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van Oosterom, S.J.M.; Mitici, M.A.

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# Analyzing the impact of battery capacity and charging protocols when dispatching electric vehicles for aircraft towing

Simon van Oosterom* and Mihaela Mitici †
*Faculty of Aerospace Engineering, Delft University of Technology, Delft, the Netherlands*

**The aviation industry aims for net-zero emissions by 2050. In this line, achieving climate-neutral ground operations is one of the first objectives. Electric vehicles that tow aircraft during taxiing are a promising technology to achieve climate-neutral ground operations. In this paper, we consider the dispatching of electric towing vehicles at an airport. We study the impact of the maximum battery capacity of these vehicles and the battery recharging protocols, on the total number of electric towing vehicles required at an airport. We propose a mixed-integer linear program to determine the size of the fleet of electric towing vehicles under various battery capacities and various battery recharging protocols. We illustrate our model for one day of operations at Amsterdam Airport Schiphol. The results show that 41, 29, and 24 ETVs are required to tow all aircraft when batteries capacities of 100 kWh, 320 kWh, and 500 kWh are considered, respectively. Compared with the best performing approach existing in literature, our model reduces the required size of the fleet of electric towing vehicles by 27% when considering a nominal battery size of 320 kWh.**



## I. Introduction

Striving to meet climate-neutral targets set by the Paris Accords [1], the aviation industry aims for net-zero emissions by 2050 [2, 3]. For some actors, like the Schiphol Group airport operator [4], the first step to achieve this is by creating climate neutral ground operations by 2030.

Aircraft taxiing has been shown to be a large contributor to airport ground emissions, and will have to be addressed in order to achieve zero ground emissions. In fact, it has been shown that around 56% of the $NO_x$ emissions at London Heathrow result from taxiing aircraft [5]. Additionally, taxiing from and to the runway has been estimated to produce between 4% and 9% of the total flight emissions [6].

One of the promising means to reduce emissions in the near future is to tow aircraft using Electric Towing Vehicles (ETVs). The management of a fleet of ETVs is, however, a complex logistical problem. It concerns the assignment of to-be-towed aircraft to ETVs, while ensuring that enough time remains for the vehicles to recharge their batteries, which can take up to several hours. An efficient management of the ETV fleet is key for a successfully implementation.

ETV fleet management optimization has been addressed scarcely, and only with simple battery recharging protocols. For instance, in Soltani et al. [7] the authors consider an ETV fleet where each vehicle has to be assigned to a subset of flights from a given flight schedule such that the environmental impact of the ETV fleet is maximized. The authors consider a charging protocol where ETVs can only recharge during the night. As such, the energy available for each ETV is limited, and hence it can tow only a limited number of aircraft. The same problem has been addressed by Van Baaren and Roling [8], while allowing for multiple battery charges during the day. This study assumes a charging protocol where ETVs can recharge their battery throughout the day, and where their batteries are charged up to full capacity at each visit. The authors also assume that ETVs charge for a fixed amount of time, irrespective of the remaining state of charge of the batteries. This, however, results in an overestimation of the charging time. As a consequence, the required vehicle fleet size is overestimated and the ETV available for towing are used inefficiently.

To address these limitations, we consider the management of a fleet of ETVs with a preemptive charging protocol. In this protocol, the charging time of ETVs depends on the residual battery charge, and allows for multiple partial recharging opportunities during the day of the operations. Also, the ETVs do not necessarily recharge to their maximum capacity at each visit to a charging station. All flights that are eligible to be towed are towed by ETVs. As such, the objective of our optimization problem is to minimize the required number of ETVs to tow all aircraft. The output of the model is an assignment of ETVs to aircraft throughout the day, as well as a battery recharging schedule for each ETV. We formulate our model as a Mixed Integer Linear Programming problem.

*PhD student, Air Transport Operations research group, S.J.M.vanOosterom@tudelft.nl
†Assistant Professor, Air Transport Operations research group, M.A.Mitici@tudelft.nl

We illustrate our approach for a day of operations at Amsterdam Airport Schiphol, where we analyze the impact of the ETV battery size and used charging protocol. We compare our preemptive charging protocol with the ones used in Soltani et al. [7] and in Van Baaren and Roling [8]. The flight schedule from the 14th of December of 2019 is used, where 750 flights are considered eligible to be towed. We consider a range of ETV battery capacities between 100 kWh and 500 kWh, where 500 kWh is sufficiently large to tow aircraft continuously. Special attention is given to the nominal case where the battery capacity is 320 kWh. In this case, ETVs are able to tow about 10 aircraft on a single charge.

The results show that the partial charging protocol provides a significant reduction in ETV fleet size over the formulations used in Van Baaren and Roling and in Soltiani et al.. In the nominal case (320 kWh batteries), the ETV scheduling model with a preemptive charging protocol requires a fleet of 29 ETVs, whereas the methods from Van Baaren and Roling and from Soltani et al. require 40 ETVs and 66 ETVs, respectively. Second, we observe a significant trade-off between the ETV battery size and the required fleet size. Decreasing the battery size from 320 kWh to 100 kWh results in requiring 12 additional ETVs, whereas an increase to 500 kWh or more is required in order to remove battery life as a constraining factor.

The remainder of this paper is organized as follows. In Section II the ETV scheduling problem is introduced, and in Section III we describe the energy consumption model of the ETVs. A Mixed Integer Linear Programming formulation of the ETV scheduling problem is presented in Section IV, and this model is applied in a case study in Section V. Finally, the conclusions of this study are presented in Section VI.

## II. Problem description - Electric Towing Vehicles scheduling

We consider the dispatchment of a fleet of ETVs for towing aircraft to and from gates and runways. During the day, the ETVs may need to recharge their batteries. While recharging, the ETVs are not available for towing. We study the impact of the maximum battery capacity of the and the protocols for battery charging on the size of the fleet of ETVs.

### A. Airport taxiway and service road network

We consider an airport with two road networks: the taxiway network, used by aircraft towed by ETVs, and the service road network, used for ETVs not attached by an aircraft. The taxiway network is given by a graph $G_X = (N_X, E_X)$ consisting of nodes $N_X$ and directed edges $E_X$. Distances on the taxiway network are given by $d_X : E_X \to \mathbb{R}$. The service road network, used by ETVs to traverse the airport when not towing aircraft, is given by the graph $G_S = (N_S, E_S)$ with nodes $N_S$ and edges $E_S$. Distances on the service road network are given by $d_S : E_S \to \mathbb{R}$.

Let $N_R$ and $N_G$ denote the set of runway entrance and exit nodes and gate nodes, respectively. These are the locations where an aircraft can be picked-up or dropped-off by an ETV. These nodes are in both the taxiway and serviceroad network ($N_R \cup N_G \subset N_X \cap N_S$). Finally, there are a number of ETV recharging stations within the service road network: $N_{CS} \subset N_S$. Figure 1 gives an example of the airport road networks.

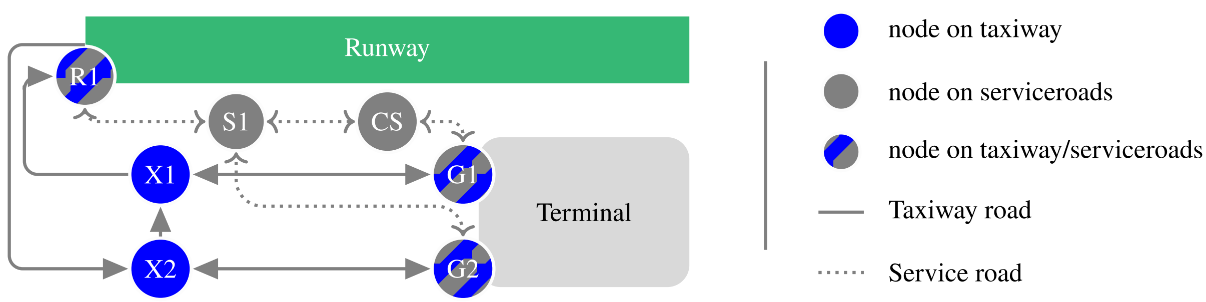



**Fig. 1 Example of an airport taxiway network and a service road network. Here $N_X = \{R1, X1, X2, G1, G2\}$, $E_X = \{(R1, X2), (X2, X1), (X1, R1), (X1, G1), (G1, X1), (G2, X2), (X2, G2)\}$, $N_S = \{R1, S1, CS, G1, G2\}$ and $E_S = \{\{R1, S1\}, \{S1, G2\}, \{S1, CS\}, \{CS, G1\}\}$. The runway entrance and exit is located at node $R1$, and the gates are located at nodes $G1$ and $G2$. The charging station is located at node $CS$.**

We are interested in determining the minimum size of a fleet of ETVs such that all aircraft operating a set of flights $A$ are towed. For this fleet of ETVs we will propose an assignment of ETVs to tow specific flights from $A$, and a battery recharging schedule conform a charging protocol.

### B. ETV specifications

We consider a single type of ETV to tow all eligible flights. These ETVs are equipped with a battery of capacity $Q$, which has a gravimetric energy density of $m_q$. The basic mass of an ETV, excluding the battery, is given by $m_0$. The total mass of an ETV is given by $m = m_0 + m_q \times Q$. The power required by ETVs to traverse the airport is given by $P$, which is a function of the velocity and towed mass. Finally, ETVs recharge their batteries with power $P^c$.

We assume that ETVs traverse the road networks with constant velocity and using the shortest path. A velocity of $v_x$ and $v_s$ is maintained on the taxiway and service roads respectively. For any two nodes $m, n \in N_X$, denote the shortest distance from $m$ to $n$ on $G_X$ (using $d_X$ as a distance metric) as $d_X^{SP}(m, n)$. Similarly, for two nodes $m, n \in N_S$, denote the shortest distance from $m$ to $n$ in $G_S$ (using $d_S$ as a distance metric) as $d_S^{SP}(m, n)$. Both $d_X^{SP}$ and $d_S^{SP}$ can be computed with, e.g., Dijkstra's shortest path algorithm.

### C. Aircraft arrival/departure flight schedule

Let the interval $T$ denote a day of operations at the airport, with a length of 24 hours. Let $A$ denote the set of flights which arrives at or departs from the airport during $T$ and are eligible/certified to be towed by an ETV. Each arriving aircraft is to be towed from its pick-up runway node in $N_R$ to its drop-off gate node in $N_G$; the reverse holds for departing aircraft. For an aircraft $a \in A$, let $n_a^p \in N_G \cup N_R$ denote its pick-up location and let $n_a^d \in N_G \cup N_R$ denote its drop-off location. The time at which $a$ is to be picked-up at $n_a^p$ is given by $t_a^p \in T$. As such, the drop-off time of $a$ at $n_a^d$ is given by $t_a^d = t_a^p + d_X^{SP}(n_a^p, n_a^d)/v_X$.

### D. ETV battery charging protocol

By towing aircraft and driving across the service roads, ETVs deplete their battery. ETVs recharge their batteries at one of the charging station in $N_{CS}$. Charging is done with power $P^c$. At the end of the day of operations, all vehicles return to a depot $n^{dep} \in N_{CS}$ to fully recharge their battery before the start of the next day of operations.

In this paper we consider three different charging protocols:

1) **ETV battery night-charging (NC)**: This battery charging protocol assumes that the ETVs are recharged only after performing their last tow of the day. In other words, we assume that the battery of the ETVs is large enough to support several towing tasks during a day of operations. Recharging is required only during the night, when no more towing tasks need to be performed. This protocol has been used in Soltani et al. [7].
2) **The constant-time ETV battery charging (CTC)**: This battery charging protocol allows for ETVs to charge throughout the day of operations. Under this protocol, every time ETVs re-charge their batteries they are charged to full capacity. Battery recharging takes a constant time $Q/P^c$, irrespective of the residual charge of the battery. This protocol has been used in Van Baaren and Roling [8].
3) **The partial ETV battery charging (PC)**: This battery charging protocol allows for ETV battery charging throughout the day, but permits preemptive charging. As such, ETVs may leave the charging station without a full battery. The charge loaded in the battery depends on the time spent at the charging station.

Fig. 2 shows a simple example of charging protocols NC, CTC and PC. For simplicity, in this example we assume that towing an aircraft always requires 30% of the battery capacity of an ETV. The NC protocol postpones charging for the night period, while CTC and PC protocols allow for battery charging during the day.

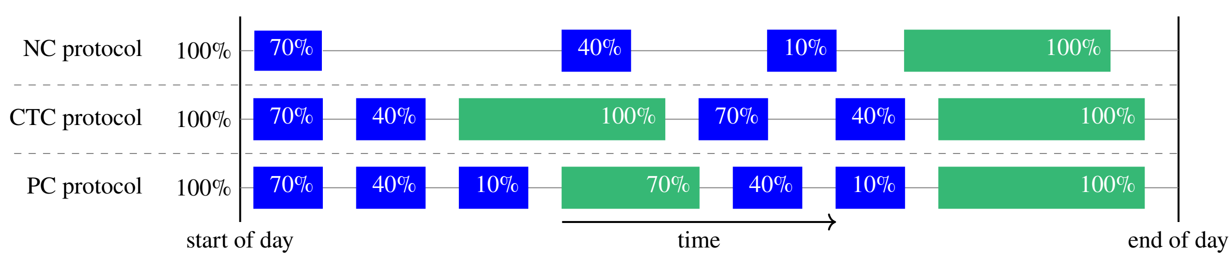



**Fig. 2 Example of ETV battery re-charging schedules under charging protocols NC, CTC, and PC. In this example, towing an aircraft always requires 30% of the ETV battery capacity (blue blocks). ETV battery recharging is indicated by green boxes.**

# III. ETV energy consumption

The energy consumed by an ETV per unit of time, $P$, depends on the velocity $v$ and mass that it is towing $m_{tow}$:

$$P(v, m_{tow}) = \mu^g(v) \times (m + m_{tow}) \times g \times v, \tag{1}$$

$$\mu^g(v) = \mu^0 \times \left(1 + v/v^0\right), \tag{2}$$

where $\mu^g$ is the coefficient of rolling resistance, which depends on the velocity and on the constants $\mu^0$ and $v^0$. The gravitational acceleration is denoted by $g$. As such, the energy consumed by an ETV while towing aircraft $a \in A$ is denoted by $q^X(a)$ and is given by:

$$q^X(a) = d_X^{SP}(n_a^p, n_a^d)/v_x \times P(v_x, m_a) \tag{3}$$

The energy required by an ETV to traverse the service roads (where $m_{tow} = 0$) from $n$ to $m \in N_S$ is given by:

$$q^S(n, m) = d_S^{SP}(n, m)/v_s \times P(v_s, 0) \tag{4}$$

For simplicity, we use the following notation for aircraft $a, b \in A$:

$$q_f^S(a) := q^S(n^{dep}, n^p(a)), \qquad q_l^S(a) := q^S(n^d(a), n^{dep}), \qquad q_d^S(a, b) := q^S(n^d(a), n^p(b)), \tag{5}$$

where $q_f^S(a)$ denotes the energy to drive from the depot to the pick-up point of $a$, $q_l^S(a)$ the energy to drive from the drop-off point of $a$ back to the depot. Finally, $q_d^S(a, b)$ denotes the required energy to drive directly from the drop-off point of $a$ to the pick-up point of $b$.

# IV. Model formulation

In this section, we propose a Mixed Integer Linear Programming (MILP) to optimally schedule a fleet of ETVs for aircraft towing and battery re-charging. We consider multiple battery charging protocols (see Section II.D).

## A. Notation

Depending on the assumed charging protocol, ETVs may have the opportunity to recharge their battery between aircraft towing tasks. ETVs always use the charging station closest to the pick-up point of their next task $b$, which is denoted by $n^C(b) \in N^{CS}$. We use the following abbreviations for energy consumption:

$$q_{C1}^S(a) := q^S(n^C(a), n^p(a)), \tag{6}$$

$$q_{C2}^S(a, b) := q^S(n^d(a), n^C(b)) + q^S(n^C(b), n^p(b)), \tag{7}$$

where $q_{C1}^S(a)$ denotes the required energy to drive to the pick-up point of aircraft $a \in A$ from $n^C(a)$, and $q_{C2}^S(a, b)$ denotes the required energy to drive from the drop-off point of $b$ to the pick-up point of $a$ via $n^C(b)$.

Next, we define the sets of aircraft which can be towed by the same ETV consecutively. Let $A_a^{in}$ and $A_a^{out}$ denote the sets of aircraft which can be towed before and after towing $a$, respectively. For $a \in A$, let $b \in A_a^{out}$ if $t^d(a) + d_S^{SP}(n^d(a), n^p(b))/v_s \leq t^p(b)$. For two tasks $a \in A, b \in A_a^{out}$, let $t^C(a, b)$ denote the available charging time between towing $a$ and $b$. Let $t_l^C(a)$ denote the available charging time after towing $a$ until the end of the day.

Under the CTC protocol, it is possible to charge between towing $a$ and $b$ if $t^C(a, b)$ is longer then $Q/P^c$, the time required to fully recharge a depleted battery. We denote this set by $A_a^{CTC} \subset A_a^{out}$. Under the PC protocol, it is possible to charge between towing $a$ and $b$ if $t^C(a, b)$ is positive and if, after charging, the state of charge of the ETV at the start of towing $b$ can be larger than it would have been if it did not charge. We denote this set by $A_a^{PC} \subset A_a^{out}$.

## B. Decision variables

We consider the following decision variables in order to determine the order in which the aircraft are towed:

$$x_{ab} = \begin{cases} 1 & \text{if } a, b \in A \text{ are} \\ & \text{towed consecutively} \\ 0 & \text{else} \end{cases} \qquad x_a^f = \begin{cases} 1 & \text{if } a \in A \text{ is the} \\ & \text{first an ETV tows} \\ 0 & \text{else} \end{cases} \qquad x_a^l = \begin{cases} 1 & \text{if } a \in A \text{ is the} \\ & \text{last an ETV tows} \\ 0 & \text{else} \end{cases} \tag{8}$$

Additionally, the $q$ variables follow the battery state throughout the day of operations:

$$q_a \in [q^X(a), Q] \qquad \text{ETV battery state-of-charge at the start of towing } a \in A \tag{9}$$

## C. Objective function

We aim to minimize the required size of the ETV fleet such that all flights from $A$ can be towed; denote this number by $n_{ETV}$. We claim that $n_{ETV} = \min_{x,q}\{\sum_{a \in A} x_a^f\}$. In order to see this, note that all flights can only be towed by one ETV and hence that for $a \in A$, $x_a^f = 1$ implies that a unique ETV has to leave the depot and start its day by towing $a$. Conversely, if for a specific ETV there is no flight that it serves first on the day, it is not towing any flights at all that day and hence is not required.

## D. Constraints

We consider the following constraints. These hold for all three charging protocols:

$$x_a^f + \sum_{b \in A_a^{in}} x_{ba} = 1 \qquad \forall a \in A, \tag{10}$$

$$x_a^l + \sum_{b \in A_a^{out}} x_{ab} = 1 \qquad \forall a \in A, \tag{11}$$

$$q_a \leq Q - x_a^f q_f^S(a) \qquad \forall a \in A, \tag{12}$$

$$0 \leq q_a - x_a^l (q^X(a) + q_l^S(a)) \qquad \forall a \in A, \tag{13}$$

$$Q \leq q_a - \left[q^X(a) - q_l^S(a)\right] + \left[P^c \times t_l^C(a)\right] + Q \times (1 - x_b^l) \qquad \forall a \in A. \tag{14}$$

Constraint (10) ensures that each aircraft $a$ is either the first towed aircraft of the day by an ETV or is preceded by another aircraft that is towed. Constraint (11) ensures that each aircraft is either the last towed aircraft of the day by an ETV or an ETV subsequently tows another aircraft. Constraint (12) limits the battery charge at the start of the day, and Constraint (13) ensures that at the end of the day the ETV has sufficient energy to reach the depot. Last, Constraint (14) ensures that there is enough time to recharge the battery of an ETV at the end of the day.

### *NC protocol specific constraints*

Under the NC protocol, charging is only performed after the last towing task (at the end of the day of operations). Constraints (14) ensure that there is enough time for recharging before the start of a new day of operations. Throughout the day, the battery charge depends only on what task has been executed previously:

$$q_b \leq q_a - x_{ab}(q^X(a) + q^S(a,b)) + (1 - x_{ab}) \times Q \qquad \forall a \in A, b \in A_a^{out} \tag{15}$$

This constraint limits the battery state-of-charge between two consecutively aircraft towing tasks.

### *CTC protocol specific constraints*

Under the CTC protocol, charging is performed between two towing tasks if and only if the available charging time in-between is large enough to fully recharge the battery. As such, the following two constraints determine the state of charge of the ETV throughout the day:

$$q_b \leq q_a - x_{ab}(q^X(a) + q^S(a,b)) + (1 - x_{ab}) \times Q \qquad \forall a \in A, b \in A_a^{out} \setminus A_a^{CTC}, \tag{16}$$

$$q_b \leq Q - x_{ab} q_C^S(b) \qquad \forall a \in A, b \in A_a^{CTC}. \tag{17}$$

Constraint (16) is identical to constraint (15) of the NC-protocol, but only applies to the couples of aircraft between towing which the ETVs battery cannot be fully charged. When this can be done, it is replaced with Constraint (17), which resets the ETV battery to full capacity.

*PC protocol specific constraints*

Under the PC protocol, batteries may be partially charged throughout the day of operations. In order to accommodate this, an additional constraint is added:

$$q_b \leq q_a - x_{ab}(q^X(a) + q^S(a,b)) + (1 - x_{ab}) \times Q \qquad \forall a \in A, b \in A_a^{out} \setminus A_a^{PC}, \tag{18}$$

$$q_b \leq Q - x_{ab} q_C^S(b) \qquad \forall a \in A, b \in A_a^{PC}, \tag{19}$$

$$q_b \leq q_a - x_{ab}(q^X(a) + q_C(a,b) - P^c \times t^C(a,b)) + Q(1 - x_{ab}) \qquad \forall a \in A, b \in A_a^{PC}. \tag{20}$$

Constraints (18) and (19) are the same as Constraints (16) and (17) before. Constraint (20) limits the ETV battery charge if a charging station is visited between towing two aircraft. This is done by adding the charged energy $P^C \times t^C(a,b)$ to the ETV battery.

## V. Case study

In this section, we apply the ETV scheduling models in a case study at Amsterdam Airport Schiphol (AAS), using the flight schedule of December 14, 2019. First, we shall study the ETV schedules for the different charging protocols assuming a single battery size in Subsection V.A. After this, we shall compare the optimal fleet size for different combinations of ETV battery sizes and charging protocols in Subsection V.B.

Figure 3 shows the map of AAS which we use for our case study, based one the Schiphol aerodrome charts [9]. The runway and gate nodes are indicated by vertically hatched circles and the charging stations (C1 up to C5) are indicated by horizontally hatched circles. The ETV depot is assumed to be located at charging station C5. The service roads and taxiway network are indicated by dashed and solid lines, respectively.

We consider the flight schedule of an entire day of operations at AAS, using flight data from December 14, 2019. We assume that the narrow-body aircraft, 750 in total, are eligible to be towed by an ETV. Figure 4 shows the distribution of arriving and departing narrow-body aircraft throughout the day. Flights arrive/depart between 6AM (on December 14) and 3AM (on December 15). The masses of the towed aircraft are given by either the MTOW, for departing flights, or the EOW, for arriving flights.

Finally, the ETV specifications can be found in Table 1. The ETVs use Li-Ion batteries with a specific energy density of 6.25 kg/kWh [10].

### A. Results: Nominal battery size

First, we consider a base case in which we assume that the ETVs will be equipped with batteries with a capacity $Q = 320$ kWh. In this case, the NC, CTC, and PC protocols require a fleet size of 66, 40 and 29, respectively. Figures 5a, 5b and 5c show Gannt-charts for the ETV schedules for the NC, CTC and PC protocol, respectively. When an ETV is towing an aircraft, a solid blue bar is displayed, and when it is recharging its battery, a hatched green bar is displayed. Specifications of the schedules are detailed in Table 2, which gives the average number of towed aircraft, charging cycles and utilization time per ETV. A charging cycle is given as a switch from discharging a battery to charging. The utilization time is defined as the total time during which an ETV is either towing an aircraft, driving across the service roads or charging, i.e. the total time it is not idle. Last, the corresponding state-of-charge of the ETV of these schedules can be found in Figure 6.

As can be seen in the schedule, and in the schedule specifications in Table 2, using the NC protocol has a drastic impact on the ETV utilization. Because of the choice to only recharge the battery once every day of operations, the

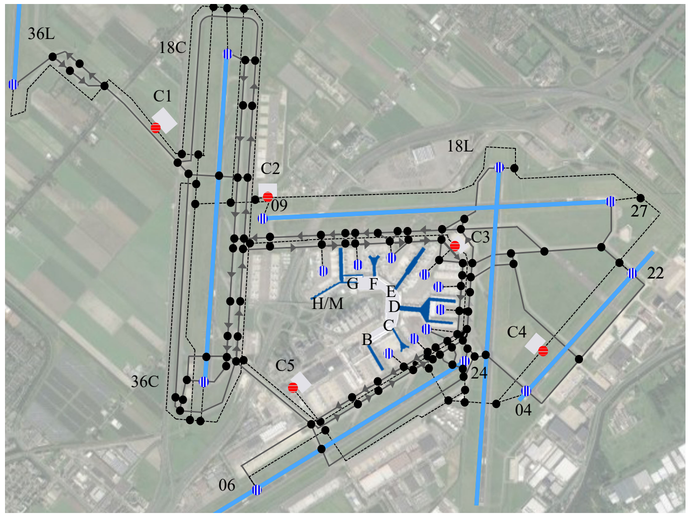



**Fig. 3 Runways $N^R$ and gate nodes $N^G$, together with taxiways (solid lines), service roads (dashed lines) and charging stations (C1, ..., C5) at AAS. The map is based on the Schiphol aerodrome charts [9].**

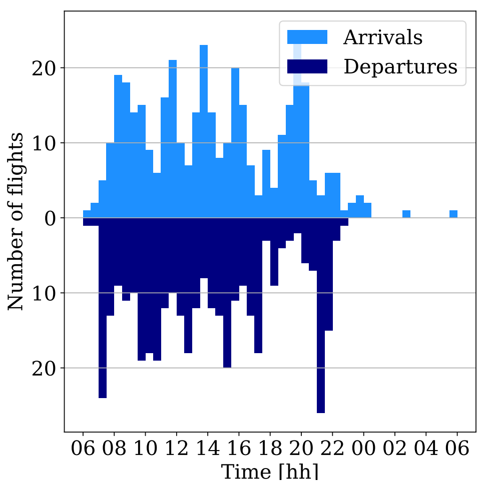



**Fig. 4 Distribution of $t^p(a)$ for all narrow-body aircraft arriving and departing from AAS on December 14, 2019.**

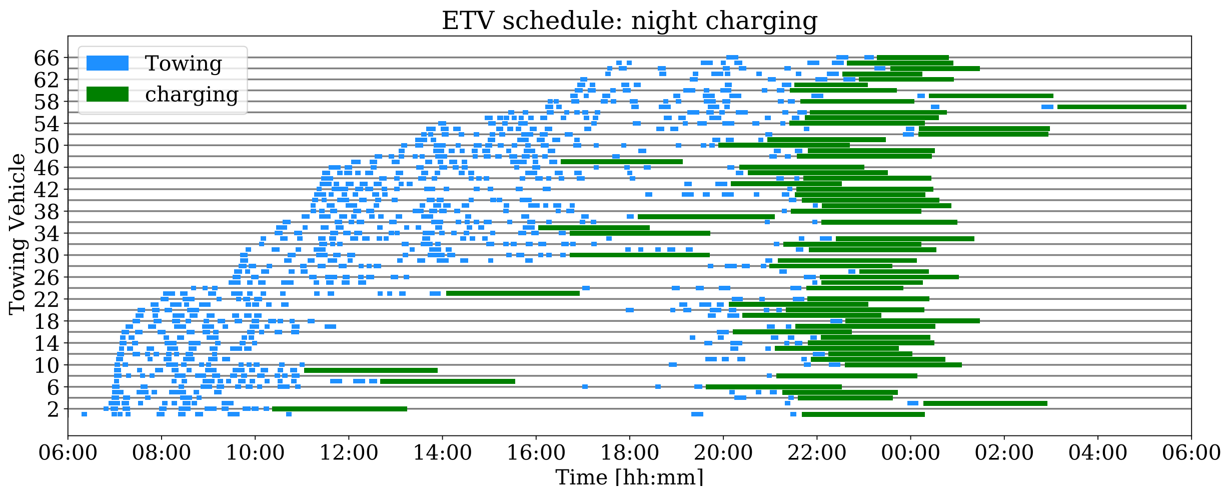
| Parameter | Explanation | Value |
|---|---|---|
| $Q$ [kWh] | Battery capacity | 100 - 500 |
| $m_0$ [kg] | ETV base mass | 12000 [8] |
| $m_q$ [kg/kWh] | ETV battery energy density | 6.25 [10] |
| $P^c$ [kW] | Charging power | 100 [8] |
| $\mu_0$[-] | Rolling resistance coefficient | 0.1 [11] |
| $v_0$ [km/h] | Rolling resistance base velocity | 41.16 [11] |
| $v_s$ [km/h] | Service road velocity | 30 [12] |
| $v_x$ [km/h] | Towing velocity | 42.5 [13] |

**Table 1 Electric towing vehicle specifications.**

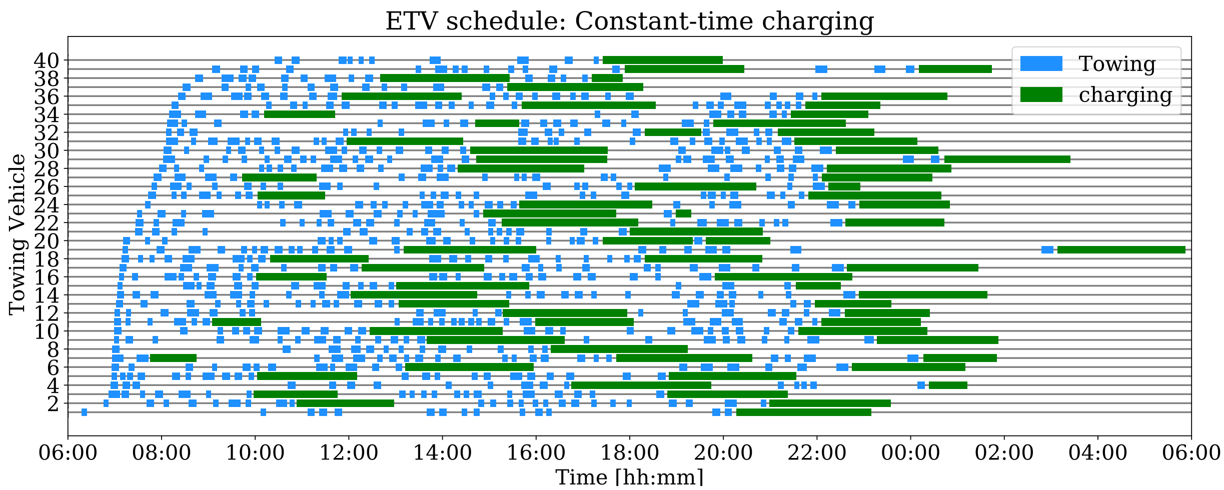
number of aircraft which an ETV can tow is relatively limited to just over 11 on average. Towing these aircraft and recharging the battery takes an ETV roughly no more then half of the day of operations (e.g. from 7AM to 1PM for ETV 2), and thus leaves the ETV out of service for the other half of the day. Hence, for this combination of $Q$ and $P$, night charging does not seem to provide an efficient solution.

When using the CTC protocol, the ETVs tow 18.75 aircraft on average (+65% compared to the NC protocol) at the cost of requiring 1.85 charging cycles on average. In Figure 5b one can see that the tows are distributed much more evenly throughout the day per ETV and that the utilization is larger than when using the NC protocol. On the other hand, there are still relatively large gaps in the schedule (e.g. between 4PM and 8PM for ETV 1) as a result of charging only if the time gap is large enough.

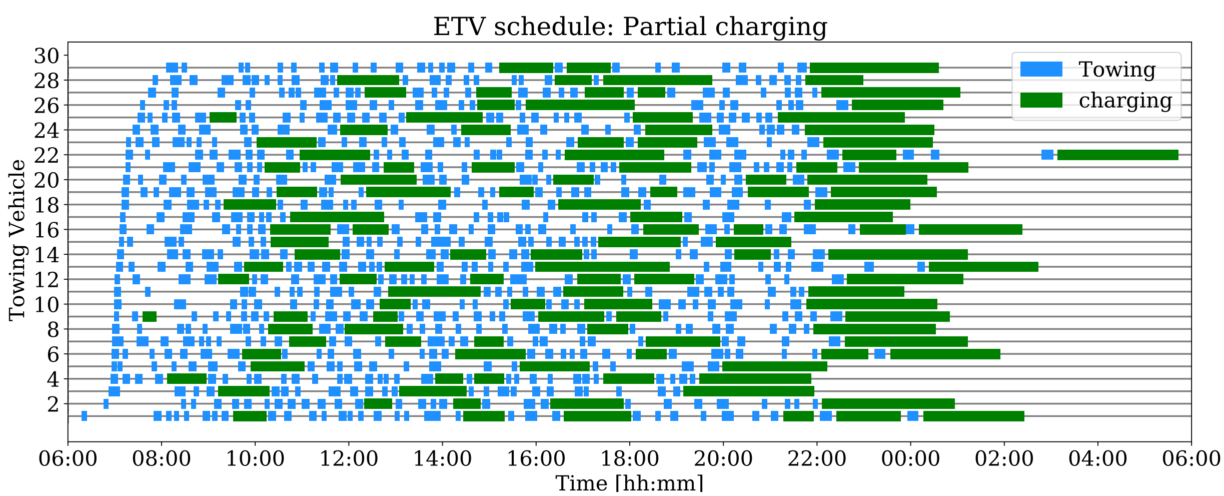
Finally, when using the PC protocol the highest ETV fleet utilization is used, the ETVs tow 25.86 aircraft on average (+ 128% compared to the NC protocol) at the cost or requiring 4.17 charging cycles. In Figure 5c, one can see that similar to the CTC protocol the ETVs tow aircraft evenly distributed throughout the day, but that there are much less long gaps in which they are idle. This is also reflected by the average utilization time of 12:26 hours.




**(a) ETV schedule for the night-charging (NC) protocol.**




**(b) ETV schedule for the constant-time-charging (CTC) protocol.**

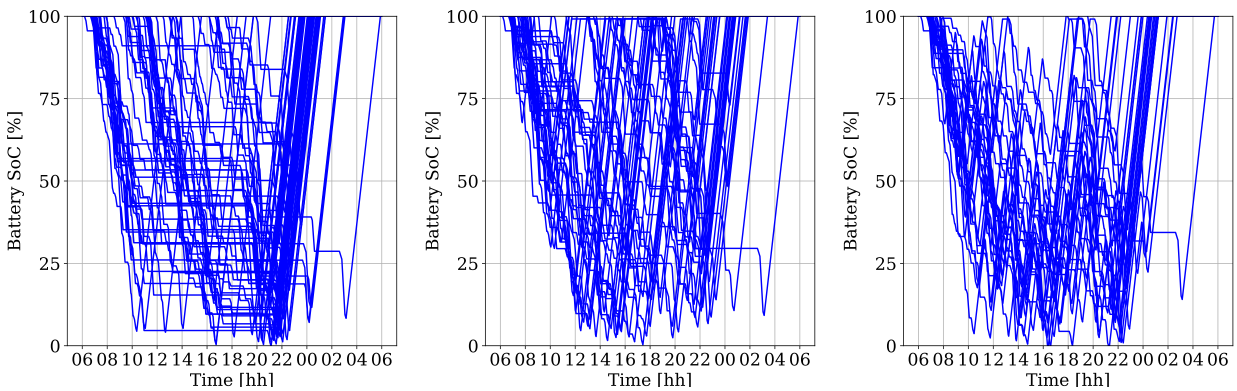



**(c) ETV schedule for the preemptive charging (PC) protocol**

**Fig. 5 ETV schedules for the nominal use case with a battery capacity of 320 kWh for charging protocols NC, CTC and PC. Blue bars indicate an ETV is towing an aircraft. Green hatched bars indicate that an ETV is recharging its battery.**

| Charging protocol | Average Towed aircraft | Charging cycles | Utilization [hh:mm] |
|---|---|---|---|
| NC | 11.36 | 1.00 | 05:29 |
| CTC | 18.75 | 1.85 | 08:55 |
| PC | 25.86 | 4.17 | 12:26 |

**Table 2 Specifications of the ETV schedules from Figure 5 for the three corresponding charging protocols.** ***Towed aircraft, Charging cycles, and Utilization*** **give the average number of towed aircraft, charging cycles, and non-idle time per ETV.**




**(a) SoC of the ETVs for the night-charging (NC) protocol.** **(b) SoC of the ETVs for the constant-time-charging (CTC) protocol.** **(c) SoC of the ETVs for the preemptive charging (PC) protocol**

**Fig. 6 State-of-Charge of the ETV batteries for the nominal use case with a battery capacity of 320 kWh for charging protocols NC, CTC and PC. These graphs correspond to the schedules from Figure 5**

### B. Results: ETV fleet size vs ETV battery capacity

Last, Figure 7 shows the impact of the ETV battery capacity on the required towing vehicle fleet size. We have varied the battery capacity between $Q = 100$ and $Q = 500$ kWh in steps of $\Delta Q = 20$ kWh. For each value of $Q$, we have applied the models from Section IV for each of the three charging protocols, in order to obtain the minimum possible fleet size. The fleet sizes for each charging protocol are graphed in Figure 7. It highlights the nominal case of Subsection V.A, where $Q = 320$ kWh, with a larger gray marker. Finally, without battery life constraints, the minimum required fleet size is 24 ETVs, and this line is also displayed in Figure 7.

There are a number of notable features in Figure 7. First, for any value of $Q$ the ETV fleet size is always smallest for the PC protocol, followed by the CTC protocol and by the NC protocol. For the PC protocol, the fleet size varies between 41 and 24 ETVs, such that for $Q = 500$ kWh, the battery capacity is no longer a limiting factor in the ETV schedule. For the CTC protocol, the fleet size varies between 45 and 40 ETVs. Finally, the vehicle fleet for the NC protocol varies between 210 ETVs, outside the bounds of this graph, and 45 ETVs. In the best case scenario, the CTC and the NC protocol require a 67% and 87% larger fleet then the PC protocol, respectively, but in all cases it provides the smallest fleet size.

The second notable feature of Figure 7 is that the vehicle fleet size for the CTC protocol is almost not sensitive to the battery capacity. Instead of decreasing with increasing battery size, the ETV fleet size remains more-or-less constant, and even attains its smallest value at $Q = 320$ kWh, almost in the middle of the domain of $Q$. This could be explained by the fact that when the battery size increases, and thus the number of aircraft which can be towed on a single charge with it, the time that an ETV has to retire to charge its battery also increases with it. Hence on average, the number of aircraft which can be towed within a given time remains constant. This continues up until the moment when the battery size is sufficiently large to not form a constraining factor in the schedule anymore.

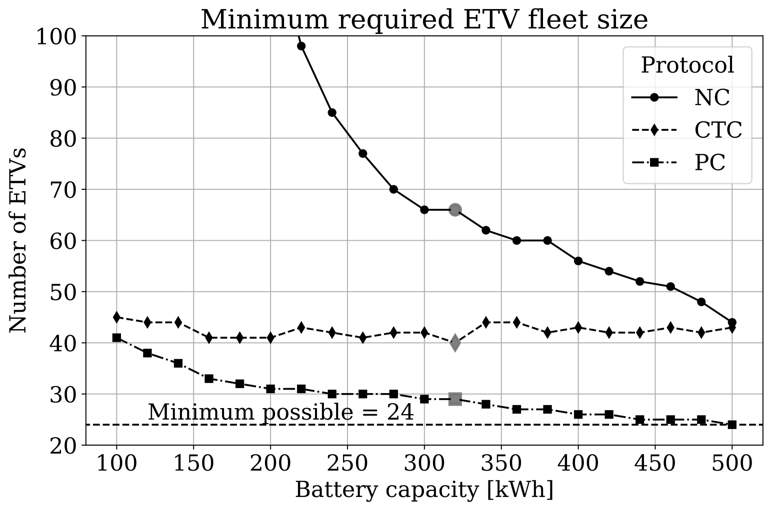



**Fig. 7 Pareto front of the required number of ETVs to tow all eligible flights against the battery capacity of an ETV, for each charging protocol (night charging (NC), constant time charging (CTC), and partial charging (PC)). The nominal case where $Q = 320$ kWh is highlighted with a larger, gray, marker. The smallest possible fleet size (when battery constraints are ignored) is 24 ETVs.**

This is opposed by the NC protocol, which is very sensitive to the ETV battery size. This can be explained by the fact that the number of aircraft which can be towed by an ETV on a single charge is approximately linear in $Q$. As each ETV in the NC protocol only uses one battery charge, the number of required ETVs should be proportional with $1/Q$, which corresponds to the results.

# VI. Conclusion

This paper compares the effect of battery size and recharging protocol on the impact which electric towing vehicles (ETVs) are able to make at large airports. This is done by using a Mixed-Integer-Linear-Optimization program to determine the smallest possible ETV fleet required to tow all considered aircraft. We consider three versions of this model, corresponding to the three charging protocols: night, constant time, and partial charging. The battery size considered ranges from 100 kWh to 500 kWh.

We have applied the model in a case study at Amsterdam Airport Schiphol and found that the partial charging protocol yields a significant improvement over the other protocols. The considered flight schedule consists of 750 narrow-body aircraft, arriving throughout the day of operations. In the nominal case, when we consider an ETV battery of 320 kWh, the required fleet size is 66, 40 (-39%) and 29 (-56%) for the night charging, constant time charging, and partial charging protocol, respectively. Additionally, it was found that the constant time charging protocol is almost insensitive to the battery size.

Future research could consider creating a cost-benefit analysis of the environmental impact as a function of the ETV fleet size. Additionally, the economic impact of using more charging cycles could be studied.

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