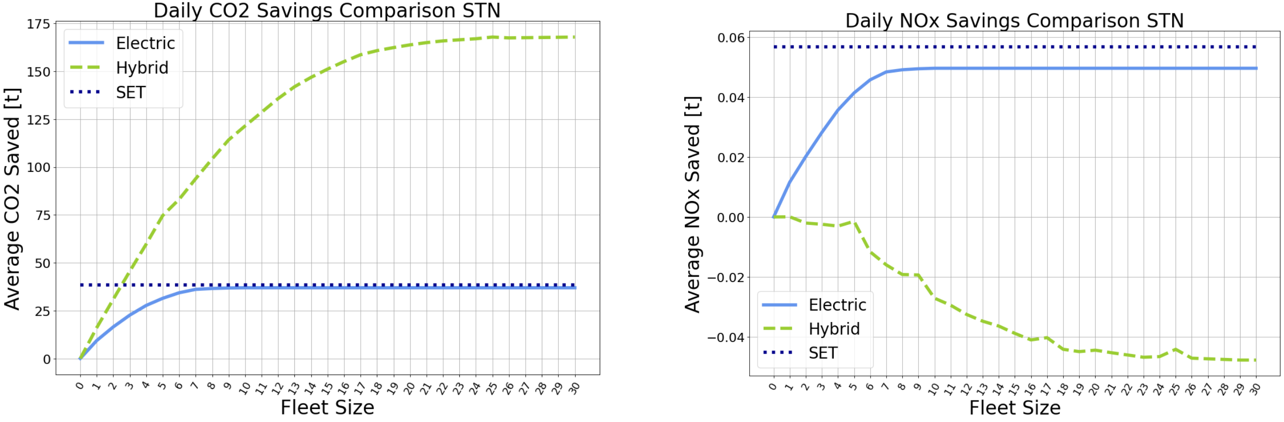
Figure B.25: Jet Fuel and Emissions Savings at SAW

London Stansted Airport: STN



(a) Fuel Savings Comparison STN

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) STN

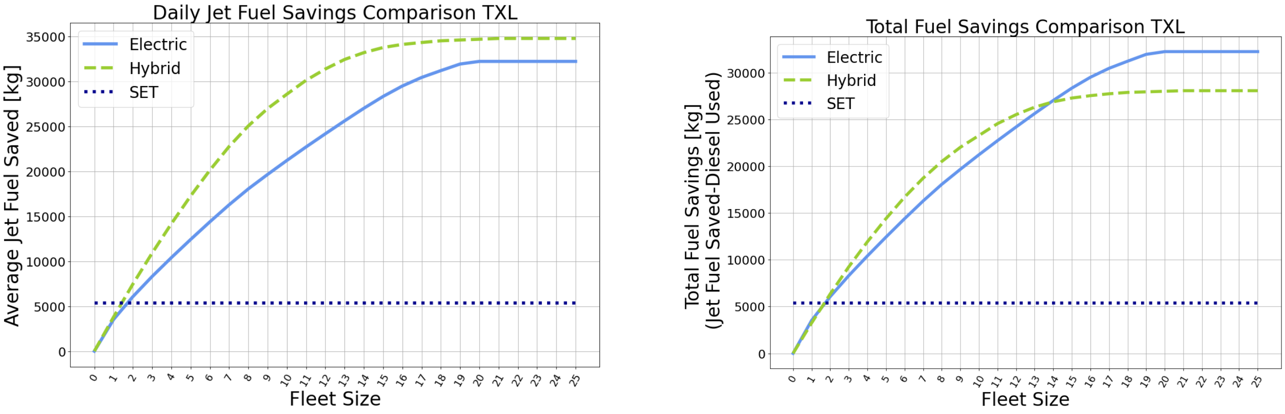


(c) CO_2 Savings Comparison STN

(d) NO_x Savings Comparison STN

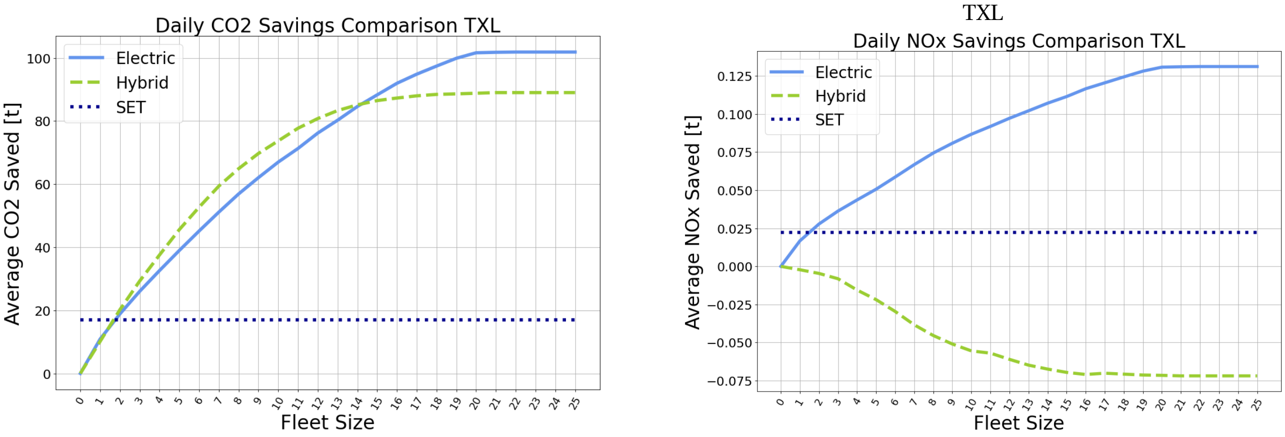
Figure B.26: Jet Fuel and Emissions Savings at STN

Berlin-Tegel Airport: TXL



(a) Fuel Savings Comparison TXL

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) TXL

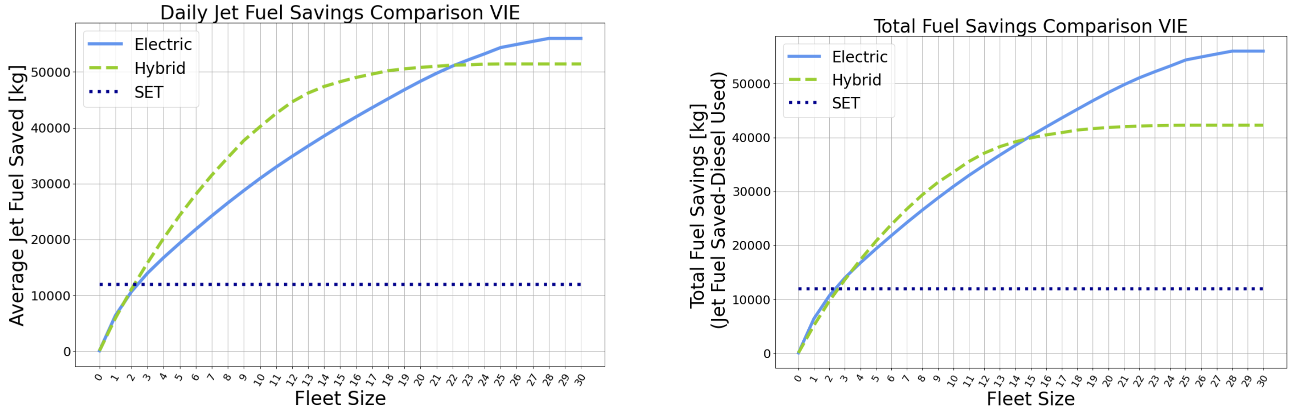


(c) CO_2 Savings Comparison TXL

(d) NO_x Savings Comparison TXL

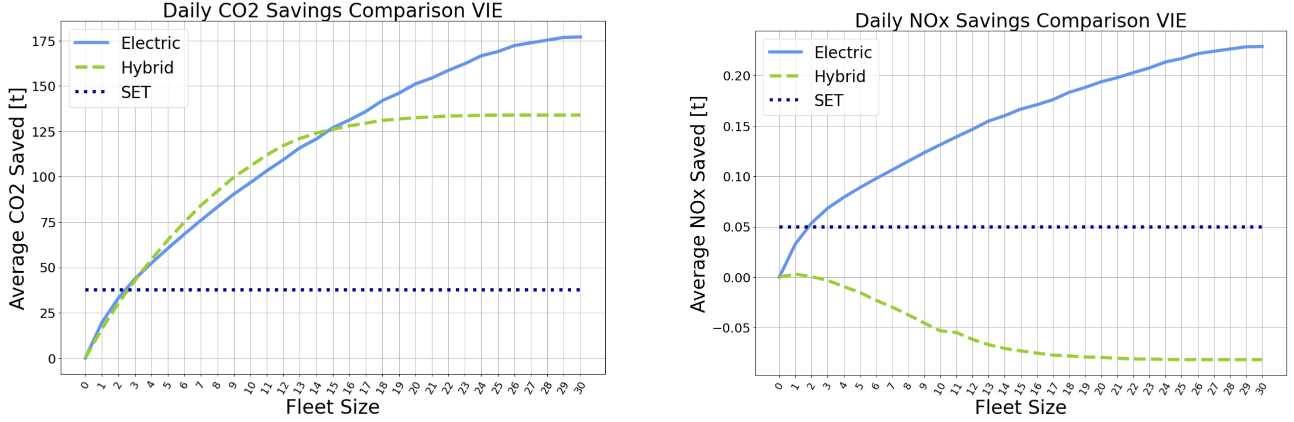
Figure B.27: Jet Fuel and Emissions Savings at TXL

Vienna International Airport: VIE



(a) Fuel Savings Comparison VIE

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) STN

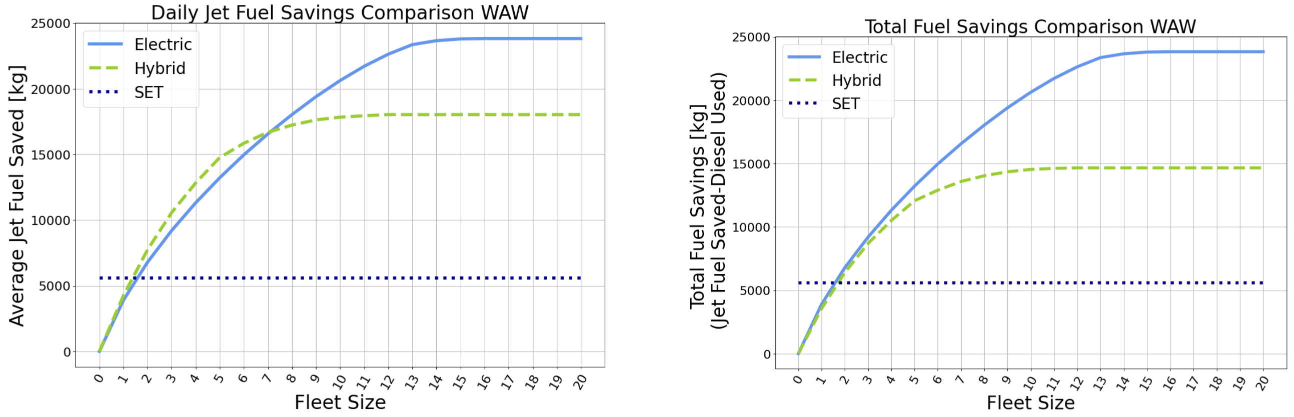


(c) CO_2 Savings Comparison STN

(d) NO_x Savings Comparison STN

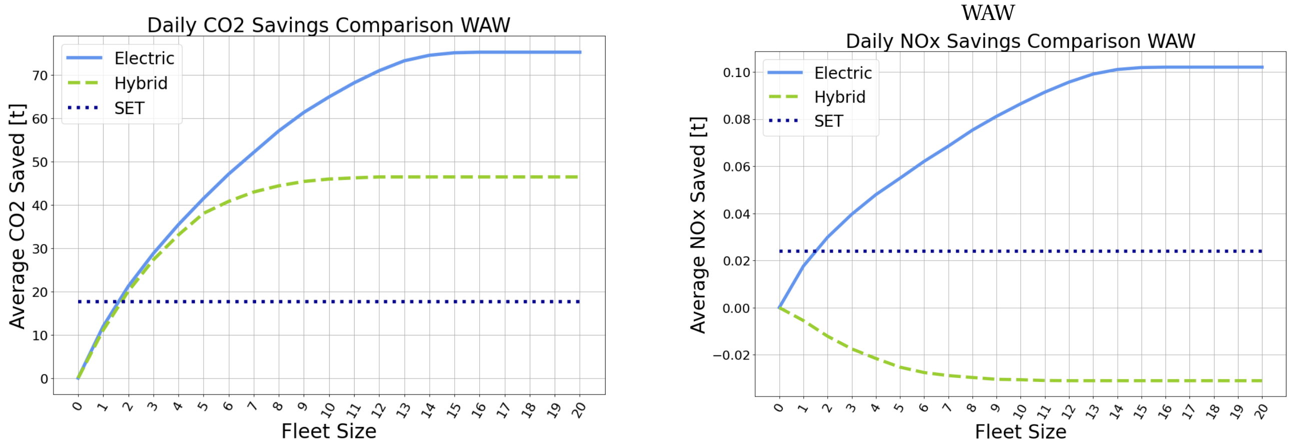
Figure B.28: Jet Fuel and Emissions Savings at STN

Warsaw Chopin Airport: WAW



(a) Fuel Savings Comparison WAW

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) WAW

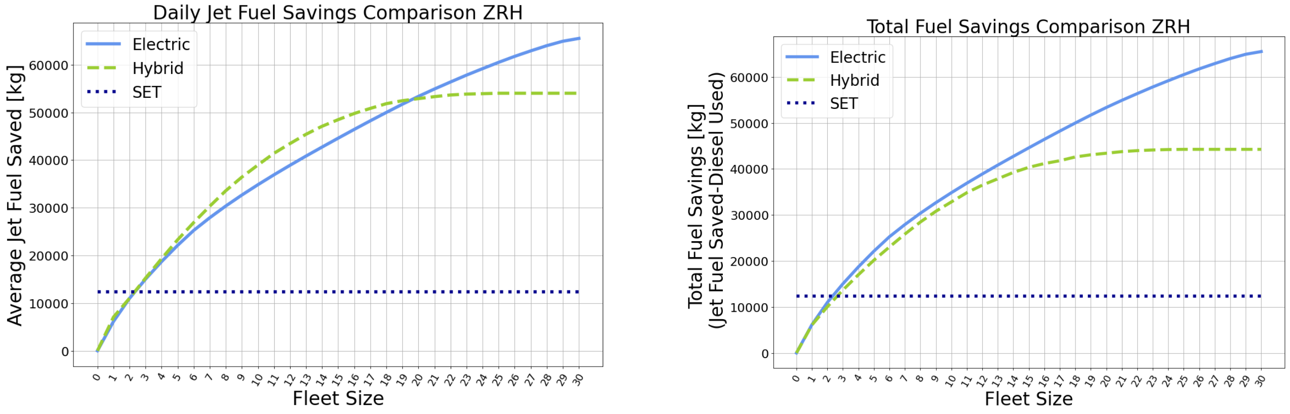


(c) CO_2 Savings Comparison WAW

(d) NO_x Savings Comparison WAW

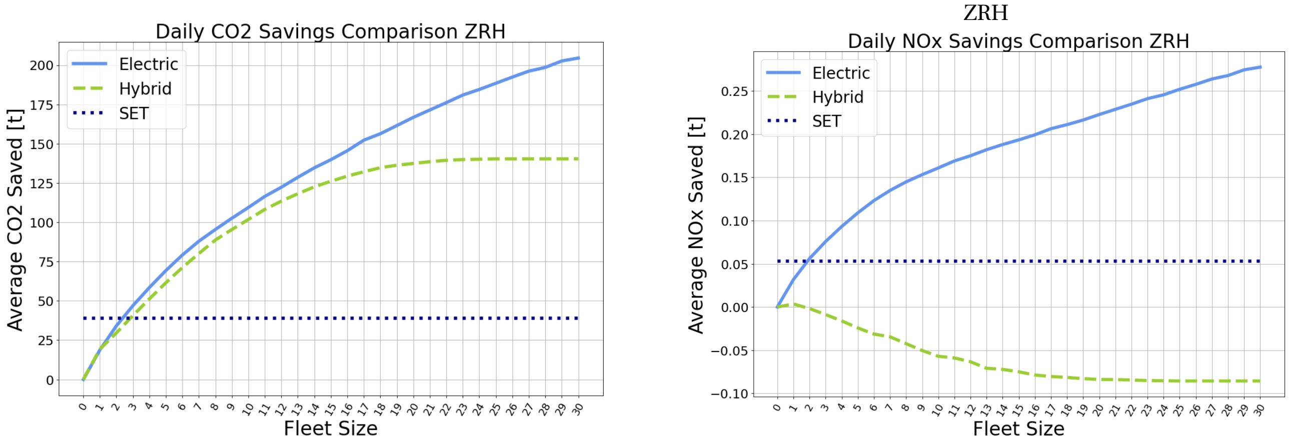
Figure B.29: Jet Fuel and Emissions Savings at WAW

Zurich Airport: ZRH



(a) Fuel Savings Comparison ZRH

(b) Total Fuel Comparison (Jet Fuel Savings - Diesel Used) ZRH



(c) CO_2 Savings Comparison ZRH

(d) NO_x Savings Comparison ZRH

Figure B.30: Jet Fuel and Emissions Savings at ZRH

C

Appendix C: Aircraft Engine Pairings

In Table C.1, the engine types used for each aircraft type are presented. The values presented in this table are used for the fuel flow and emissions calculations of each flight, as explained in the methodology section of the research paper. Values for emission indexes are taken from the International Civil Aviation Organization (2021) Aircraft Engine Emissions Databank.

Table C.1: Aircraft and engine pairings.

Identifier OAG2018	**Aircraft Type**	**Assumed Engine Type**	**Number Engines**	$\mathbf{EI_{CO_2}}$	$\mathbf{EI_{HC}}$	$\mathbf{EI_{NOx}}$
100	Fokker 100	1RR017	2	88.23	92.74	1.83
142	Avro RJ 85	LF507-1F	4	37.83	4.72	3.28
141	Avro RJ 70	LF507-1F	4	37.83	4.72	3.28
290	Embraer E190-E2	11GE147	2	41.73	4.02	3.69
C310	Cessna Super 310	propellor	-	-	-	-
313	Airbus A310-300	CF680C	2	43.91	9.74	3.67
318	Airbus A318	CFM56-5B5/3	2	41.77	3.55	3.81
319	Airbus A319 neo	01P18PW153	2	27.93	0.43	4.84
320	Airbus A320	7CM050	2	44.1	4.4	3.2
321	Airbus A321	1IA003	2	12.43	0.105	4.7
330	Airbus A330-300	7PW082	2	15.9	0.2	5.2
332	Airbus A330-200	5GE085	2	37.02	9.53	4.69
333	Airbus A330-300	7PW082	2	15.9	0.2	5.2
340	Cessna 340	CT79B	2	21.52594	10.95083	2.068706
C340	Cessna 340	propellor	-	-	-	-
343	Airbus A340-300	1CM011	4	32.6	5.35	4.26
345	Airbus A340-500	8RR045	4	9.96	0.13	6.09
346	Airbus A340-600	8RR045	4	9.96	0.13	6.09
350	Beechcraft King Air 350	propellor	-	-	-	-
351	Airbus A350-1000	01P18RR124	2	21.46	1.03	4.41
359	Airbus A350-900	01P18RR124	2	21.46	1.03	4.41
380	Airbus A380-800	01P18RR104	4	13	0.04	5.51
388	Airbus A380-800	01P18RR104	4	13	0.04	5.51
717	Boeing 717	4BR007	2	17.85	0.06	4.28
733	Boeing 737-300	1CM007	2	26.8	1.42	4.3
734	Boeing 737-400	1CM007	2	26.8	1.42	4.3
735	Boeing 737-500	1CM007	2	26.8	1.42	4.3
736	Boeing 737-600	01P11CM116	2	30.94	1.75	4.27
737	Boeing 737-700	3CM032	2	22	2.4	4.4
738	Boeing 737-800	01P11CM116	2	30.94	1.75	4.27
739	Boeing 737-900 / Boeing 737-900ER	3CM032	2	22	2.4	4.4
744	Boeing 747-400 / Boeing 747-400ER	01P03GE187	4	17.45	1.31	4.91
747	Boeing 747	1PW041	4	11.6	0.66	5
752	Boeing 757-200	3RR028	2	13.31	0.37	3.46
753	Boeing 757-300	3RR028	2	13.31	0.37	3.46
757	Boeing 757	13AA008	2	16.79	2.88	4.3
762	Boeing 767-200	1PW026	2	8.84	1.25	4.1
763	Boeing 767-300 / Boeing 767-300ER	1RR011	2	11.75	0.74	4.78

Table C.1: Aircraft and Engine pairings

Identifier OAG2018	Aircraft Type	Assumed Engine Type	Number Engines	EI_{CO_2}	EI_{HC}	EI_{NOx}
764	Boeing 767-400ER	8GE101	2	16.69	1.14	4.59
767	Boeing 767	1PW026	2	8.84	1.25	4.1
772	Boeing 777-200 / Boeing 777-200ER	8GE100	2	12.69	0.41	6.09
773	Boeing 777-300	9GE128	2	29.23	2.49	5.55
777	Boeing 777	9GE128	2	29.23	2.49	5.55
787	Boeing 787	12GE150	2	19.73	0.64	4.37
788	Boeing 787-8	12GE150	2	19.73	0.64	4.37
789	Boeing 787-9	12GE150	2	19.73	0.64	4.37
31Y	Airbus A310 Freighter	2GE037	2	21.97	1.9	4.49
32A	Airbus A320 (sharklets)	1IA003	2	12.43	0.105	4.7
32B	Airbus A321 (transcon)	1IA003	2	12.43	0.105	4.7
32N	Airbus A320neo	8IA010	2	12.43	0.11	4.7
32S	Airbus A320 (sharklets)	8IA010	2	12.43	0.11	4.7
33F	Airbus A330-200F	5GE085	2	37.02	9.53	4.69
33X	Airbus A330-200F	5GE085	2	37.02	9.53	4.69
73C	Boeing 737-300 Winglets	1CM007	2	26.8	1.42	4.3
73E	Boeing 737-500 Winglets	1CM007	2	26.8	1.42	4.3
73F	Boeing 737-400 Freighter	1CM007	2	26.8	1.42	4.3
73G	Boeing 737-700 / Boeing 737-700ER	3CM032	2	22	2.4	4.4
73H	Boeing 737-800 Winglets	3CM034	2	17.9	1.7	4.8
73J	Boeing 737-900 Winglets	3CM032	2	22	2.4	4.4
73L	Boeing 737-200	01P11CM116	2	30.94	1.75	4.27
73M	Boeing 737-800	01P11CM116	2	30.94	1.75	4.27
73N	Boeing 737-800	01P11CM116	2	30.94	1.75	4.27
73P	Boeing 737-400 Freighter	1CM007	2	26.8	1.42	4.3
73Q	Boeing 737-800	01P11CM116	2	30.94	1.75	4.27
73S	Boeing 737-200	01P11CM116	2	30.94	1.75	4.27
73W	Boeing 737-700 Winglets	3CM032	2	22	2.4	4.4
73Y	Boeing 737-800	01P11CM116	2	30.94	1.75	4.27
74E	Boeing 747-400M	1PW041	4	11.6	0.66	5
74F	Boeing 747-Freighter	1PW041	4	11.6	0.66	5
74H	Boeing 747-Hybrid	1PW041	4	11.6	0.66	5
74N	Boeing 747-8F	11GE139	4	18.95	0.57	4.43
74X	Boeing 747-Freighter	11GE139	4	18.95	0.57	4.43
74Y	Boeing 747-400F / Boeing 747-400ERF	01P03GE187	4	17.45	1.31	4.91
75F	Boeing 757-F	3RR028	2	13.31	0.37	3.46
75T	Boeing 757-300 (winglets)	3RR034	2	11.76	0.28	3.52

Table C.1: Aircraft and Engine pairings

Identifier OAG2018	Aircraft Type	Assumed Engine Type	Number Engines	EI_{CO_2}	EI_{HC}	EI_{NOx}
75W	Boeing 757-200 (winglets)	3RR028	2	13.31	0.37	3.46
76F	Boeing 767-F	1GE025	2	48.02	11.17	3.7
76W	Boeing 767-300 Winglets / Boeing 767-300ER	01P02GE188	2	18.42	1.43	4.81
76Y	Boeing 767-Freighter	1GE025	2	48.02	11.17	3.7
77F	Boeing 777-Freighter	8PW085	2	14.3	3.8	3.15
77L	Boeing 777-200LR	01P21GE217	2	34.58	3.64	5.51
77W	Boeing 777-300ER	01P21GE217	2	34.58	3.64	5.51
77X	Boeing 777-200 Freighter	8PW085	2	14.3	3.8	3.15
7M8	Boeing 737 MAX 8	01P20CM138	2	13.77	0.46	4.68
7M9	Boeing 737 MAX 9	01P20CM138	2	13.77	0.46	4.68
7S8	Boeing 737-800	01P11CM116	2	30.94	1.75	4.27
A32	Antonov An-32	propellor	-	-	-	-
A4F	Antonov 124 Ruslan	1AA005	4	6.9	0.3	5.8
A81	Antonov An-148	1AA005	4	6.9	0.3	5.8
AB6	Airbus A300-600	2GE040	2	19.76	1.59	4.68
ABF	Airbus A300	2GE039	2	18.89	1.48	4.76
ABX	Boeing 767-200s	1PW026	2	8.84	1.25	4.1
ABY	Airbus A300-600	2GE040	2	19.76	1.59	4.68
AR8	Avro RJ85	AS907-3-1E-A3	4	28.08	0.84	4.04
ARJ	Comac ARJ-21-700 Xiangfeng	CF34-10A16	2	52.05	6.96	3.45
AT4	ATR 42F	propellor	-	-	-	-
AT7	ATR72-600	propellor	-	-	-	-
ATF	ATR 72F	propellor	-	-	-	-
ATP	British Aerospace ATP	propellor	-	-	-	-
ATR	ATR 42	propellor	-	-	-	-
ATZ	ATR 42F	propellor	-	-	-	-
BEH	Beechcraft 1900	propellor	-	-	-	-
BET	Hawker Beechcraft Twin Turboprop	propellor	-	-	-	-
CNA	Cessna 402	propellor	-	-	-	-
CNC	Cessna Light aircraft-single turboprop engine	propellor	-	-	-	-
CR2	Canadair Regional Jet 200	CF34-8C5	2	18.25	0.13	4.6
CR7	Canadair Regional Jet 700	CF34-8C5A1	2	17.85	0.13	4.65
CR9	Canadair Regional Jet 900	CF34-8C5A2	2	17.3	0.13	4.7
CRF	Canadair Regional Jet Freighter	CF34-8C5	2	18.25	0.13	4.6
CRJ	Canadair Regional Jet	CF34-8C5	2	18.25	0.13	4.6
CRK	Canadair Regional Jet 1000	CF34-8C5A3	2	16.71	0.12	4.76
CS1	Bombardier CS100	01P20PW184	2	19.3	0.1	5.6

Table C.1: Aircraft and Engine pairings

Identifier OAG2018	Aircraft Type	Assumed Engine Type	Number Engines	EI_{CO_2}	EI_{HC}	EI_{NOx}
CS3	Bombardier CS300	01P20PW184	2	19.3	0.1	5.6
D38	Dornier 328	propellor	-	-	-	-
DH1	Bombardier Dash-8-100	propellor	-	-	-	-
DH3	Bombardier Dash-8-300	propellor	-	-	-	-
DH4	Bombardier Dash-8-400	propellor	-	-	-	-
DH8	Bombardier Dash-8	propellor	-	-	-	-
E70	Embraer 170	01P22PW169	2	14.2	0.01	5.1
E75	Embraer 175 (short wing)	CF34-8E5	2	18.16	0.13	4.61
E7W	Embraer 175 (long wing)	CF34-8E5	2	18.16	0.13	4.61
E90	Embraer 190	11GE147	2	41.73	4.02	3.69
E95	Embraer 195	11GE147	2	41.73	4.02	3.69
EM2	Embraer 120 Brasilia	propellor	-	-	-	-
ER3	Embraer RJ135	01P06AL034	2	41.29	4.1	4.12
ER4	Embraer RJ145	01P06AL030	2	38.47	3.81	4.27
ERD	Embraer ERJ-140	01P06AL030	2	38.47	3.81	4.27
ERJ	Embraer RJ135	01P06AL030	2	38.47	3.81	4.27
F50	Fokker 50	propellor	-	-	-	-
FRJ	Fairchild Dornier 328JET	PW306A	2	36.35	4.36	4.26
IL9	The Ilyushin Il-96	1AA005	4	6.9	0.3	5.8
J31	Jetstream 31	propellor	-	-	-	-
J32	Jetstream 32	propellor	-	-	-	-
M1F	McDonnell Douglas MD-11	12PW102	3	42.61	10.86	3.78
M80	McDonnell Douglas MD-80	1PW007	2	14.14	3.12	2.9
M82	McDonnell Douglas MD-82	4PW068	2	15.31	0	4.57
M83	McDonnell Douglas MD-83	JT8D-219		17.19	0	4.16
M88	McDonnell Douglas MD-88	1PW018	2	12.27	3.33	3.7
M90	Mitsubishi SpaceJet	11GE147	2	41.73	4.02	3.69
PL2	Pilatus PC-12	propellor	-	-	-	-
S20	Saab 2000	PW127A	2	9.3	0	6.6
SH6	Short 360	propellor	-	-	-	-
SU9	Sukhoi Superjet 100-95	SaM146-1S18	2	27.55	0.82	3.82
T20	Arcturus T-20	propellor	-	-	-	-
TGV	Airbus A310	8PW086	2	84.1	36.5	3.1

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Appendix D: Aircraft Compatibility

In Table D.1, the aircraft compatibility matrix and wake turbulence categorization of each aircraft is presented. The values presented in this table are used for the compatibility constraints of the MILP assignment model as explained in the methodology section of the research paper. Compatibility data is based on data from the vehicle manufacturers Smart Airport Systems (2020a,b); Goldhofer (2022).

Table D.1: Vehicle compatibility per aircraft type.

Identifier OAG2018	**Aircraft Type**	**Taxibot NB**	**Taxibot WB**	**Phoenix E**	**Wake Turbulence Category**
100	Fokker 100	0	0	0	M
142	Avro RJ 85	0	0	0	M
141	Avro RJ 70	0	0	0	M
290	Embraer E190-E2	0	0	1	M
C310	Cessna Super 310	0	0	0	L
313	Airbus A310-300	0	0	0	M
318	Airbus A318	1	0	1	M
319	Airbus A319 neo	1	0	1	M
320	Airbus A320	1	0	1	M
321	Airbus A321	1	0	1	M
330	Airbus A330-300	0	1	1	H
332	Airbus A330-200	0	1	1	H
333	Airbus A330-300	0	1	1	H
340	Cessna 340	0	0	0	M
C340	Cessna 340	0	0	0	L
343	Airbus A340-300	0	1	1	H
345	Airbus A340-500	0	1	1	H
346	Airbus A340-600	0	1	1	H
350	Beechcraft King Air 350	0	0	0	L
351	Airbus A350-1000	0	1	1	H
359	Airbus A350-900	0	1	1	H
380	Airbus A380-800	0	1	0	J
388	Airbus A380-800	0	1	0	J
717	Boeing 717	0	0	0	M
733	Boeing 737-300	1	0	0	M
734	Boeing 737-400	1	0	0	M
735	Boeing 737-500	1	0	0	M
736	Boeing 737-600	1	0	0	M
737	Boeing 737-700	1	0	0	M
738	Boeing 737-800	1	0	0	M
739	Boeing 737-900 / Boeing 737-900ER	1	0	0	M
744	Boeing 747-400 / Boeing 747-400ER	0	1	0	J
747	Boeing 747	0	1	0	J
752	Boeing 757-200	1	0	1	M
753	Boeing 757-300	1	0	1	M
757	Boeing 757	1	0	1	M
762	Boeing 767-200	0	1	1	H

Table D.1: Vehicle compatibility per aircraft type.

Identifier OAG2018	**Aircraft Type**	**Taxibot NB**	**Taxibot WB**	**Phoenix E**	**Wake Turbulence Category**
763	Boeing 767-300 / Boeing 767-300ER	0	1	1	H
764	Boeing 767-400ER	0	1	1	H
767	Boeing 767	0	1	1	H
772	Boeing 777-200 / Boeing 777-200ER	0	0	1	H
773	Boeing 777-300	0	0	1	H
777	Boeing 777	0	0	1	H
787	Boeing 787	0	1	1	H
788	Boeing 787-8	0	1	1	H
789	Boeing 787-9	0	1	1	H
31Y	Airbus A310 Freighter	0	0	0	M
32A	Airbus A320 (sharklets)	1	0	1	M
32B	Airbus A321 (transcon)	1	0	1	M
32N	Airbus A320neo	1	0	1	M
32S	Airbus A320 (sharklets)	1	0	1	M
33F	Airbus A330-200F	0	1	1	H
33X	Airbus A330-200F	0	1	1	H
73C	Boeing 737-300 Winglets	1	0	0	M
73E	Boeing 737-500 Winglets	1	0	0	M
73F	Boeing 737-400 Freighter	1	0	0	M
73G	Boeing 737-700 / Boeing 737-700ER	1	0	0	M
73H	Boeing 737-800 Winglets	1	0	0	M
73J	Boeing 737-900 Winglets	1	0	0	M
73L	Boeing 737-200	1	0	0	M
73M	Boeing 737-800	1	0	0	M
73N	Boeing 737-800	1	0	0	M
73P	Boeing 737-400 Freighter	1	0	0	M
73Q	Boeing 737-800	1	0	0	M
73S	Boeing 737-200	1	0	0	M
73W	Boeing 737-700 Winglets	1	0	0	M
73Y	Boeing 737-800	1	0	0	M
74E	Boeing 747-400M	0	1	0	J
74F	Boeing 747-Freighter	0	1	0	J
74H	Boeing 747-Hybrid	0	1	0	J
74N	Boeing 747-8F	0	1	0	J
74X	Boeing 747-Freighter	0	1	0	J
74Y	Boeing 747-400F / Boeing 747-400ERF	0	1	0	J

Table D.1: Vehicle compatibility per aircraft type.

Identifier OAG2018	Aircraft Type	Taxibot NB	Taxibot WB	Phoenix E	Wake Turbulence Category
75F	Boeing 757-F	1	0	1	M
75T	Boeing 757-300 (winglets)	1	0	1	M
75W	Boeing 757-200 (winglets)	1	0	1	M
76F	Boeing 767-F	0	1	1	H
76W	Boeing 767-300 Winglets / Boeing 767-300ER	0	1	1	H
76Y	Boeing 767-Freighter	0	1	1	H
77F	Boeing 777-Freighter	0	0	1	H
77L	Boeing 777-200LR	0	0	1	H
77W	Boeing 777-300ER	0	0	1	H
77X	Boeing 777-200 Freighter	0	0	1	H
7M8	Boeing 737 MAX 8	1	0	1	M
7M9	Boeing 737 MAX 9	1	0	1	M
7S8	Boeing 737-800	1	0	1	M
A32	Antonov An-32	0	0	0	M
A4F	Antonov 124 Ruslan	0	0	0	J
A81	Antonov An-148	0	0	0	J
AB6	Airbus A300-600	0	0	0	H
ABF	Airbus A300	0	0	0	H
ABX	Boeing 767-200s	1	0	1	H
ABY	Airbus A300-600	0	0	0	H
AR8	Avro RJ85	0	0	0	M
ARJ	Comac ARJ-21-700 Xiangfeng	0	0	0	M
AT4	ATR 42F	0	0	0	M
AT7	ATR72-600	0	0	0	M
ATF	ATR 72F	0	0	0	M
ATP	British Aerospace ATP	0	0	0	M
ATR	ATR 42	0	0	0	M
ATZ	ATR 42F	0	0	0	M
BEH	Beechcraft 1900	0	0	0	M
BET	Hawker Beechcraft Twin Turboprop	0	0	0	M
CNA	Cessna 402	0	0	0	M
CNC	Cessna Light aircraft-single turboprop engine	0	0	0	M
CR2	Canadair Regional Jet 200	0	0	0	M
CR7	Canadair Regional Jet 700	0	0	0	M
CR9	Canadair Regional Jet 900	0	0	0	M
CRF	Canadair Regional Jet Freighter	0	0	0	M
CRJ	Canadair Regional Jet	0	0	0	M

Table D.1: Vehicle compatibility per aircraft type.

Identifier OAG2018	**Aircraft Type**	**Taxibot NB**	**Taxibot WB**	**Phoenix E**	**Wake Turbulence Category**
CRK	Canadair Regional Jet 1000	0	0	0	M
CS1	Bombardier CS100	0	0	1	M
CS3	Bombardier CS300	0	0	1	M
D38	Dornier 328	0	0	0	M
DH1	Bombardier Dash-8-100	0	0	0	M
DH3	Bombardier Dash-8-300	0	0	0	M
DH4	Bombardier Dash-8-400	0	0	0	M
DH8	Bombardier Dash-8	0	0	0	M
E70	Embraer 170	0	0	1	M
E75	Embraer 175 (short wing)	0	0	1	M
E7W	Embraer 175 (long wing)	0	0	1	M
E90	Embraer 190	0	0	1	M
E95	Embraer 195	0	0	1	M
EM2	Embraer 120 Brasilia	0	0	0	M
ER3	Embraer RJ135	0	0	0	M
ER4	Embraer RJ145	0	0	0	M
ERD	Embraer ERJ-140	0	0	0	M
ERJ	Embraer RJ135	0	0	0	M
F50	Fokker 50	0	0	0	M
FRJ	Fairchild Dornier 328JET	0	0	0	M
IL9	The Ilyushin Il-96	0	0	0	H
J31	Jetstream 31	0	0	0	M
J32	Jetstream 32	0	0	0	M
M1F	McDonnell Douglas MD-11	0	0	1	H
M80	McDonnell Douglas MD-80	0	0	0	M
M82	McDonnell Douglas MD-82	0	0	0	M
M83	McDonnell Douglas MD-83	0	0	0	M
M88	McDonnell Douglas MD-88	0	0	0	M
M90	Mitsubishi SpaceJet	0	0	0	M
PL2	Pilatus PC-12	0	0	0	L
S20	Saab 2000	0	0	0	M
SH6	Short 360	0	0	0	M
SU9	Sukhoi Superjet 100-95	0	0	0	M
T20	Arcturus T-20	0	0	0	M
TGV	Airbus A310	0	0	0	M

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