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An investigation of operational management solutions and challenges for electric taxiing of aircraft

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ABSTRACT

Taxiing aircraft using electric towing vehicles (ETVs) is expected to significantly contribute to the objective of climate-neutral aviation by 2050. This study reviews existing work on operational aspects of electric towing of aircraft, and discusses management solutions. We first discuss the varying electric taxi systems currently under development, and their implementation progress at airports. We outline the current specifications of ETVs and the procedures needed to perform electric taxiing movements. We next discuss the management needs for implementing ETVs at an airport, by reviewing existing mathematical models for ETV fleet management: dedicated vehicle routing models, ETV to flight assignment models, fleet sizing models and battery charging optimisation models. Last, we identify remaining research challenges. For instance, a main challenge is to increase the robustness of ETV routing and towing scheduling against disruptions due to flight delay. This paper summarizes the main research directions needed to support large-scale ETV implementation in the next few decades.

1. Introduction

In 2017, the CO_2-emissions of the aviation sector accounted for 3.8% of total emissions. By 2050, the European Green Deal aims to reduce aviation emissions by 90%, compared to 1990 (European Commission (2021)). In 2021 the United States set the goal of achieving net-zero greenhouse gas emissions from the aviation sector by 2050 (Federal Aviation Administration (2021)). To achieve these goals, a large amount of research has focused on electric flying or flying using sustainable fuels such as hydrogen. However, 7% of total flight fuel use, 43% of HC emissions, 41% of CO emissions, and 12% of NOx emissions are attributed to aircraft taxiing at airports, rather than the flight phase, according to Turgut, Usanmaz, and Rosen (2013). Electric aircraft taxiing is expected to significantly reduce these emissions. In fact, the research output dedicated to electric aircraft taxiing has increased steadily in the last years, see Fig. 1.

The current standard is to taxi with one or both of the aircraft's jet engines at roughly 7% power (Balakrishnan, Deonandan, and Simaiakis (2008); Hospodka (2014)). However, this is a very fuel-inefficient way of taxiing (Lukic, Giangrande, Hebala, Nuzzo, and Galea (2019)). Electric taxiing systems (ETS) are therefore a promising solution. When using an ETS, the jet engines of the aircraft are not powering the taxiing movement, thus reducing fuel consumption and emissions. ETSs are classified into two types: on-board systems and external systems. On-board systems are integrated into the aircraft and provide electric power to the nose or main landing gear when taxiing. An external system consists of a fleet of electric taxiing vehicles (ETVs) that tow the aircraft along taxiways.

One external ETS, the TaxiBot (Smart Airport Systems (2022)), has been certified for use with a significant number of aircraft types and is operating at a number of airports, while on-board solutions and other green airport solutions are still in the development phase. Lukic et al. (2019) wrote a detailed technical review on the varying ETSs, and Hospodka (2014) wrote a detailed cost-benefit analysis for the introduction of external ETSs from the aircraft perspective. However, to our knowledge no review on the operational management aspects of ETSs has been written. Although there has been research into some of these aspects separately, there is little understanding of the overall challenges to the effective implementation of this emerging technology.

This paper reviews the research on operational management problems of *external* ETSs, and identifies the challenges that need to be addressed in the near future. To this end, the methods, assumptions and

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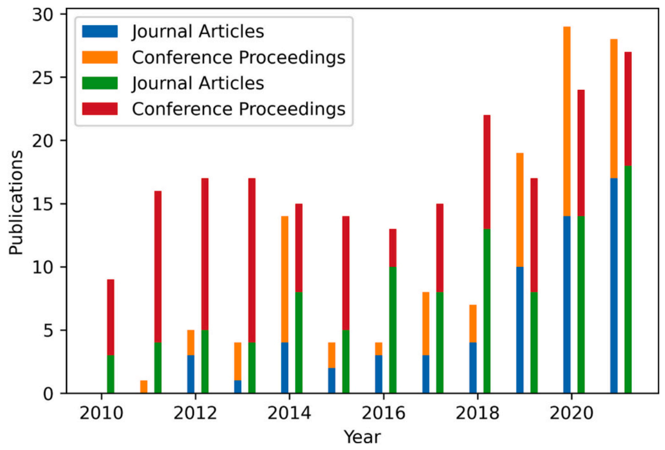


Fig. 1. Research output containing the phrase “electric taxiing” (blue and orange, left columns) and the phrase “airport surface movement” (green and red, right columns), as indexed by Scopus (2022) (accessed 11-03-2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results of varying approaches are discussed, on three separate topics: the vehicle routing problem, the fleet scheduling assignment problem, and the charging aspect of electric taxiing. These topics comprise the main operational management challenges that airports face when implementing external electric taxiing. The main contribution of this work is that it aims to provide a clear view on the achievements and challenges within these topics. Together with the reviews from other viewpoints, it forms a general overview on this many faceted subject, that can aid the industry and academia in moving towards more effective and speedy implementation of ETSs. This is crucial for timely accomplishment of the goals that have been set for the reduction in aviation emissions.

In addition, this paper discusses the differences between varying ETSs and their current implementation progress, and provides a detailed description of the taxiing process with an external ETS. For this, the specifications of ETVs and the requirements for operation are identified.

The initial selection of research contributions to consider in this work has been done by querying search engines such as Google Scholar and Scopus using the terms ‘electric taxiing’ and ‘airport surface movement’. Afterwards, references from these works, as well as papers that cited these works, were added to the collection. These contributions were used as basis to write Section 2, which introduces and compares promising ETS concepts, and Section 3, which outlines the procedures associated with maintaining and operating a fleet of towing vehicles for electric taxiing. Then, the contributions that specifically concern the operational management aspects of external electric taxiing were selected for further review. These contributions all pertain to one or more of three areas: vehicle routing, fleet assignment and charging infrastructure. Section 4 reviews these works from the perspective of these three areas and identifies operational management problems that remain to be solved. Finally, Section 5 summarizes the findings and the recommendations for future research.

2. Electric Taxi Systems currently under development

In this section we illustrate the various electric taxiing concepts that are currently under development in the industry, as well as their advantages and disadvantages. This information serves as the basis needed to review the operational management aspects of electric taxiing in later sections. For an extensive review of the technical aspects of various electric taxiing systems, please refer to Lukic et al., 2019.

2.1. On-board ETS

We will discuss three of the most promising on-board electric taxi solutions:

a) Main Landing Gear systems.

A main landing gear system consists of electric motors placed in the main landing gear (MLG) of an aircraft. The installation of such a system would increase the aircraft weight by roughly 400 kg (Lukic et al. (2019)). Advantages of an on-board system placed in the MLG are that a large torque can be attained, and that the turning radius of the aircraft becomes smaller than during regular operation (Raminosoa, Hamiti, Galea, and Gerada (2011); Galea et al. (2014); Re and De Castroy (2014); Kelch, Yang, Bilgin, and Emadi (2017); Huang, Ochieng, Nie, and Zhang (2019)). Furthermore, the traction on the airport surface is expected to be sufficient, since the MLG carries 90% of the aircraft weight (Lukic et al. (2019)). A disadvantage is that implementing a motor within the MLG is very challenging since the presence of the brakes both limits space within the MLG and provides an unwanted heat source (Lukic et al. (2018)).

Safran and Honeywell were developing an MLG system, but they stopped developing the project in 2016. This system was able to provide a power of 120 kW and during demonstrations in 2013 an A320 aircraft equipped with the system was able to attain a taxiing speed of 37 km/h (Lukic et al. (2018)).

b) Nose Landing Gear systems.

A nose landing gear system consists of two electric motors placed on the rim of the nose landing gear (NLG) of an aircraft. These motors increase the aircraft weight by about 140 kg (Lukic et al. (2019)). An advantage of such a system is that it allows for easy manoevrability and therefore a simplified and faster turnaround and pushback process (Huang, Nie, and Zhang (2016); Lukic et al. (2018)). A disadvantage is that the system is powered by the APU, which has limited power. This has the following drawbacks: a) the system might not be able to provide enough traction under adverse operating conditions, b) the maximum taxiing speed that can be obtained with this ETS is 17 km/h, and c) it is unlikely that the system can be applied to wide-body aircraft in the future, according to Lukic et al. (2019).

An NLG system is currently being developed by WheelTug. This system has been in the process of certification by the FAA and EASA for several years. Production and operation are expected to start soon and the WheelTug company has received orders from at least 20 airlines, but as of, 2022, the system is still in the testing phase (Lukic et al. (2018)).

c) Hydrogen powered systems.

In a collaboration with Lufthansa Technik, the German Aerospace Centre (DLR) is developing an on-board solution in the NLG consisting of a permanent magnet synchronous motor which is to be powered by on-board hydrogen fuel cells (Schier, Rinderknecht, Brinner, and Hellstern (2011)). This ETS has been shown to be able to perform electric taxiing with narrow-body aircraft at a top speed of 25 km/h (Lukic et al. (2018)) and is reported to reduce the aircraft emissions by up to 27% (Raminosoa et al. (2011)). Disadvantages are that the needed magnets are relatively expensive and that the ETS produces a power of only 50 kW, which makes it yet unsuitable for actually towing aircraft (Re and De Castroy (2014)). Furthermore, it is still challenging to store hydrogen on board an aircraft, due to the high energy content and flammability (Testa, Giammusso, Bruno, and Maggiore (2014)). Last, hydrogen is currently still difficult and expensive to synthesize (Westenberger (2016)).

Fig. 2. TaxiBot in operation at Frankfurt Airport Smart Airport Systems (2022).

Several studies have analyzed the economical and environmental impact of on-board systems, e.g. Hospodka (2014); Lukic et al. (2018); Dzikus, Fuchte, Lau, and Gollnick (2011) and Nicolas (2013). Hospodka (2014) calculate fuel and CO_2 emissions savings when using a 300 kg on-board ETS on an A320 aircraft: taxiing electrically reduces the needed amount of taxiing fuel by 80%. After subtracting the increased fuel need due to the added weight of the ETS, this figure is reduced to 75%, which corresponds to 0.65 tons of CO_2 per flight. Dzikus et al. (2011) find that 99% of flights in the US airspace would save fuel when equipped with a 200 kg on-board ETS, on average 3% of total fuel. Nicolas (2013) show that fuel reduction depends on the combination of flight time and total taxi time: e.g. under their model an A320 equipped with an on-board ETS with 14 min total taxi time will not experience fuel savings for flight lengths over 2400 km.

2.2. External ETS

An external electric taxiing solution consists of a fleet of electric towing vehicles that can connect to the NLG of an aircraft and perform pushback and taxiing movements. Currently, there is a similar system that has completed the development stage and is operational at airports: the TaxiBot, developed by Israel Aerospace Industries (IAI) (Israel Aerospace Industries (2022)). These vehicles are currently powered by diesel engines, which are to be replaced by electrically powered versions within several years. A TaxiBot can produce a power of 500 kW and achieve a taxiing speed of 43 km/h for narrow-body aircraft (Lukic et al. (2019)). Currently, only the narrow-body towing truck, with 8 wheels and a cost of 1.5 million USD, is operational. Soon, the wide-body vehicle, with 12 wheels and a cost of 3 million USD, is expected to become operational (Airside International (2018)). An example of a narrow-body towing vehicle in operation is given in Fig. 2. The NLG of the aircraft is clamped onto the ETV while towing.

Several studies about external ETSs have discussed the expected effects of ETSs on the operational costs, fuel use and emissions (Deonandan and Balakrishnan (2010); Dzikus et al. (2011); Vaishnav (2014); Guo, Zhang, and Wang (2014); Khammash, Mantecchini, and Reis (2017); Postorino, Mantecchini, and Gualandi (2017); Lukic et al. (2019)), noise reduction (Hein and Baumann (2016)) and operational safety (Bernatzky, Kemmerzell, Klingauf, and Schachtebeck (2017)). These works typically investigate the feasibility of an external ETS at an airport, and are often based on average taxiing times and distances. Most do not take into account the variable demand or the precise routing and scheduling involved at the operational stage. Khammash et al. (2017) show that the introduction of 4 ETVs at Lisbon Airport (LPPT) can reduce CO_2-emissions by more than 18% and lead to costs savings for both the airport and airlines. Similar results are obtained by Postorino et al. (2017) for Bologna Airport (LIPE). When comparing diesel-powered dispatch towing to regular taxiing, Deonandan and Balakrishnan (2010) find that taxiing fuel use can be reduced by 75% and that taxiing emissions can be reduced by for instance 70% of CO_2. Dzikus et al. (2011) expand on this by specifically considering the economic viability of towing short-haul flights. Vaishnav (2014) and Guo et al. (2014) consider more cost factors such as the operation and maintenance costs for towing vehicles, compare electric taxing to other solutions such as single engine taxiing, and consider many different airports. In general, studies find that implementing external electric taxiing a) will lead to significant fuel savings in all cases, increasing with increasing taxiing distance, and b) can lead to an increase in taxiing times, especially when airports are congested.

2.3. Differences between the ETSs

Table 1 outlines the main differences between on-board and external ETSs. From a management perspective the most important difference between the on-board and external ETS is that both the need for investment and the responsibility lie with the airline or the airport, respectively. From the airport perspective, a large advantage of on-board systems is that no investment is required on their part. In order

Table 1
Comparison between on-board and external ETSs.

Investment	On-board ETS	External ETS
Acquisition costs per system	Undisclosed	USD 1.5 M (NB), 3.0 M (WB)
Adjustment aircraft	Install system at NLG or MLG	N/A
Adjustment airport	Not required	Management fleet of ETVs and charging and routing infrastructure
Suitable aircraft types	NB	All
Implementation progress		
First demonstration (manufacturer, aircraft, airport)	2005 (WheelTug, B767, KMZJ)	2013 (IAI, B737, EDDF)
First operational ETS (manufacturer, aircraft, airport)	N/A	2019 (IAI, A320, VIDP)
Certified aircraft type (year)	Ongoing	B737 (2014), A318–21 (2017)
Airports (nr ETVs in use, year)	N/A	EDDF (1, 2014), VIDP (2, 2019), EHAM (2,2020), VOBL (1,2021)
Operational aspects		
Taxiing speed	17 km/h	42 km/h
Additional operations	N/A	Connecting/Disconnecting ETV to/from aircraft
Engine warm-up	During taxiing/near runway	During taxiing/near runway
Engine cool-down	At gate	At gate
Electricity source	APU	ETV battery
Charging	APU generator	Charging stations
Added aircraft weight	140 kg	N/A
Environmental effects		
Fuel saving (B737)	85%	50–85%

to adopt the external system, the airport needs to change the airside infrastructure, add charging infrastructure and manage the towing vehicle fleet. External ETSs require only a short pilot training for the airline and no changes to the aircraft. This is because the NLG is situated on a rotatable turret on the back of the ETV (see Fig. 2), so that the latter can be controlled by the pilot as they would control the NLG during regular taxiing or pushback, as shown in Schiphol (2020).

On-board taxiing systems are not yet operational. In contrast, the narrow-body external electric taxiing system has been certified for multiple aircraft types (comprising 70+ % of worldwide commercial airline flights Smart Airport Systems (2022); Lukic et al. (2018)). The first demonstration took place in 2013 at Frankfurt Airport Airport Technology (2015), and the first airport to use the ETS for operational towing was New Delhi Airport in 2019 Airports International (2023). The ETS is currently in use for testing and non-operational towing at Frankfurt, New Delhi, Amsterdam and Bangalore airports Lukic et al. (2018); Israel Aerospace Industries (2020); Airports International (2023). Several airports are planning to move to operational towing in the near future: Bangalore Airport in 2023 and Schiphol Airport in 2024. New Delhi Airport is planning to expand their ETV fleet to 15 vehicles by 2025 International Airport Review (2022); Muthukrishnan and Ahmed (2022).

Table 1 also summarizes the operational differences between the on-board and external electric taxiing systems. During regular taxiing the aircraft taxiing speed is 56 km/h (Schiphol (2021c)). Roling, Sillekens, and Curran (2015) show that the minimum taxiing speed needed to prevent airport surface congestion at Amsterdam Airport Schiphol is 32 km/h. Therefore, the use of the on-board system is expected to increase the taxi time substantially. Nevertheless, the average pushback time is expected to be reduced, since no pushback vehicle needs to be connected to and disconnected from the aicraft (Aircraft Commerce (2020); Okuniek and Beckmann (2017)). When operating the external system, a connecting and disconnecting procedure is still required, but now to the ETV, rather than the pushback vehicle. This procedure requires three minutes, according to Schiphol (2020).

Lastly, both ETSs are expected to greatly reduce the needed taxiing fuel, and consequently, the taxiing emissions. Tests with the external ETS at Amsterdam Airport Schiphol with a Boeing 737 resulted in taxiing fuel savings of 90%, which reduces to 50–85% when taking into account (dis)connecting and engine warm-up. Schiphol (2021b) show that taxiing with an on-board ETS saves 85% of fuel. The APU powering an on-board ETS is charged during flight. On the other hand, external ETSs charge on the ground and thus require charging infrastructure at the airport. Since the aircraft is not modified when using an external ETS, any fuel savings also directly contribute to weight reduction of the aircraft, and therefore to further fuel and emission savings during the flight.

3. ETV fleet management procedures

In the previous section we have observed that the external ETS is the system that is at the most advanced implementation stage. In this and following sections we focus on external ETSs.

Implementing an external ETS implies integrating a fleet of electric taxiing vehicles into the regular airport surface traffic. This poses several management challenges. This section outlines the management procedures for electric towing operations, and the roles played by the ETVs, the airport, the aircraft, and Air Traffic Control (ATC).

Fig. 3 shows the regular aircraft taxiing procedure and the procedure for towing aircraft using ETVs. When considering *regular taxiing* (Fig. 3a), the aircraft lands on the runway, and starts taxiing. The jet engines cool down during taxiing. After arriving at the apron, the aircraft parks at a gate, or a pushback vehicle is connected to the aircraft, and pushes it into a parking position. For taxi-out, the procedure is reversed, and the jet engines warm up while taxiing.

When considering *electric taxiing* (Fig. 3b), the aircraft connects to an ETV directly after landing. The ETV tows the aircraft to a parking position at the apron. For an aircraft departure, an ETV tows the aircraft from the parking position to the runway. Here, the ETV is disconnected and the aircrafts jet engines are warmed up for take-off. Below a detailed description of electric taxiing with an ETV is given.

Non-towing ETV: Before an arriving aircraft lands, an ETV is on its way towards the runway. It can come from a previous task at a gate or a runway, an ETV depot, or an ETV charging station. For most airports it is expected that ETVs will use service roads for non-towing movements, to avoid a large increase of traffic on the taxiways that needs to be regulated (Schiphol (2021c); Zaninotto, Gauci, and Zammit (2021)). A typical maximum speed on these service roads is 30 km/h (Schiphol (2022); Munich International Airport (2016)).

Landing and connecting: After an arriving aircraft lands on a runway, it needs to connect to the ETV. The connection process takes roughly three minutes Schiphol, 2020, and some runways receive arriving aircraft at a rate faster than one per three minutes. Therefore, it is expected that airports should designate a separate space near the runway exit for the connection and engine cool-down processes to take place, without interfering with the runway traffic (Okuniek and Beckmann (2017); Lukic et al. (2019); Schiphol (2021a)). In Fig. 3b this space is indicated as a *runway stand*. Ideally the runway stand would consist of a paved area separate from the taxiway, large enough for maneuvering. In that case, self-taxiing aircraft would be able to pass by connecting aircraft, avoiding blockage of the taxiway near the runway exit Schiphol (2021a).

Towing: After connecting, the ETV tows the aircraft along the taxiways. During regular taxiing, trailing aircraft need to keep a safe separation distance from a leading aircraft to avoid its jet blast. This distance directly influences the throughput of aircraft on the ground. A typical value for a safe separation distance is 200 m (Roling and Visser (2008); Jiang, Liao, and Zhang (2013); Smeltink, Soomer, de Waal, and van der Mei (2004)). During electric taxiing, there is no jet blast. However, the reaction time of the pilot and the braking distance of the aircraft still need to be accounted for: the separation distance is expected to remain necessary, but smaller. Lastly, ATC retains its task of conflict avoidance on the taxiways, but now with changed taxiing speeds and separation distance.

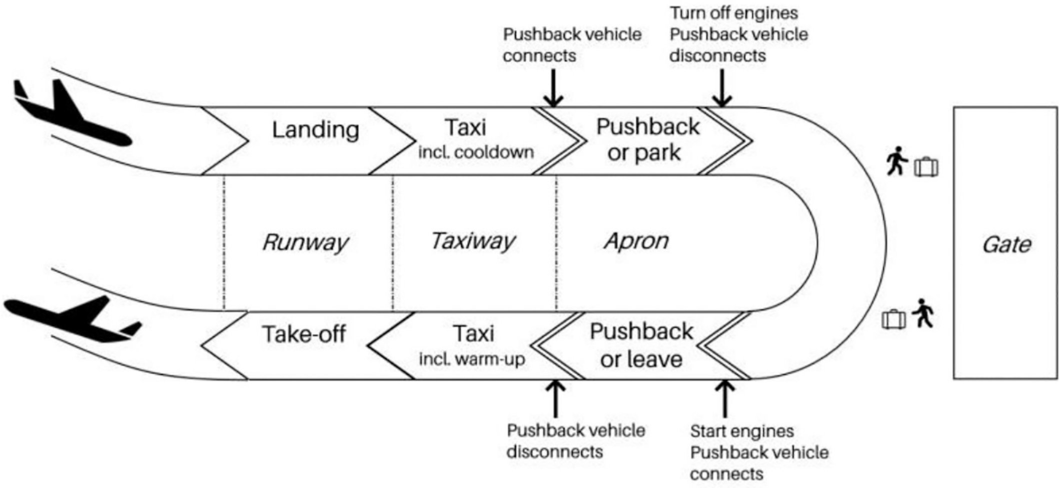
Parking: Upon arriving at the apron, the ETV tows the aircraft into parking position, without the need for a pushback truck. When the aircraft is in position at the gate, the ETV disconnects from the aircraft in 3 min (Schiphol (2020)).

Engine warm-up: When the aircraft is ready to depart, an ETV connects to it at the gate, and tows it to a runway stand. The main difference with the arrival procedure is that the jet engines of a departing flight need to warm up before take-off. In normal operation, regular taxiing warms up the engines sufficiently. During electric taxiing, the jet engines are not used (Smart Airport Systems (2022)).

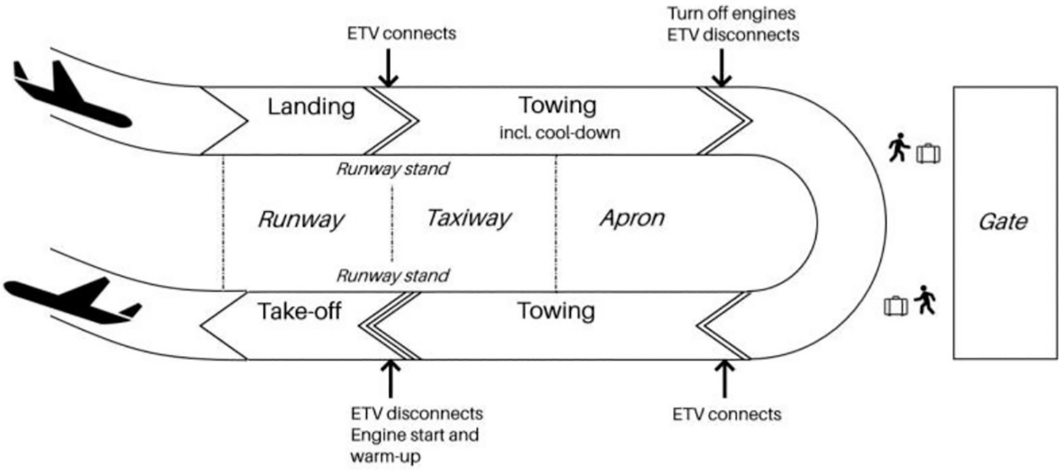
There are several possibilities for the location of the engine warm-up:

i. Engine warm-up at the runway stand. This minimizes the amount of time the engines are running before take-off, and therefore minimizes the engine emissions.
ii. Engine warm up during towing. This could raise safety concerns: if there are problems with the engine during towing, then the taxiway traffic will be disrupted.
iii. Engine warm-up at the apron, as is the case for regular taxiing. A disadvantage is that the engines produce emissions during the entire towing process.

The engine warm-up time, sometimes referred to as ESUT (Engine Start-Up Time), is typically estimated between 3 min (Schiphol (2020); Salihu, Lloyd, and Akgunduz (2021)) and 5 min (Lukic et al. (2018); Dzikus et al. (2011)).



(a) Regular taxiing



(b) Electric taxiing

Fig. 3. The taxiing process for a turnaround (arrival and departure) for regular taxiing and electric taxiing with an ETV.

Table 2 summarizes the relevant operational specifications of the ETV, the aircraft, and the airport.

4. Management challenges for electric towing vehicles

The economic, environmental, and technical aspects of implementing external electric taxiing solutions have been reviewed by Hospodka (2014) and Lukic et al. (2019). Complementary to these studies, this section reviews existing work on the operational management of external ETSs, using three main challenges as starting points for identifying challenges: the routing of ETVs, ETV fleet assignment and electric infrastructure.

Table 2
Operational specifications for electric taxiing.

Speed on taxiways	42 km/h
Speed on service roads	30 km/h
Connecting & disconnecting time	3 min
Engine warm-up and cool-down time	3–5 min
Minimum separation distance	200 m or less

4.1. *ETV vehicle routing problem*

Given the daily flight schedule, airport planners assign a route along the taxiways for each departing/arriving aircraft. Departing aircraft taxi from gate to runway, and arriving aircraft from runway to gate. The routes need to planned in such a way that conflicts are avoided and taxi time is minimized.

The *vehicle routing problem* (VRP) aims to answer the question: “Which is the optimal route to take for a certain vehicle to reach an ordered list of destinations?” for every vehicle in a fleet. This problem appears in many types of delivery or collection problems, such as for postal companies or robot planning in warehouses (Margaritis, Anagnostopoulou, Tromaras, and Boile (2016)). Often, additional constraints are involved, such as time windows, loading and unloading or vehicle capacity.

The problem of obtaining optimal taxiing routes for taxiing aircraft from gates to runways or vice versa is also usually posed as a VRP. When considering electric taxiing, such a VRP can be extended with charging constraints for the ETVs.

Table 3 provides an overview of methodologies and assumptions used in literature for electric taxiing. In this section we compare these approaches.

Table 3

Assumptions and approaches to VRPs and FSAs used in literature on electric taxiing.

Author-Year	Objectives	Problem formulation	Conflict avoidance	Airport	Number movements	Fleet size range
Sirigu, Cassaro, Battipede, and Gili (2018)	shortest path	simulation	no	LIMF	N/A	N/A
van Baaren and Roling (2019)	minimize taxiing fuel	MILP	no	EHRD&EHAM	39&1430	0 to 42
Zaninotto, Gauci, Farrugia, and Debattista (2019)	minimize taxi time, conflicts	simulation	penalties	LMML	36	Unconstrained
Soltani, Ahmadi, Akgunduz, and Bhuiyan (2020)	minimize taxiing fuel & delays	MILP	yes	CYUL	205	0 to 20
Salihu et al. (2021)	minimize taxiing costs	simulation	yes	CYUL	644	10 to 30
van Oosterom, Mitici, and Hoekstra (2022)	minimize number of ETVs	MILP+Greedy	MILP	EHAM	913–1258	38 to 50

4.1.1. *Graph representation of airport layout*

All studies considered in Table 3 use a graph representation of the airport surface. The edges represent the taxiways and service roads, and the nodes represent intersections, gates or gate groups, runway entrances and exits, runway stands and ETV depots. For example, Soltani et al. (2020) use multiple runway entrance and exit nodes, and Zaninotto et al. (2019) use runway stands and ETV depots.

Fig. 4 shows a schematic representation of an airport with six gates and two runways. In this example, towing vehicles and other ground support equipment are not allowed to drive on the taxiways. Therefore it should be possible to travel between any combination of runway and gate via both taxiways and service roads. Furthermore, multiple runway entrance and exit points are reachable.

The layout of the airport and the possible runway configurations influence the performance of an ETV fleet. Zaninotto et al. (2019) consider one of the runways of LMML, but in later work also apply their algorithm to LFBO, LLBG and KDFW Zaninotto et al. (2021). Soltani et al. (2020) and Salihu et al. (2021) use three runways with 20 entrance/exit nodes of CYUL. van Baaren and Roling (2019) consider EHRD, which has 1 runway with a 2 km taxiing route, and EHAM, which uses 2 or 3 runways with a regularly changing configuration, and a longest taxiing route of 11 km.

4.1.2. *Modeling approach*

Given these inputs, routing can be performed on the airport surface. Sirigu et al. (2018) consider the algorithms (Modified) Hopfield Neural Networks, Dijkstra and A* to find the shortest taxiing routes. Soltani et al. (2020), van Baaren and Roling (2019) and van Oosterom et al. (2022) formulate the routing and scheduling problem as an MILP. All possible routes between gates and runways are calculated in advance, and the usage of a route is included in a decision variable.

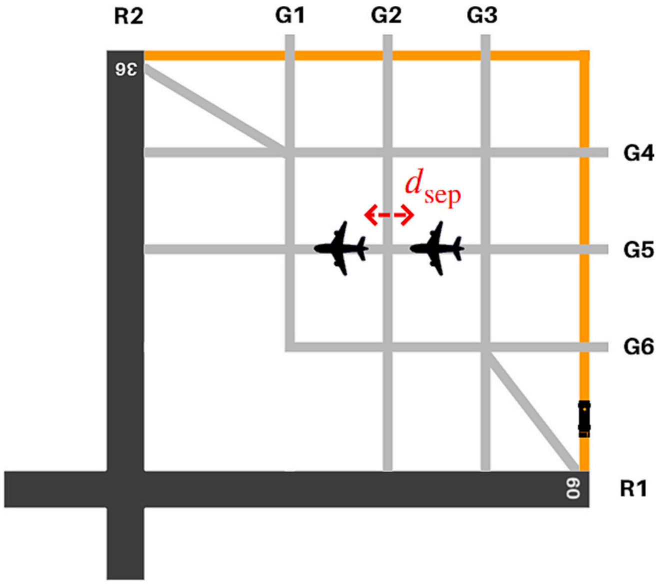


Fig. 4. Schematic representation of a sample airport. Wide dark gray lines represent the runways R1 (09) and R2 (36). Light gray lines represent the taxiways, where aircraft may taxi, and orange lines represent service roads, where ETVs may drive. Gates G1–6 are indicated. The separation distance d_{sep} between two aircraft has to be respected.

On the other hand, Zaninotto et al. (2019) and Salihu et al. (2021) develop a simulation, in which each movement is scheduled sequentially, and routing is performed using Dijkstra's algorithm. Except for Zaninotto et al. (2019), who divide the optimization time into 20-s time windows, all approaches in Table 3 use continuous time values.

4.1.3. *Routing conditions*

Conflict avoidance for surface movement: Including conflict avoidance in taxi route planning makes it more realistic, and can help identify problems such as traffic jams at taxiway intersections. Zaninotto et al. (2019) include conflict avoidance by introducing penalties for using already occupied edges for a new route, and found a trade-off between minimizing the number of conflicts and increasing the taxi time. Soltani et al. (2020) include eight constraint sets in their MILP formulation to ensure conflict avoidance on all edges and nodes in the routing solution. van Oosterom et al. (2022) create and solve a separate MILP formulation for routing vehicles, which enforces conflict avoidance through constraints, before solving the MILP formulation for scheduling. The performance of the latter is compared to that of a greedy algorithm. Salihu et al. (2021) enforce conflict avoidance in their simulation by respecting the separation distance and following a first-in-first-out procedure at intersections. Regarding the movement of unloaded ETVs, Soltani et al. (2020) and Salihu et al. (2021) assume they travel on the taxiways, but clear the way for aircraft. van Baaren and Roling (2019), van Oosterom et al. (2022) and Zaninotto et al. (2019) assume these ETVs will use the service roads, except when no other route is available. In short, in the reviewed literature, conflict avoidance for unloaded ETVs is assumed to not be required.

ETV movement between tasks: An ETV that is not towing or charging is waiting for its next towing task. The behavior of the ETV during this time constitutes a management choice:

i. In case all routes for an ETV have been determined in an optimization model, one can choose to let the vehicle proceed to the starting point of its next task, as in van Baaren and Roling (2019).
ii. The ETVs remain idle at the location where they performed their task, as in Salihu et al. (2021).
iii. In case there are multiple ETV depots: one can choose to have ETVs return to one of the depots, as in Zaninotto et al. (2019). This can be used as a technique to pursue a good spread of ETVs on the airport surface. One can for example select the closest depot, or the depot with the least amount of other idle ETVs.

Start and end time of the taxiing procedure: In order to keep to the schedule, it is important to minimize deviation from the scheduled taxiing start and end time. Soltani et al., 2020 create an upper and lower bound for the start and end time of all taxiing movements in their MILP model. van Baaren and Roling (2019) assume no en-route delays occur and set the start and end of taxiing to a fixed moment in time. van Oosterom et al. (2022) calculate these times to ensure conflict avoidance. On the other hand, Zaninotto et al. (2019) investigate to what extent deliberately delaying the start of taxiing by a fixed amount can help decrease the number of routing conflicts.

4.1.4. Assumptions about model parameters

The specifications of aircraft and ETVs have a large influence on routing. An example is the assumed connecting and disconnecting time of ETVs. Zaninotto et al. (2019) and Salihu et al. (2021) assume one minute for these operations, while for example the TaxiBot requires three minutes (Smart Airport Systems (2022)).

Another routing parameter is the minimum separation distance between taxiing aircraft. Zaninotto et al. (2019) use a minimum separation distance of 300 m, based on minimum clearance, pilot reaction time and braking distance. In contrast, Salihu et al. (2021) use a distance of only 15 m, based on Australian Civil Aviation regulations.

A third parameter is the taxiing speed. Sirigu et al. (2018) assume a constant taxiing speed of 10 m/s. van Baaren and Roling (2019) and van Oosterom et al. (2022) use the specifications of the TaxiBot, i.e. 11.8 m/s. Salihu et al. (2021) assume a regular aircraft taxiing speed of 7 m/s, and speeds of 4 m/s and 7 m/s for a towing and non-towing ETV, respectively. Zaninotto et al. (2019), van Oosterom et al. (2022) and van Baaren and Roling (2019) include the acceleration and deceleration of ETVs in their simulation. The others keep to a constant velocity.

The value for separation distance and taxiing speed directly influence the taxiway capacity: they can make the difference between a model showing that electric taxiing leads to small increases in taxi time, such as for van Baaren and Roling (2019) or that it leads to large Salihu et al. (2021) or even unacceptable taxiing delays. Therefore, it is important to obtain realistic estimations for these parameters.

Lastly, the engine warm-up needs to be incorporated in the planning of a departing aircraft. Salihu et al. (2021) and van Baaren and Roling (2019) incorporate this into their model but do not specify the exact time taken. Salihu et al. (2021) assume warm-up occurs during taxiing and van Baaren and Roling (2019) and van Oosterom et al. (2022) assume warm-up occurs after taxiing.

4.1.5. Challenges

ETV manager to assist Air Traffic Control: Managing a fleet of ETVs increases the work load and responsibilities of Air Traffic Controllers: the Ground Controller, who manages the traffic on the taxiways (Smeltink et al. (2004)), now also needs to route all ETVs and make sure conflicts are avoided. ATC will need to be aware which aircraft are taxiing by themselves and which are towed by a vehicle. A possible solution is to add a separate role, that of *ETV manager*, to the airport. The ETV manager can be involved both in the routing and scheduling of the ETV fleet, as well as monitoring of the actual movement and dealing with disruptions in the schedule. They should be in close contact with ATC to ensure smooth operation at the airport. Workload is also increased at the airport surface; each of the ETVs will need a driver. Airport planners will have to take into account the working times and breaks of the drivers when creating the towing schedule with its driving and charging periods.

Autonomous airport surface movement: Another solution to mitigate the increased ATC workload is to aim for autonomous routing and scheduling of all airport surface movement (ASM) (Soltani et al. (2020)). For example, EUROCONTROL is working towards an Advanced Surface Movement Guidance and Control System (A-SMGCS), which is an automatic system that supports ATC in monitoring ASM operations by e.g. creating routes, monitoring possible conflicts, and operating stop bars and lights automatically (EUROCONTROL (2020)). An autonomous system can increase the safety, predictability and reliability of operations, by avoiding ground incidents, miscommunications and other human errors, and decrease delay and costs due to smart planning (Lukic et al. (2019); Schmidt et al. (2016, 2015)).

Several authors have been working towards autonomous ASM: an example is Zaninotto et al. (2021), who simulate ASM by connecting various programmed modules, such as a *Vehicle Simulator*, *Path Planning with Dynamic Obstacles* and *Tow Trucks Optimisation System*. Such a simulation can form the underlying model for an autonomous system for ASM. Going even further, Morris et al. (2015) apply self-driving vehicle technology to the problem of towing aircraft. In their model, towing vehicles drive by themselves, but are supervised by ATC in a Human-Machine Interface. Although the routing and scheduling is performed by an algorithm, resolving separation constraint violations remains the task of the controller. Okuniek and Beckmann (2017) note that the successful implementation of A-SMGCS depends on the ability of aircraft to follow the required surface movement plan: an autonomous system of intercommunicating ETVs can contribute to this goal. For example, one could program the ETVs in such a way that they communicate with each other to avoid conflicts and enforce separation distances, but also to avoid unnecessary braking and speed changes. This is expected to help the ETVs to follow the most fuel-efficient driving strategy.

Airport routing guidelines and taxi times: The additional operations associated with electric taxiing, combined with the reduced maximum taxiing speed (discussed in Section 2 and 3) can lead to increased taxi times and congestion of airport surface movement. There are several management measures that airports can consider when aiming to increase the efficiency of ETV routing. As discussed earlier, airports that are expected to experience taxiway congestions due to unloaded ETV movements on their taxiways, might seek to construct wider or more service roads. The implementation of runway stands for arriving aircraft that are connecting to an ETV could alleviate congestion near arrival runways. An airport that aims to implement external towing but needs to limit total taxiing time might consider allowing ETVs to travel faster on the service roads. Another option is to investigate whether the taxiing separation distance can be reduced, since there is no jet blast from a leading aircraft when it is being towed. The challenge of increased taxi times and congestion is expected to be particularly important for airports to address, since they will aim to implement electric taxiing without having to reduce the throughput of aircraft.

4.2. ETV fleet scheduling assignment problem

The *fleet scheduling assignment problem* (FSA) is the problem of assigning vehicles to tasks in a travelling schedule. This problem appears for example in taxi fleet scheduling, and the assignment of aircraft to flight numbers. When considering electric taxiing, all towing tasks need to be assigned to a specific ETV. This can be formulated as an FSA, which can be optimized for varying objectives.

Fig. 5 shows an example of fleet assignment on an airport, with three aircraft in three different situations.

4.2.1. Modeling approach

The models used in literature minimize the taxiing time (Zaninotto et al. (2019)), the taxiing fuel (van Baaren and Roling (2019); Soltani et al. (2020)), combine this into a taxiing cost (Salihu et al. (2021)), or minimize the number of used ETVs (van Oosterom et al. (2022)). The linear programming models aim to find the best routes and assignments for all aircraft movements at once, while the simulation approaches move through the flight schedule and perform route planning and vehicle assignment for each aircraft sequentially. The constraints used are typically grouped as:

i) Assignment constraints, for example: an aircraft should have only one vehicle assigned to it (see van Baaren and Roling (2019) eq. 3);
ii) Route flow and route timing constraints, for example: the arrival time at a node is calculated with the edge speed and the departure time of the previous node (see Soltani et al. (2020) eq. 6, 7);
iii) Collision avoidance constraints, for example: two aircraft that reach the same node from different edges must be separated by a separation time or distance (see Soltani et al. (2020) eq. 13, 14);

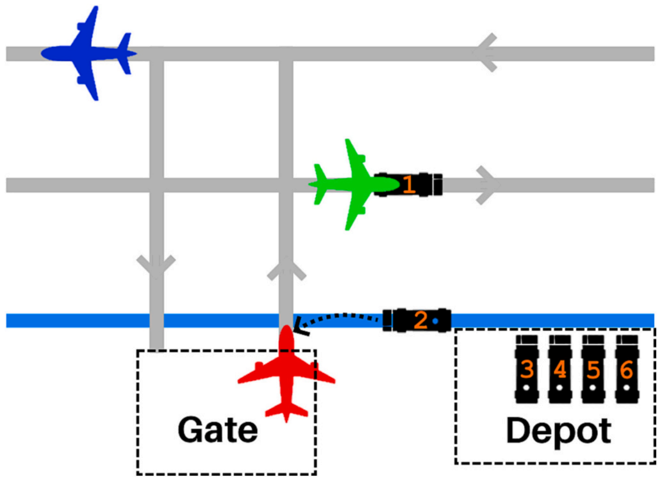


Fig. 5. Schematic representation of fleet assignment on an airport. The red aircraft is waiting at a gate for ETV 1 to arrive, so that it can be towed towards a runway. The green aircraft is being towed by ETV 2. Other ETVs are waiting to be deployed at a depot. The blue aircraft is taxiing by itself. Taxiway directions are indicated by arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

iv) Energy or fuel constraints, for example: the energy required for an upcoming task should be smaller than the current state of charge of the ETV (see van Baaren and Roling (2019) eq. 10).

4.2.2. Results

For EHRD and EHAM, van Baaren and Roling (2019) show that electric taxiing is slower than regular taxiing in all cases except a portion of departures at EHAM, but that electric taxiing uses less fuel than regular taxiing in all cases. Using their simulation model that balances taxi delay and routing conflicts, Zaninotto et al. (2019) show that halving the number of aircraft conflicts in a schedule leads to an increase of 13% in taxi time. Furthermore, allowing aircraft up to four minutes waiting time before starting the towing procedure can also reduce the number of conflicts. While towing all aircraft with ETVs provides the largest fuel and emissions savings, Salihu et al. (2021) calculate that at CYUL, the most economical solution is to only use electric taxiing for departing aircraft.

Fleet sizing: An important parameter which is often the subject of optimization or sensitivity analyses is the size of the ETV fleet. Zaninotto et al. (2019) assume an infinite number of tow trucks, while Soltani et al. (2020) find that the economic optimum for the fleet size at CYUL is 12 vehicles, when taking into account ETV operating costs, fuel and delay costs. Salihu et al. (2021) arrive at an optimum of 16 vehicles for electric towing of departing aircraft, when taking into account the annual total taxi time and annual operating costs. When considering electric towing of all aircraft, they find an optimum of 26 vehicles. van Baaren and Roling (2019) show that introducing 5 towing vehicles at EHRD decreases the fuel use by 65% and introducing 24 towing vehicles at EHAM decreases the fuel use by 75%. Furthermore, they show that increasing the fleet size further is less cost effective due to decreasing marginal fuel savings. van Oosterom et al. (2022) use the fleet size as the objective of the MILP formulation, and find that it has a roughly linear relation to the number of flights.

4.2.3. Scheduling management decisions

An important scheduling decision is which aircraft are to be towed and which aircraft will taxi by themselves. van Baaren and Roling (2019) choose regular taxiing if it is more fuel-efficient than electric taxiing, but find for both airports that this occurs in none of the cases. Furthermore, they have aircraft taxi regularly when their taxi time is smaller than the engine warm-up time. Unlike e.g. for delivery problems, not towing an aircraft still results in the aircraft participating in the airport surface movement. This means both the towed and self-taxiing aircraft are factors to consider in scheduling management decisions. Soltani et al. (2020) select the self-taxiing option when the cost of the delay incurred by waiting for an ETV is larger than the fuel saving benefit. In Salihu et al. (2021), all aircraft are towed, and it is shown that this leads to enormous costs and delays if the ETV fleet is not large enough.

Second, the wide-body aircraft have to be towed by the wide-body ETV and the narrow-body aircraft preferably by the narrow-body ETV. van Baaren and Roling (2019) incorporate these two types of ETVs in their optimization. van Oosterom et al. (2022) allow a heavy-wide body vehicle in addition.

Last, one needs to decide whether an ETV should be present at the aircraft at the scheduled taxiing starting time (van Baaren and Roling (2019); Zaninotto et al. (2019); Soltani et al. (2020)), or whether the ETV starts to move towards the aircraft at this time (Salihu et al. (2021)).

4.2.4. Challenges

Based on the literature with regard to ETV fleet scheduling, the following challenges for future research are identified:

Robust scheduling and disruption management: When creating a schedule it is often assumed that all operations take place as planned. However, at execution disruptions can take place, such as flight delay, mechanical failures of an aircraft or ETV, or unavailability of a road, gate or runway. Airside disruptions present a relevant challenge specifically for this type of ground operations, since effective operation requires the vehicles to be present at the correct gate or runway at the correct (disrupted) time, while the fleet is likely spread around the airport during operation. This is in contrast to other ground vehicles, which operate mainly in the gate areas. This means it might be more difficult to find an ETV that is near enough to perform a task it was not originally assigned to. Zaninotto et al. (2021) introduce a probabilistic version of their vehicle movement simulation by varying the vehicle speed. When comparing this to the algorithm defined in their previous work, Zaninotto et al. (2019), they obtain double the amount of vehicle conflicts (violations of separation distance) for LFBO, for arrival rates larger than 30 aircraft per hour. This illustrates that such disruptions can cause negative effects on the carefully optimized schedule objective. Soltani et al. (2020) recommend to consider stochastic events such as weather conditions, deicing operations and the reliability of ETVs.

Steps can be taken to reduce these effects both before operation (*robust scheduling*) and during the operation (*disruption management*). Robust scheduling can be performed by considering the effects of possible disruptions on a given schedule. For example, one can run a simulation of a given schedule, where disruptions occur with a given probability. These probabilities can be estimated or predicted based on earlier occurrences and other factors. Based on such a simulation, changes can be made to an FSA to make it more robust. Another option is to create a robust schedule from scratch, by incorporating constraints that guarantee the robustness into the scheduling problem. An example of robust scheduling in literature is Jamili (2017), who create an MILP and a Simulated Annealing heuristic for robust aircraft routing and scheduling using traffic on O—D pairs as input. Cadarso and de Celis (2017) consider stochastic demand figures and uncertain operating conditions in a robust planning model for flight timetables and fleet assignments, and show that the number of misconnected passengers can be reduced.

Disruption management is a continuous process: as soon as planners are aware of a disruption, they will need to make changes to the schedule. Towing routes might have to be deconflicted, and gate, runway or ETV assignments might have to change. A typical objective in disruption management is to minimize the number of changes needed to reach a feasible or locally optimal schedule again. More changes means an increased workload for personnel and increased uncertainty for passengers, and often leads to increased costs. van Oosterom et al.

(2022) perform disruption management by testing their MILP and greedy algorithms in a 30-min rolling horizon approach, and investigating which fraction of the amount of originally towed aircraft can still be towed. Using this approach, they find fractions of 94% (greedy) and 98% (MILP) for the busiest test day. Another example of disruption management in aerospace is Lee, Marla, and Jacquillat (2018), who develop an optimization model of disruption recovery for a network of airports, and integrate a stochastic queueing model of congestion therein. This approach reduces expected disruption recovery costs by 1 to 4%. Tang, Lin, and He (2019) develop a dynamic model to simultaneously optimize vehicle schedules and electric fleet sizes of electric buses. The model incorporates road-traffic stochasticity to mitigate the breakdown of a vehicle.

Note that robust scheduling and disruption management have only limited capability to mitigate disruptive effects, due to the stochastic nature of disruptions. This means that it is likely that there will be departing or arriving aircraft that need an ETV at a time when their scheduled ETV is unavailable. One solution would be for the aircraft to perform self-taxiing. Another would be to maintain a group of separate ETVs that are not assigned to any aircraft, but tow aircraft for which no other ETV is available. On a large airport with many gates and runways entrances/exits that take long to drive to, such a spare ETV may take a long time to arrive at the aircraft. A trade-off is expected between the costs of extra delay for the aircraft and the costs of maintaining a larger group of ETVs for this purpose.

Technological developments: As the development of operationally deployable external ETSs progresses, more becomes clear about the technological specifications of the towing vehicles. Such specifications can be used in research to make models for scheduling and routing ETVs more realistic. For example, the list of aircraft types that have been certified for using the external ETS (as shown in Table 1) can be used to create a routing and scheduling model that represents an intermediate implementation situation where only a part of the aircraft fleet may be towed. Similarly, including both the narrow-body and wide-body ETVs and their specifications in a model introduces several unaddressed scheduling considerations: the fleet sizing problem with two types of vehicles, the utilization of either type, but also the influence of differing charging rates and electricity usage of the two types on the routing and scheduling.

4.3. Charging for electric vehicles

Currently, the towing vehicles operating at the airports shown in Table 1 are diesel-powered. Eventually, all towing vehicles are expected to become actual ETVs, which regularly need to recharge their batteries. This can take considerably longer than refueling for vehicles operating on fossil fuels, so that the recharging time becomes an important part of the vehicle planning. Given a taxiing schedule for an airport, one can find an optimal charging strategy, depending on e.g. the size and type of batteries in the ETV. The locations of charging stations influence both the routing and the charging schedule, and it is therefore vital to optimize their placement on the airport surface.

Most of the electric taxiing literature investigating VRPs and FSAs does not take into account charging for their routes and schedules, see Table 3. In this subsection, we review literature that considers the charging aspect of managing a fleet of electric vehicles (EVs), from both airport surface movement and other fields. Table 4 provides an overview of this literature.

4.3.1. Optimal charging strategy

Since charging an EV can be a time-consuming process, it is important to find the best time for charging and the best charging method, while taking into account the requirements and specifications involved.

Charging period: When an EV is being charged, it can be charged to its capacity (*full recharge*), or for a fixed amount of time or time steps (*fixed charging time*). A third option is to charge until it is needed for operation (*partial recharge*). In van Baaren and Roling (2019), every vehicle is charged for a fixed time in between any two jobs, and it is assumed that the vehicles is fully charged after this. Similarly, Hiermann et al. (2016) assume that a vehicle is recharged till full, when it arrives at a charging station, and Lin et al. (2019) fully recharge electric buses overnight. On the other hand, Gulan et al. (2019) and Xiang et al. (2021) allow partial recharging. In these studies, every vehicle is given attributes such as the charging level, vehicle activity, vehicle type and availability for tasks. Based on these attributes and the tasks that need to be performed, a selection is made which vehicle will be charged during this time step and which will be sent to perform a task. Schiffer and Walther (2017) allow both full and partial recharging, as do van Oosterom et al. (2022) who define the amount of charge through keeping track of the state of charge of a vehicle after towing an aircraft.

In addition to the actual charging period, a vehicle needs to travel to and from a charging station. van Baaren and Roling (2019), van Oosterom et al. (2022) and Hiermann et al. (2016) include the routing of EVs to and from tasks and charging stations in their schedules. However, Gulan et al. (2019) and Xiang et al. (2021) do not take into account travelling between tasks and charging stations. Instead, a large time step of 15 min is taken in which vehicles are either charging or performing their duties.

Problem formulation and model inputs: Gulan et al. (2019) perform a Monte Carlo simulation and Pareto front analysis to test combinations of input parameter values on their joint objective: minimizing the needed amount of electric vehicles and minimizing the amount of gas used by gas vehicles (the alternative to the EVs). These input parameters include the number of charging stations, the number of each type of vehicle and the maximum electrical load of the terminal. The GSE tasks are derived from synthetic flight schedules, and the simulation runs for three schedule days. Xiang et al. (2021) create a sequencing algorithm to perform a similar simulation with the goal of maximizing the usage of electric vehicles. The charging algorithm is an input to a larger model that investigates the costs of an airport energy microgrid including hydrogen, solar and battery energy sources. The authors used a year of historical flight data from Chengdu Airport (ZUUU) to find the GSE tasks that need to be performed and the electrical load needed at the airport.

In their MILP approach to the ETV routing and scheduling problem at EHAM and EHRD, van Baaren and Roling (2019) include constraints enforcing vehicles to charge in between tasks. van Oosterom et al. (2022) control the charging process by enforcing constraints regarding the state of charge of vehicles after towing an aircraft. Hiermann et al.

Table 4
Literature on the management of charging a fleet of electric vehicles. GSE indicates Ground Support Equipment and MILP indicates Mixed Integer Linear Programming.

Author-Year	Electric application	Model formulation	Charging strategy	Charging station placing method
Hiermann, Puchinger, Ropke, and Hartl (2016)	General	MILP	Full recharge	Bidirectional labelling
Schiffer and Walther (2017)	General	MILP	Full & partial recharge	Included in MILP
van Baaren and Roling (2019)	Aircraft taxiing	MILP	Full recharge	Given
Lin, Zhang, Shen, Ye, and Miao (2019)	Buses	MILP	Full recharge	Candidate locations selected in MILP
Gulan, Cotilla-Sanchez, and Cao (2019)	GSE	Monte Carlo simulation	Partial recharge	Given
Xiang, Cai, Liu, and Zhang (2021)	GSE	Sequencing algorithm	Partial recharge	Given
van Oosterom et al. (2022)	Aircraft taxiing	MILP	Partial recharge	Given

(2016) create an extensive model solving vehicle routing with time windows, charging station placement and fleet sizing at the same time. Their goal is to cover a set of customers on the routes, while minimizing the number of needed EVs and their total travelled distance. They compared two different solution approaches: an MILP formulation, and a combination of Adaptive Large Neighbourhood Search and local search algorithms. A bidirectional labelling algorithm was used to determine the optimal placement of charging stations. These approaches are able to solve instances with 15 customers and 2 to 8 charging stations within a gap of 1% compared to best known results. Similarly, Schiffer and Walther (2017) consider a model incorporating charging station placement, capacity constraints, time windows and recharging. Several objectives were considered in this model, such as minimizing travel distance, the number of needed vehicles and charging stations, and the total costs. The authors show that reducing the solution space to strengthen the model formulation ensures that more benchmark instances of 5, 10 or 15 customers can be solved to optimality, in a shorter computation time.

Battery specifications: Important specifications with regard to charging are the battery capacity, and the charging and depletion rate of the battery. Most studies shown in Table 4 do not specify battery capacity, recharging time or energy consumption rate. The medium towing vehicle introduced by van Baaren and Roling (2019) has a battery capacity of 840 kWh and a maximum power of 1400 kW. They find that an average tow of a medium aircraft would require 33 kWh at EHAM. The vehicles used by van Oosterom et al. (2022) have capacities ranging from 400 to 3200 kWh, and charging power ranging from 100 to 500 kW. Adegbohun, von Jouanne, and Lee (2019) note that fully charging the battery of a 50–100 kWh EV requires two to three hours, or 0.5 to 1 h for fast charging. Modern electric pushback trucks, capable of towing fully loaded aircraft for short distances, have a battery capacity of up to 165 kW, and can be fully charged in under an hour assuming fast charging with a linear charging profile Munich International Airport (2021); Goldhofer (2021). Soares and Wang (2021) envisions a 500 kW fast-charging system for an airport, capable of recharging a 300 kW pushback truck battery pack in 40 min. As shown in Table 5, the varying charging rates found throughout literature have a large impact on the scheduling of an ETV fleet, and can determine whether ETVs can operate for a full day and charge overnight, or if they will need to be partially charged during the day.

Electrical load on the network: Charging many powerful ETVs at the same time, for example with overnight charging, can be a burden on the electricity grid of an airport, especially if faster charging techniques are used. Adegbohun et al. (2019) notice that fast DC charging of EVs at 50 kW and up can lead to unsustainable load spikes on the distribution grid, and could critically affect its reliability and stability. Silvester et al. (2013) find that charging a thousand electric cars at EHAM would be equivalent to the total electricity peak load at the airport (2.5 MW). As can be deducted from Table 5, a relatively small fleet of ETVs can already be very demanding for the electricity network, depending on the charging rate. van Baaren and Roling (2019) calculate that electric towing for all aircraft will cost 90.4 MWh of energy at EHAM and 1.1 MWh at EHRD, without losses due to charging. This is equivalent to 36 h of 2013 peak load every day. Xiang et al. (2021) take into account the available grid power and its costs in their optimization model for charging GSE at an airport, where it is used as an alternative for hydrogen fuel cell generation and battery storage systems. Lin et al. (2019) include a decision variable in their MILP model to decide which charging station is connected to which power grid node, and include the maximum power such nodes can provide as a constraint.

Battery swapping: For some vehicles, such as electric cars (Yang and Sun (2015); Adegbohun et al. (2019)), electric aircraft (Mitici, Pereira, and Oliviero (2022); Salucci, Trainelli, Faranda, and Longo (2019)), and electric container transporters (Schmidt, Meyer-Barlag, Eisel, Kolbe, and Appelrath (2015)), battery swapping, sometimes in combination with regular charging, is being investigated as an alternative charging strategy. Battery swapping allows one battery to be charged without being in the vehicle, while another is being used by the vehicle. The main benefit of battery swapping is that the refueling time is comparable to that of fossil fuels, as opposed to battery charging, which can take multiple hours, depending on the used charging technology. Battery swapping can thus avoid long downtime due to charging. Another advantage of battery swapping is that peak loads on the power grid can be reduced because battery charging can be spread out during the day or night.

Yang and Sun (2015) use heuristics to solve an MILP formulation for a location routing problem for battery swapping stations, for general EVs. Adegbohun et al. (2019) describe the design and working of battery swapping stations for electric cars. Such facilities are already operational, for example in China for NIO cars (NIO, n.d.).

Mitici et al. (2022) investigate battery swapping for electric aircraft during turnaround, by solving an MILP formulation to decide which batteries will be swapped, and consequently, at which charging station they will be charged. Other outputs are the fleet size, the aircraft to flight schedule, the number and location of charging stations, and the number of batteries needed. Using the combination of battery swapping and charging, three times more missions can be performed with electric aircraft than the fleet size. Salucci et al. (2019) also identify the number of spare batteries needed as one of the key points for achieving smooth operations, and use simulation modeling to perform infrastructure planning for electric aircraft at airports.

Schmidt et al. (2015) investigate charging strategies for charging automated guided vehicles in container terminals, and find that the best balance between high productivity, low costs and low waiting time is to use 1.6 batteries per vehicle in the charging system.

4.3.2. Placement of charging stations

In the case that there are not enough charging stations at an airport, or they are not placed strategically, there will be vehicles that cannot perform their duties and are lining up at the charging stations. On the other hand, it is expensive to keep many charging stations operational if not all of them are used enough. This trade-off is a consideration when implementing a fleet of ETVs at an airport.

Establishing the number of charging stations: Gulan et al., 2019 perform their analysis for a range of 27 to 80 electric ground support vehicles, combined with a range of 25 to 45 charging stations, for one airport terminal. Schiffer and Walther (2017) show how to obtain a lower bound on the number of needed charging stations and EVs, to reduce the needed computational time for solving their MILP formulation. Hiermann et al. (2016) find that in benchmark instances where normally a set of 21 charging stations was required to serve all EVs, optimizing the fleet mix leads to a situation where less then half of these stations are needed. Doctor, Budd, Williams, Prescott, and Iqbal (2022) makes use of

Table 5
Battery specifications and their influence on ETV performance based on various studies. The columns 'full charging time' and 'charging time for one tow' are calculated using the parameters from van Baaren and Roling (2019) and assuming a linear charging profile.

Author-Year	Charging method	Charging rate	Full charging time	Charging time for one tow
Adegbohun et al. (2019)	Regular charging	30 kW	28 h	66 min
Adegbohun et al. (2019)	Fast charging	100 kW	8.4 h	20 min
Goldhofer (2021)	Fast charging	165 kW	5.1 h	12 min
Soares and Wang (2021)	Fast charging	500 kW	1.7 h	4 min

discrete event simulation to determine the best number of charging stations at London Heathrow (EGLL) for electric aircraft. They consider fixed charging times of various lengths and illustrate the influence of an electric fleet on the airport throughput and turnaround times.

Deciding the location of charging stations: In the studies in Table 4 that consider electric taxiing or ground support equipment, the locations of charging stations are considered fixed. In other applications of EVs, the so-called location routing problem (LRP) has been investigated: Hiermann et al. (2016) model both the choice of locations and the choice of the number of charging stations for EVs by inserting stations on given routes where needed, using a bidirectional labeling algorithm. Lin et al., 2019 formulate an MILP model to select charging station locations for electric buses, from a list of candidate locations. The aim is total cost minimization, where factors such as facilities, transportation and grid power loss are considered. The authors used the model to select 12 charging stations from 30 candidate locations in Shenzhen, China, which hosts more than 16,000 electric buses.

4.3.3. Challenges

Charging stations on the airport surface: Table 4 shows that optimization regarding the charging stations has not been performed in the context of airport surface movement. There the locations and amount of charging stations have been assumed given. However, the number of charging stations for ETVs can depend on many variables, such as the airport layout, runway usage, the fleet size, the vehicle electricity usage and the electric power available. A suitable location should be quickly reachable from the service road network, have sufficient space for multiple charging points, and it should be possible to connect the location to the airport electricity network with high-voltage cables Salucci et al. (2019); Doctor et al. (2022).

Multi-stage approach: As shown in Section 4.2.4, it is important to consider the development of ETV usage in the future. As more aircraft types become certified to be towed by ETVs, it is expected that airports will slowly increase the size of their ETV fleet, and consequently their need for the associated charging infrastructure. For example, Schiphol currently has a fleet of only three ETVs, but by 2030 it is envisioned that all aircraft can be towed by ETVs (Schiphol (2020)). It is possible that a charging station location that is suitable for the ETV fleet in 2025 does not fit in the optimal charging station configuration for the ETV fleet in 2030. In order to make sure that charging stations do not need to be relocated, one can develop a multi-stage approach to the charging station placement problem for electric taxiing. Such an approach has been developed by Lin et al. (2019) for electric buses, where the first stage was defined as the coming ten years, and the second stage as the twenty years thereafter. The authors obtained expected values for the number of buses and charging stations, the energy demand, and the station construction costs, for the two stages. The charging station placement problem was then solved for both stages simultaneously, prohibiting station relocation. The authors show that multi-stage optimization reduces the total cost by 17% when compared to single-stage optimization. When considering the charging station configuration for ETV, developing a multi-stage approach would require knowledge of the expected ETV fleet size and amount of charging stations during the coming years, but also other factors that might influence the charging network. For example, the introduction of the wide-body version of the ETV, which will likely have a different battery capacity and depletion rate, can be modelled in one of the stages.

Battery specifications: To construct a realistic charging model for ETVs, there are several factors that should be considered. In literature, the charging and depletion rate of EV batteries are most often assumed to be constant. In contrast, Goeke and Schneider (2015) incorporate speed, gradient and load distribution in their model of EV energy consumption, and Mitici et al. (2022) and van Oosterom et al. (2022) assume a bilinear charging profile for electric aircraft. When considering ETVs the batteries may also exhibit nonlinear charging behavior. The depletion rate will be influenced by vehicle speed and acceleration, but also by factors such as the outside circumstances, the weights of the aircraft that are being pulled, and the acceleration profile.

Energy demand: Silvester et al. (2013) assert that achieving sufficient electrical distribution capacity is the largest bottleneck for successful operation of a fleet of EVs. Charging a fleet of ETVs at an airport is expected to require a large amount of energy. An approach to the demand for electricity for an ETV fleet should consider:

i) The power supply available at the airport during the entire day of operations. For example, Gulan et al. (2019) propose a model describing a trade-off between available power supply and energy demand. Specifically, a trade-off between using gas-powered GSE and electric GSE is obtained.
ii) The charging protocol, e.g. overnight or daytime charging (Lin et al. (2019)), full or partial charging (Gulan et al. (2019)), and fast or regular charging.
iii) The price of energy at different moments during the day/year, as well as the expected price of electricity and batteries.

When all of these aspects are integrated in a model, its results can be used to make management decisions with regard to investments in electrical infrastructure at an airport.

Alternative charging strategies: As outlined above, battery swapping technology can help avoiding ETV downtime, increasing the usability, and reducing peak loads on the power grid. Improved usability can in turn lead to a smaller fleet size, saving operating costs. On the other hand, depending on the amount of spare batteries used, it may lead to an increased peak energy load on the airport.

Another alternative charging strategy is to charge EVs using wireless power transfer technology (WPT). Rather than charging EVs at a set of charging stations, it is possible to use dynamic wireless charging (DWC) to charge EVs while driving along roads. The first commercial EV using DWC was deployed in 2009 (Miller, Jones, Li, and Onar (2015)), and since then a significant amount of research has been conducted towards implementing DWC for varying EVs. Many authors view DWC technology as a promising solution for future EVS (Jang (2018)). Alwesabi, Liu, Kwon, and Wang (2021) develop an MILP model to determine the needed amount of electrical buses and wireless cable length to serve a given bus schedule. By placing the cables strategically along the bus routes, the electric buses can suffice with a battery of 18 kWh. Oliveira, Ulahannan, Knight, and Birrell (2020) aggregate human factor data to determine the best location for DWC cables that serve electric taxis. Their solution involves placing cables under taxi ranks. DWC techniques could be of interest to airports as well, especially those that aim for electrification of all ground support equipment (Gulan et al. (2019); Xiang et al. (2021)). Since ETVs and other GSE regularly drive along the same roads, strategically placing DWC cables under these roads can provide these vehicles with power for a significant part of their driving time. Therefore, implementing DWC technology for ETVs is expected to reduce or remove the need for charging stations at the airport, and possibly the needed battery size. This in turn may reduce the vehicle's weight, which is expected to lead to further improvement in energy use (Soares and Wang (2021)).

5. Discussion and conclusion

Electric taxiing is expected to significantly contribute to the reduction of air traffic emissions, and has attracted increasing research attention. Although scientific reviews have been written from a technical and economic perspective, the existing literature has not been reviewed from an operational perspective. This study has reviewed the operational aspects of managing a fleet of electric taxiing vehicles (ETVs) at an airport and has identified challenges for future research.

In the past 10 to 15 years, multiple electric taxiing systems (ETSs) have been proposed to reduce airport emissions due to taxiing. The systems are commonly classified into on-board and external systems.

On-board systems become part of an aircraft and do not require a fleet of vehicles to be routed on the airport surface. External systems require no changes to aircraft, can attain a large taxiing speed, are technically less difficult to implement, and are currently operational at airports on a small scale.

The electric taxiing procedure for an aircraft that makes a turnaround has been compared to regular operation in detail. In addition to the required changes in the procedure, time and space will have to be reserved for the connecting and disconnecting of vehicle and aircraft, for the engine-warm up of the aircraft, and for charging the vehicles. The ETV replaces the pushback truck, but will add to the traffic on the taxiways or service roads.

The challenges associated with the operational management of ETVs have been treated from the perspective of three main topics. The first topic is the routing of vehicles and aircraft. The vehicle routing problem for electric taxiing is different from regular VRPs, because of the separation requirements, the many one-way taxiways, the use of two types of roads for ETVs (taxiways and service roads) and the specific delay characteristics of air traffic. Some authors represent this problem with a simulation, allowing for sequential routing of aircraft. Others set up an MILP, which is then solved for a full day. The simulation approach allows for a more straightforward conflict avoidance, while the MILP approach requires many additional constraints. The assumed values of several key parameters differ across the literature: taxiing separation distance, speed and engine warm-up time and place. Routing challenges identified are as follows: first, there are possibilities for airports to adjust the current rules and procedures on the airport surface to better facilitate swift electric taxiing. Second, the increased workload posed by the necessary management of the ETV fleet on ATC must be addressed, for example with a dedicated ETV manager, or in the long term by implementing A-SMGCS.

The second topic is the assignment of vehicles to aircraft. Typical objectives from literature are to minimize taxiing time or used fuel. Factors that have a large influence on these objectives are the size of the ETV fleet, the manner of conflict avoidance, and the instances where the aircraft taxi in the regular way. An important scheduling challenge is dealing with airside disruptions, such as flight delays, which can cause disruptions of the ETV schedule and increased workload of personnel, since the ETVs need travel time to arrive on time at gates and runways around the airport. The development of robust scheduling algorithms and disruption management procedures for the airport surface movement can reduce the effects of these airside disruptions. Another challenge is to solve the scheduling problem with realistic technological specifications of external ETSs, so that the expected performance can be modelled accurately, and possible bottlenecks can be identified. Airside disruptions present a relevant challenge for this type of ground operations, since effective operation requires the vehicles to be present at the correct gate or runway at the correct (disrupted) time, while the fleet is likely spread around the airport during operation. This is in contrast to other ground vehicles, which operate mainly in the gate areas.

The last topic is comprised by the complications due to the electrical aspect of ETVs. There have been but a few operational management approaches to ETVs that include this aspect. Some subjects that are interesting for ETVs have been treated for other types of electric vehicles: Typical objectives are to minimize the number of vehicles or charging stations, or the taxiing distance. Several characteristics of the problem such as the charging period, the influence on the electrical network and possibilities for battery swapping are topics of interest in current research. The main challenge is to apply the optimization problems with their characteristics as reviewed here to the problem with ETVs. Specifically, the location routing problem for charging stations has not been attempted for ETV fleets to the knowledge of the authors. Possible additions to these optimization problems are to devise a multistage approach for the electric infrastructure, to make sure the demand for electrical power can be met by the airport, and to use realistic battery specifications. Lastly, alternative charging techniques such as dynamic wireless charging can be of interest for the ETV charging problem.

Overall, we have seen that important research steps have been taken in implementing of external electric taxi systems, but numerous research directions and challenges remain. Addressing these challenges will help the industry move to large-scale ETV implementation in the next decades and thereby hopefully significantly reduce airport ground emissions.

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CRediT authorship contribution statement

M. Zoutendijk: Conceptualization, Investigation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **M. Mitici:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **J.M. Hoekstra:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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