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Evaluating Potential Fuel-Savings of External Alternative Ground Propulsion Systems

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Abstract
This study evaluates the potential taxi fuel-savings from using external Alternative Ground Propulsion Systems (AGPS) at Zurich Airport, based on Automatic Dependent Surveillance–Broadcast (ADS-B) surface trajectory data collected from May 1 to September 30, 2024. Using the Aircraft Emissions Databank of the International Civil Aviation Organization, we estimate the fuel consumption of departing turbojet aircraft during the taxi phase for both conventional and AGPS-assisted taxiing modes. Our findings suggest that adopting AGPS at Zurich Airport could reduce taxi fuel consumption by up to 58.5 %. During the considered observation period, towing all aircraft from the stand to the runway could have saved 5178.6×10^3 kg of jet fuel, which is equivalent to approximately 16.36 million kg of CO_2 emissions. Extrapolated to an entire year, external AGPS might save approximately 30 million kg of CO_2 emissions, which is considerably more than the Scope 1 and 2 emissions of 23.86 million kg reported by Zurich Airport for the year 2024. Due to significant variations in taxi times between flights, our study highlights the significance of selecting aircraft with longer taxi durations for towing to maximise fuel-saving benefits. Even with limited AGPS resources, substantial reductions can be achieved; for instance, deploying just four AGPS units could cut taxi fuel consumption by up to 34.8 %. While the study offers a promising approach to reducing emissions, it acknowledges that practical challenges, such as the need for operational adjustments, must be overcome to ensure the successful implementation and effective use of AGPS in real-world applications.

Keywords: Alternative ground propulsion systems; aircraft surface trajectories; automatic dependent surveillance-broadcast; aircraft emission reduction; sustainability

Abbreviations: ADS-B: Automatic Dependent Surveillance–Broadcast, AGPS: Alternative Ground Propulsion System, APU: Auxiliary Power Unit, ECS: Environmental Control System, JOAS: Journal of Open Aviation Science, MES: Main Engine Start, OSN: OpenSky Network, WUP: Warm-up Period,

1. Introduction

Flightpath 2050 [1] is the European Union's vision outlining how the aviation industry should tackle future challenges in the areas of competitiveness, performance, and sustainability. One of the sustainability goals specified is to achieve emission-free ground movements for both departing and arriving aircraft in the future. This aim is also reflected in the latest edition of the *European ATM Master Plan* [2] where the *Strategic Deployment Objective 2.3* focuses on reducing the environmental footprint by implementing (among others) engine-off taxi procedures with sustainable taxi vehicles. Nowadays, emissions generated by conventional taxi operations of aircraft can be rather substantial. For instance, 54 % of London Heathrow Airport's carbon footprint is created by aircraft on the ground, of which 8, 13, and 10 % are contributed by aircraft taxiing in, out, and holding on the ground, respectively [3].

To reduce emissions of taxi operations, a number of *alternative taxiing solutions*, divided into operational and technological measures [4], are suggested in the literature [5]. Operationally, airports and/or air traffic control units responsible for aircraft ground movements may reduce emissions by minimising taxi durations, which is implemented by actively managing queues in front of runways and providing the most direct taxi routes. Besides, flight crews may contribute to emission reductions by applying so-called single engine taxi procedures whenever possible and operationally feasible [6]. Technologically, aircraft might refrain from using their own engines for taxiing but rather rely on either internal or external emission-free Alternative Ground Propulsion Systems (AGPS). Internal AGPS are electric motors installed on board of aircraft [7]. For instance, a system provided by *WheelTug* [8] is installed in the nose wheel, while the *Electric Green Taxiing System* offered by *Safran* and *Honeywell* [9] is mounted in the main landing gear. Except during the pushback process, on-board AGPS allow the flight crew to steer the aircraft independently during the taxi procedure. However, internal AGPS add weight to the aircraft, leading to an increased fuel consumption during the flight [10]. Moreover, on-board AGPS require electrical power during operation, which in practice is usually provided by the aircraft's conventionally powered Auxiliary Power Unit (APU), a battery, or a fuel cell [5]. In contrast to on-board AGPS, external AGPS are aircraft tugs only connected to the aircraft for the duration of the taxiing process. As with cars, a distinction can be made between fuel-powered, fully electric, and hybrid-electric external AGPS. While certain external AGPS are steered either by the ground crew or drive autonomously, other external AGPS, such as systems offered by *TaxiBot* [11], can be steered by the pilots for all taxi phases but the pushback. Should external AGPS be used for both pushback and taxiing rather than just for the pushback, more resources, i.e., tugs, must be made available to handle the increased traffic volume compared to a conventional pushback. For this reason, external AGPS can be associated with high capital and operational expenses [5]. Moreover, it might well be that the usage of external AGPS increases the total duration of taxi [12].

In the literature, the question of how much fuel can be saved and emissions reduced by using AGPS has already been addressed by various authors. Edem et al. [13] assumed that the average taxi-out time of an *Airbus A320* is 20 minutes. On that basis, the authors estimated a fuel reduction of 110 kg per flight if an all-electric external AGPS is used. Camilleri and Batra [3] assessed the environmental impact of various technologies and/or strategies for aircraft taxiing by comparing a taxi procedure of aircraft on a fictitious airport following different taxi strategies including full-engine taxi, single engine taxi, internal AGPS, and external AGPS. The energy requirement of aircraft is estimated with a mathematical model considering drag and tractive forces as well as the slope of the ground. Subsequently, the fuel consumption of aircraft performing full-engine and single-engine taxi is determined with a method presented in [14], while the fuel consumption under AGPS is estimated with a method suggested by [15]. The authors conclude that the effectiveness of AGPS remains unclear: The usage of AGPS lowers the fuel consumption of aircraft. However, depending on the type of AGPS employed, the emission of hydrocarbons, carbon monoxide, and carbon dioxide might increase. Ithnan et al. [15] evaluated taxi strategies for Amsterdam Schiphol Airport and Kuala Lumpur International Airport using daily flight schedules to determine average taxi distances on the basis of existing arrival and departure runways and gates. The *Aircraft Emissions Databank* [16] of the International Civil Aviation Organisation (ICAO) was used by the authors to estimate fuel consumption and emissions of the aircraft. Compared to conventional taxiing, the authors reported a fuel consumption reduction at Amsterdam Schiphol Airport of 26.1 %, 36.5 %, and 41.0 % for single-engine taxi, external APGS, and internal AGPS, respectively. Applying a similar methodology for Zurich Airport, Fleuti and Maranini [12] estimated that the use of external AGPS reduced CO_2 emissions by 53.5 %

per narrow-body aircraft operation.

The literature includes studies focusing on potential fuel-savings from internal and external AGPS, with all studies mentioned above using the ICAO *Aircraft Emissions Databank* [16] to estimate fuel consumption during taxiing based on aircraft type, engine type, and taxi duration. However, the methods for determining the duration of taxi movements vary across different studies, either assuming a fixed average taxiing time or taxiing distances based on flight schedules and gate/runway combinations. To the best of our knowledge, there is no contribution that utilises observed surface trajectories of taxiing aircraft. Therefore, our study aims to close this gap in the literature by addressing the questions of whether and how potential fuel-savings resulting from the use of AGPS can be determined on the basis of observed Automatic Dependent Surveillance–Broadcast (ADS-B) surface trajectories sourced from the Opensky Network (OSN) [17]. To limit the scope of our study, we focus exemplary on Zurich Airport, which has excellent ADS-B ground coverage. Besides, we exclusively consider departing aircraft which taxi conventionally to the runway and compare the fuel consumption to aircraft that are (hypothetically) towed to the runway by an external AGPS. Consequently, this study advances knowledge by (i) introducing methods to estimate fuel consumption for both conventionally taxiing aircraft and those towed by an external AGPS using ADS-B surface trajectories, (ii) evaluating and discussing the potential fuel-savings achievable with external AGPS, and (iii) providing a practical example demonstrating the application of the proposed method.

The remainder of this study is structured as follows: Section 2 outlines the methods used in the research. In Section 3, the findings are presented, with a focus on the practical application of the method to a real-world case at Zurich Airport, Switzerland. Section 4 discusses the results, including the study's limitations, while Section 5 offers concluding remarks and provides an outlook for future research.

2. Methods

This section describes the methods we used to estimate the fuel-saving potential of external AGPS. First, Section 2.1 provides information on data collection and pre-processing. Section 2.2 explains how we classified pushback procedures and take-offs in ADS-B trajectory data. Subsequently, Section 2.3 describes how we estimated the taxi fuel consumption of departing aircraft during both conventional as well as external AGPS-assisted taxiing, while Section 2.4 then shows how we evaluated the fuel-saving potential for an airport.

2.1 Data Collection and Pre-Processing

To assess the fuel-saving potential of AGPS based on ADS-B data, high quality (meaning as gapless as possible) surface trajectories of departing flights between leaving the stands and reaching the runway must be available. Trajectories that meet these requirements can only be obtained from airports with reliable ADS-B receiver coverage. For example, within the OpenSky Network, Zurich Airport has had sufficient ADS-B coverage since February 2024. For this reason, we decided to demonstrate and validate the methods presented in this study using Zurich Airport as an example. However, it is important to emphasise that the methods presented hereafter are universal and, after adaptation to local conditions and circumstances, can be applied at any other airport with good availability and high quality of surface trajectories.

We obtained ADS-B trajectory data for flights observed through the OpenSky Network in the immediate vicinity of Zurich Airport between May 1 and September 30, 2024. This dataset was then reduced to observations where the aircraft either reported an altitude below 4000 ft or being *on ground*. In a further step, we resampled all trajectories at one second intervals, assigned unique IDs to each flight using the `assign_id()` function of the *traffic* library [18], and mapped all known transponder hex codes to an ICAO aircraft type using the `aircraft_data()` function of the *traffic* library. Finally, function `cumulative_distance()` was applied on all trajectories in order to calculate the cumulative distance travelled, ground speed, and ground track of the flights on the basis of observed latitude and longitude coordinates.

Although the ADS-B data quality for surface trajectories at Zurich Airport is generally very good, some trajectories may still exhibit significant noise. Such anomalies can lead to misclassified surface events (i.e., pushback, take-off), which in turn may distort results by over- or underestimating taxi durations. To remove these noisy trajectories from our dataset, we implemented the following filtering procedure: for each trajectory, we determined the first differences of the computed ground speed and cumulative distance. We then excluded all trajectories where the absolute value of the ground speed difference exceeded 200 kt per second and the cumulative distance difference exceeded 0.1 NM per second. These threshold values were determined through extensive testing and were selected to identify trajectories with unrealistically large jumps in the respective signals.

2.2 Surface Event Detection

A rule-based classification algorithm was then used to identify all flights departing from the airport in question. Subsequently, the surface trajectories of these departing flights were further analysed to obtain their taxi duration and distance, and to determine whether the flight has performed a pushback or not.

2.2.1 Classification of Take-offs

To classify departing flights, we proposed a modified version of the `takeoff()` function available in the *traffic* library. The existing function was developed for airports with limited ground coverage. At airports with good surface coverage, we have noticed increased misclassification with the legacy `takeoff()` function, encouraging us to propose modifications. Given a trajectory of a flight and an ICAO airport code, our `takeoff(method="track_based")` function determines whether and on which runway the aircraft took off by analysing the flight's initial climb trajectory and comparing it with the runway orientations at the specified airport. Initially, the trajectory data of the flight is filtered to keep the portion (i) closer than 5 nautical miles (NM) to the airport, (ii) below an altitude of 1500 feet above the elevation of the airport, (iii) where the aircraft is moving faster than 30 knots, and (iv) showing a vertical rate of at least 257 feet per minute[1]. This ensures that the data considered corresponds to the initial take-off phase. Our function then computes the median track angle of the flight during the initial climb. It compares this median track with the bearings of the airport's runways. If the airport does not have parallel runways, the function identifies the most likely runway by finding the closest match between the flight's track and the runway bearing. For airports with parallel runways, the function identifies all runways whose bearing is within 10 degrees of the flight's median track, rather than selecting the closest match. If multiple runways meet this criterion, the function further refines the selection by calculating the distance between the flight's trajectory and each runway. The runway closest to the flight's path is identified as the take-off runway.

Having identified a take-off runway, the line-up time, which refers to the time the aircraft enters the runway, is determined. To do so, we created a rectangular buffer geometry around the identified take-off runway using the `buffer` function of *shapely* [19] and checked when the surface trajectory of a flight intersected this geometry for the first time.

[1] We have observed that, in rare cases, the trajectories of landing aeroplanes exhibit a vertical rate of exactly 256 ft/min. We suspect this anomaly is the result of a decoding issue. To mitigate this potential error during the classification of take-off, we exclusively consider data points with a vertical rate exceeding 256 ft/min.

2.2.2 Classification of Pushback and Pushback-Time

Because most civil aeroplanes cannot taxi in reverse, aircraft parked on nose-in, push-out stands must be pushed back onto a taxiway before taxiing. This process is known as pushback. In the simplest scenario, aircraft are pushed backward out of the stand and manoeuvred onto the taxiway with a 90° turn, following an L-shaped path. At larger commercial airports with complex apron and taxiway layouts, more intricate pushback procedures are often employed, such as S-curves or U-shaped manoeuvres. The `pushback()` function available in the *traffic* library identifies pushbacks in surface trajectories by detecting sudden changes in the computed track angle. While this method is effective for L-shaped pushbacks, it may struggle to accurately recognise more complex pushback patterns. Therefore, this study proposes an alternative classification method for identifying pushbacks.

Our pushback classification method requires the user to first define the areas of the airport's apron consisting of nose-in, push-out stands by means of a set of *shapely* polygons. The nose-in, push-out stand areas at Zurich Airport considered in this study are indicated in Figure 1 with blue, dashed lines. Please note, the coordinates of the defined stand areas can be found in the source code provided with this study.

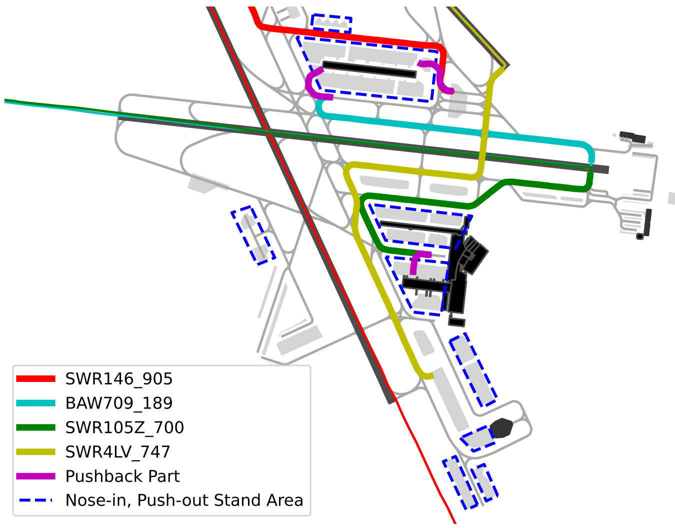

Figure 1. Observed Pushback and Taxi Movements at Zurich Airport

To determine whether a flight qualifies as a pushback candidate, we first checked whether its surface trajectory includes data points observed within one of the predefined nose-in, push-out stand areas. Next, we filtered the trajectory to retain only the portion that is at least 0.03 NM (approximately 50 m) away from the first reported position of the flight. This step removes the often noisy segment when the aircraft is stationary on the stand but already broadcasting ADS-B messages. Finally, the filtered trajectory is further refined by retaining only the parts where the 5-second rolling median of the ground speed, computed with `cumulative_distance()`, exceeds 1 kt, indicating that the aircraft is in motion. Next, we examined whether any segment classified as 'moving' includes the aircraft crossing the boundary of one of the defined nose-in, push-out stand areas. If such a segment is found, it is identified as the pushback part of the flight. Examples of L-, S-, and U-shaped pushback segments observed at Zurich Airport, classified using this method, are highlighted with magenta lines in Figure 1. Finally, we determined the start times for both pushback and taxiing: The start of the pushback is defined as the time of the first observation within the pushback segment, while the start of taxiing is defined as the time of the segment's last observation.

For departing flights that lack data points within the designated nose-in, push-out stand areas, we assumed one of two scenarios: either the aircraft left the stand under its own power, or its surface trajectory is incomplete, e.g., due to gaps in ground coverage. To identify flights that left the stand under their own power, we used the `parking_position()` function of the *traffic* library. For these flights, the start of taxi is defined as the time the aircraft vacated the identified parking position, as exemplary shown with the yellow trajectory in Figure 1. If no parking position is identified, we assumed an incomplete trajectory, and the start of taxi is taken as the time of the first recorded observation.

2.2.3 Determination of Taxi Duration and Distance

Using the identified start taxi and line-up times, we determined the duration of the taxi process $t_{j,\mathrm{taxi}}$ for a given flight j. Besides, we derived the taxi distance of a flight by evaluating the calculated cumulative distance of the trajectory between the start taxi time and line-up time.

2.2.4 Validation of Classification Algorithms

To validate our classification methods for take-off and pushback, we selected a random sample of 1000 surface trajectories from our dataset. On these trajectories, we applied both our proposed classification algorithms as well as those readily available in the *traffic* library for pushback and take-off. We then plotted and visually compared the results of our classification algorithms with the legacy ones of the *traffic* library. In this process, no take-off runway misclassification were observed. However, the accuracy of pushback classification proved to be highly sensitive to trajectory data quality. In particular, noisy trajectories frequently led to misclassification. This is one of the reasons why we decided to remove trajectories subject to significant noise from the dataset used in this study, as already explained in Section 2.1.

2.3 Estimation of Fuel Consumption

We estimated the taxi fuel consumption of departing flights by exclusively analysing the trajectories of civil commercial aircraft equipped with turbojet engines[2]. Turboprop commercial aircraft, business jets, and helicopters have been deliberately excluded due to the lack of open-access fuel consumption data for these aircraft types. To assess the potential taxi fuel-savings from the use of external AGPS, we analysed two different modes of taxi: (i) conventional taxi, during which aircraft use their own engines, and (ii) external AGPS taxi, during which aircraft are towed from the stand to the runway. As illustrated in Figure 2, for both taxi modes we considered departing flights parked on a nose-in, taxi-out stand requiring a pushback, as well as flights that can leave their stand without a pushback.

To estimate fuel consumption during taxi, we divided the taxi procedure into distinct phases. In a conventional taxi procedure without pushback, the aircraft start-up their engines on the stand and then require a certain amount of time to warm-up their engines. This phase is referred to as Main Engine Start & Warm-Up (MES & WUP) in Figure 2. During MES, the APU supplies the aircraft with electrical energy and compressed air. If a pushback is required to leave the parking position, the MES & WUP phase is usually initiated during the pushback. For the period until commencement of MES, the Environmental Control System (ECS) of the aircraft is powered by the APU. Regardless of whether pushback occurs, the aircraft taxi to the runway under own power after the MES & WUP phase, assuming a taxi thrust of 7 %, as suggested by the literature [3, 5, 12, 14, 15].

[2]For the estimation of the fuel consumption, we only considered the following ICAO aircraft types: A20N, A21N, A319, A320, A321, A332, A333, A343, A359, A35K, A388, B38M, B39M, B733, B734, B735, B736, B737, B738, B739, B744, B752, B753, B762, B763, B764, B772, B773, B77L, B77W, B788, B789, B78X, BCS1, BCS3, CRJ2, CRJ7, CRJ9, CRJX, E190, E195, E290, E295, E75L, E75S

We calculated the fuel consumption $F_{j,\mathrm{M\,\&\,W}}$ of a flight j during MES and WUP as the sum of the fuel consumption of the engines $F^{\mathrm{ENG}}_{j,\mathrm{M\,\&\,W}}$ and the APU $F^{\mathrm{APU}}_{j,\mathrm{M\,\&\,W}}$.

$$F_{j,\mathrm{M\,\&\,W}} = F^{\mathrm{ENG}}_{j,\mathrm{M\,\&\,W}} + F^{\mathrm{APU}}_{j,\mathrm{M\,\&\,W}} \tag{1}$$

For the MES, we assumed on the basis of subject matter expertise that pilots start up the engines one after the other before initiating the warm-up phase. Consequently, the fuel consumption of the engines during MES & WUP is estimated as

$$F^{\mathrm{ENG}}_{j,\mathrm{M\,\&\,W}} = f^{\mathrm{ENG}}_{j,\mathrm{idle}} \cdot \sum_{i=1}^{n_j^{\mathrm{ENG}}} (i \cdot t_{\mathrm{M}} + t_{\mathrm{W}}) \tag{2}$$

where $f^{\mathrm{ENG}}_{j,\mathrm{idle}}$ refers to the idle specific fuel consumption of a single engine of aircraft j, n_j^{ENG} to its number of engines, t_{M} to the duration required for the MES of a single engine, and t_{W} to the overall duration of the WUP. Specific idle fuel flow values for turbojet engines $f^{\mathrm{ENG}}_{\mathrm{idle}}$, corresponding to taxi thrust settings of 7 %, were obtained from the *ICAO Aircraft Engine Emissions Databank* [16] using the *openap* library [20]. Following information obtained from subject matter experts, we assumed that the start-up process of a single engine takes $t_{\mathrm{M}} = 60$ seconds, while the overall warm-up period takes $t_{\mathrm{W}} = 120$ seconds, irrespective of the aircraft and engine type.

The fuel consumption $F^{\mathrm{APU}}_{j,\mathrm{M\,\&\,W}}$ of the APU of flight j during MES & WUP is estimated as

$$F^{\mathrm{APU}}_{j,\mathrm{M\,\&\,W}} = f^{\mathrm{APU}}_{j,\mathrm{high}} \cdot n_j^{\mathrm{ENG}} \cdot t_{\mathrm{M}} + f^{\mathrm{APU}}_{j,\mathrm{normal}} \cdot t_{\mathrm{W}} \tag{3}$$

where $f^{\mathrm{APU}}_{j,\mathrm{high}}$ and $f^{\mathrm{APU}}_{j,\mathrm{normal}}$ refer to the *high* and *normal* specific fuel consumption of the APU of aircraft j. These values are sourced from the *ICAO Airport Air Quality Manual* [21], which provides typical APU fuel flow rates for different aircraft categories and APU operational modes, including *startup*,

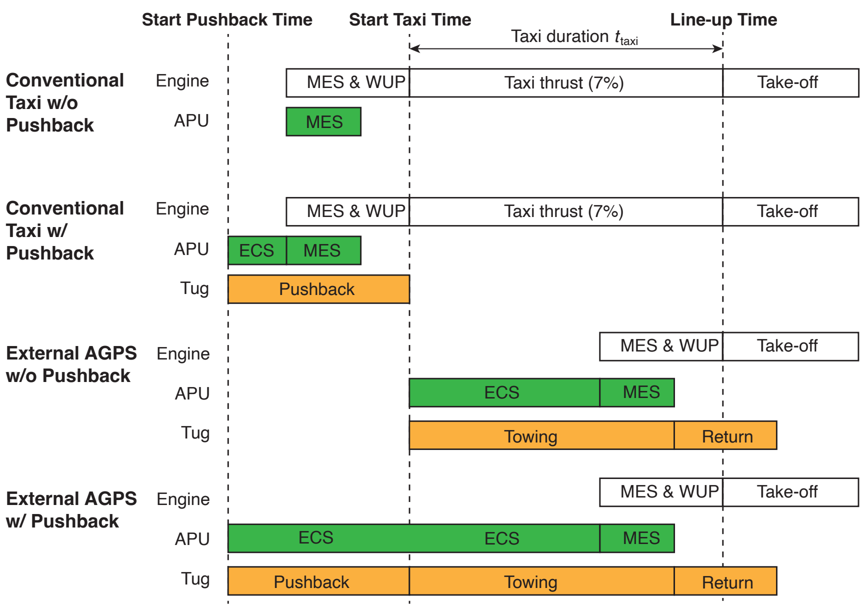

Figure 2. Considered Types of Taxi Procedures

normal, and *high*. After MES, the pilots usually switch-off the APU. Therefore, we estimated the fuel consumption of flight j during conventional taxiing $F^{\text{Conv}}_{j,\text{Taxi}}$ as

$$F^{\text{Conv}}_{j,\text{taxi}} = f^{\text{ENG}}_{j,\text{idle}} \cdot n^{\text{ENG}}_{j} \cdot t_{j,\text{taxi}} \tag{4}$$

where $t_{j,\text{taxi}}$ refers to the observed taxi duration of flight j. The mass of the aircraft, acceleration of the aircraft on the ground, etc. is not taken into account when calculating taxi fuel consumption.

For the external AGPS taxi mode, we assumed that (i) the MES & WUP phase begins just before the aircraft lines up at the runway holding position, (ii) a flight's taxi duration under AGPS operation remains equal to its observed taxi duration $t_{j,\text{taxi}}$, and (iii) for the duration of the AGPS-assisted taxiing, the aircraft's ECS is powered by its APU operating in *normal* mode. Consequently, the taxi fuel consumption of an AGPS-assisted flight is estimated as

$$F^{\text{AGPS}}_{j,\text{taxi}} = f^{\text{APU}}_{j,\text{normal}} \cdot t_{j,\text{taxi}}. \tag{5}$$

Based on the above stated equations, we finally determined the total taxi fuel consumption of flight j as:

$$F_{j,\text{taxi}} = \begin{cases} F_{j,\text{M \& W}} + F^{\text{Conv}}_{j,\text{taxi}}, & \text{for conventional taxi} \\ F_{j,\text{M \& W}} + F^{\text{AGPS}}_{j,\text{taxi}}, & \text{for external AGPS taxi} \end{cases} \tag{6}$$

2.4 Determination of Fuel-Saving Potential

We analysed the taxi fuel-saving potential at Zurich Airport for two different groups of aircraft eligible to be towed by an AGPS. Specifically, we examined the impact of AGPS when applied to all departing flights versus only those departing from runway 16. Due to its length, runway 16 is primarily used by long-haul aircraft. Since long-haul aircraft typically have higher specific fuel consumption due to their larger engines and flights departing from runway 16 have considerably longer taxi durations compared to departures from other runways at Zurich Airport, see Table 1, distinguishing this group is particularly valuable for assessing the taxi fuel-saving potential of AGPS.

For both groups of aircraft eligible to be towed by an AGPS, we conducted the following analysis: First, we investigated how the total fuel consumption of the considered flights with turbojet engines changes if all flights whose taxi duration $t_{j,\text{taxi}}$ exceeded a certain threshold value t_{AGPS} were towed to the runway by an external AGPS, while all other aircraft taxied conventionally. For this purpose, we analysed threshold values in the range of $t_{\text{AGPS}} = \{0, 1, 2, \ldots, 20\}$ minutes. These threshold values were selected on the basis of the observed taxi durations at Zurich Airport as summarised in Table 1 and Figure 3. Secondly, we analysed how the number of available external AGPS units m affects the total fuel consumption of the considered flights. To this end, we grouped our dataset of surface trajectories of departing flights into 30-minute intervals based on their start taxi times and assumed that the m longest taxi movements within these 30-minute intervals were towed to the runway with an external AGPS, while all other taxi movements taxied conventionally to the runway.

3. Results

This section contains the results of our study, which are based on surface trajectory data of departing aircraft observed via the OpenSky Network at Zurich Airport between May 1 and September 30, 2024. First, we provide a statistical overview of the dataset and its characteristics in terms of observed taxi durations and distances, followed by an analysis of the fuel-saving potential of external AGPS at Zurich Airport.

As summarised in column *OSN* of Table 1, we identified a total of 53,375 departures in the dataset of surface trajectories observed at Zurich Airport through the OpenSky Network. In the same observation period, Zurich Airport Ltd. (FZAG) reported 59,222 departures [22] (column *FZAG*), resulting in a delta between FZAG and OSN of 9.87 %. The average duration of taxiing movements $\bar{t}_{\text{taxi}}$ observed via the OpenSky Network is 8 min 7 s (SD: 4 min 52 s) and the average distance of a taxi movement is 0.83 NM (SD: 0.46 NM). The taxi duration of aircraft departing on runway 16 is considerably longer (mean: 12 min 48 sec) than the taxi duration of aircraft taking off on all other runways. This can also be clearly seen in Figure 3, which shows the dependency between taxi distance and taxi duration in a scatter plot of 3000 randomly selected taxi movements on the left and the violin plots of the duration of taxi movements on the right. The dashed lines in the left-hand illustration correspond to the 95 % confidence ellipses.

Table 1. Taxi Duration, Taxi Distance, and Number of Departing Aircraft per Runway at Zurich Airport between May 1 and September 30, 2024

Runway	Taxi Duration t_{taxi} [MM:SS]		Taxi Distance [NM]		Number of Take-offs		
	Mean	SD	Mean	SD	OSN	FZAG	Delta
10	09:56	05:00	1.04	0.32	974	1059	−8.03%
16	12:48	05:27	1.55	0.34	5220	6122	−14.73%
28	07:20	04:25	0.74	0.42	32 102	35 341	−9.16%
32	07:59	04:34	0.75	0.35	14 474	15 947	−9.24%
34	09:53	05:50	0.98	0.50	605	753	−19.65%
Overall	08:07	04:52	0.83	0.46	53 375	59 222	−9.87%

Note: The number of take-offs observed in the OpenSky Network dataset is summarised in column *OSN*. The number of departures reported by Zurich Airport Ltd [22] is shown in column *FZAG*.

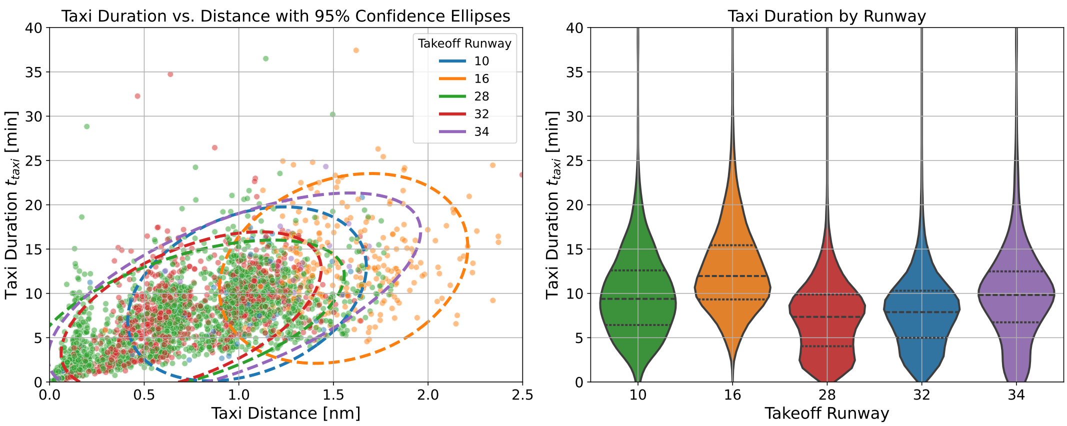

Figure 3. Observed Taxi Duration and Distances per Runway at Zurich Airport

Of the 53,375 departures recorded in the OpenSky Network dataset, 46,419 correspond to turbojet aircraft of the types specified in Footnote 2. For these turbojet aircraft, the total taxi fuel consumption was estimated using the methods outlined in Section 2. During the observation period from May 1 to September 30, 2024, turbojet aircraft taxiing conventionally, i.e., using their own engines, consumed an estimated 8851.6×10^3 kg of fuel. This value is referred to as the baseline scenario in Figures 4 and 5, as well as Tables 2 and 3. On average, each departing turbojet aircraft consumed 190.69 kg of fuel during taxiing. If only aircraft types of the Airbus A320 family are considered, the average taxi fuel consumption is 152.42 kg.

Figure 4 and Table 2 show how the use of external AGPS at Zurich Airport affects the total taxi fuel consumption of all taxiing turbojet aircraft. The red line in the left diagram of Figure 4 corresponds to the total taxi fuel consumption in the baseline scenario. The green and blue lines describe total taxi fuel consumption under external AGPS usage as function of the so-called *minimum taxi duration* for external AGPS usage t_{AGPS}. A minimum taxi duration of $t_{\text{AGPS}} = 0$ minutes indicates that all turbojet aircraft movements, regardless of their actual taxi duration $t_{j,\text{taxi}}$, are towed to the runway by an external AGPS. For minimum taxi duration values of $t_{\text{AGPS}} \geq 0$, only turbojet aircraft with taxi duration $t_{j,\text{taxi}} \geq t_{\text{AGPS}}$ are towed by an external AGPS, while all other turbojet aircraft taxi conventionally. For the green line, we considered all turbojet flight movements that fulfil $t_{j,\text{taxi}} \geq t_{\text{AGPS}}$ for towing by external AGPS. For the blue line, however, exclusively turbojet aircraft departing on runway 16 were taken into account. The right diagram in Figure 4 depicts the relative fuel-saving potential of external AGPS usage compared to the baseline scenario. The data in Figure 4 is summarised in Table 2 for minimum taxi durations of $t_{\text{AGPS}} = \{0, 5, 10, 15, 20\}$ minutes. The columns labelled *all RWY* correspond to the green lines in Figure 4, *RWY16* to the blue lines, and *baseline* to the red line, respectively. The *reduction potential* columns in Table 2 specify the relative fuel-saving potential achieved by external AGPS usage when compared to the baseline scenario.

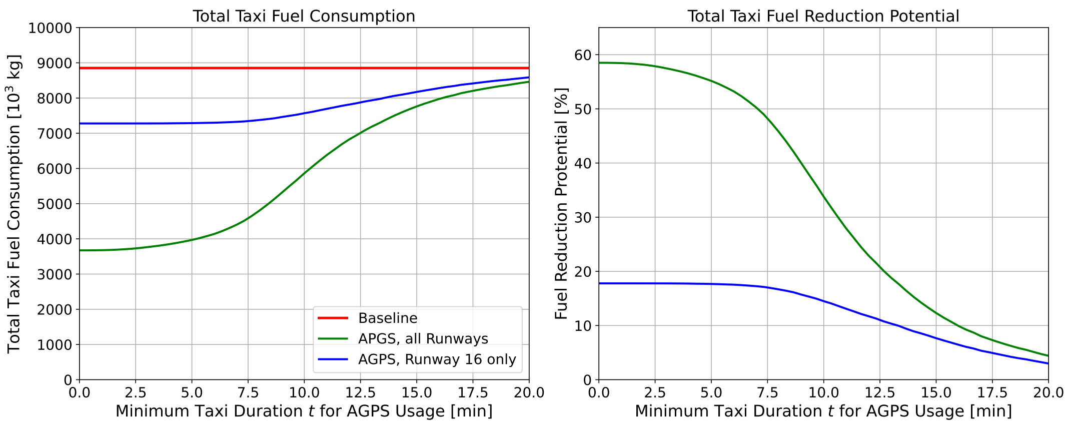

Figure 4. Estimated Taxi Fuel Consumption of Conventionally Taxiing Turbojet Aircraft and Turbojet Aircraft Towed by an External AGPS at Zurich Airport between May 1 and September 30, 2024

Table 2. Estimated Total Taxi Fuel Consumption of Turbojet Aircraft Taxiing Conventionally and Turbojet Aircraft Towed by an External AGPS at Zurich Airport between May 1 and September 30, 2024

Minimum Taxi Duration t_{AGPS} [min]	Total Taxi Fuel Consumption [10^3 kg]			Reduction Potential [%]	
	Baseline	All RWY	RWY16	All RWY	RWY16
0.0	8851.6	3673.0	7277.6	-58.5 %	-17.8 %
5.0	8851.6	3968.7	7287.0	-55.2 %	-17.7 %
10.0	8851.6	5861.2	7568.3	-33.8 %	-14.5 %
15.0	8851.6	7761.9	8173.6	-12.3 %	-7.7 %
20.0	8851.6	8461.5	8587.3	-4.4 %	-3.0 %

The influence of the available number of external AGPS units m on the total fuel consumption of taxiing turbojet aircraft at Zurich Airport is summarised in Figure 5 and Table 3. For this analysis, it was assumed that an external AGPS can only tow one single departing turbojet aircraft in a 30-minute interval. For $m = 0$, all departing turbojet aircraft taxi conventionally to the runway. For $m > 1$, the m departing turbojet aircraft movements with the longest taxi duration in every

30-minute interval are towed to the runway with an external AGPS, while all other turbojet aircraft movements taxi conventionally. The red line in the diagram on the left in Figure 5 refers to the baseline scenario. The green line shows the impact on the available number of external AGPS m on the total taxi fuel consumption when all taxiing movements are considered for towing. Analogous, the blue line depicts the total taxi fuel consumption when only turbojet aircraft departing on runway 16 are considered for external AGPS taxi. The right diagram in Figure 5 depicts the relative fuel-saving potential achieved by external AGPS usage compared to the baseline scenario. The data depicted in Figure 5 is summarised in Table 3 for $m = \{1, 2, 3, 4, 10, 15\}$ available external AGPS units. The columns labelled *all RWY* refer to the blue lines in Figure 5, while the columns labelled *RWY16* to the green lines. The columns indicated with *reduction potential* refer to the relative fuel-saving potential of AGPS-usage in relation to the baseline scenario.

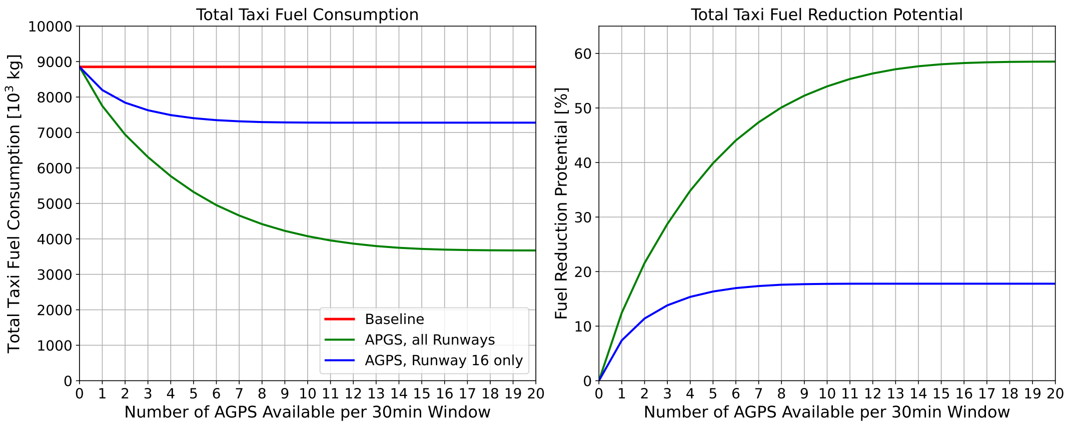

Figure 5. Estimated Taxi Fuel Consumption of Conventionally Taxiing Turbojet Aircraft and Turbojet Aircraft Towed by an External AGPS as a Function of the Available Number of AGPS Units per 30-Minute Intervals at Zurich Airport between May 1 and September 30, 2024

Table 3. Estimated Total Taxi Fuel Consumption of Turbojet Aircraft Taxiing Conventionally and Turbojet Aircraft Towed by an External AGPS as a Function of the Available Number of AGPS Units per 30-Minute Intervals at Zurich Airport between May 1 and September 30, 2024

Available Number of External AGPS Units	Total Taxi Fuel Consumption [10^3 kg]			Reduction Potential [%]	
m	Baseline	All RWY	RWY16	All RWY	RWY16
1	8851.6	7750.4	8197.4	-12.4 %	-7.4 %
2	8851.6	6942.0	7842.2	-21.6 %	-11.4 %
3	8851.6	6308.2	7628.1	-28.7 %	-13.8 %
4	8851.6	5768.9	7491.4	-34.8 %	-15.4 %
10	8851.6	4075.6	7280.0	-54.0 %	-17.8 %
15	8851.6	3716.9	7277.6	-58.0 %	-17.8 %

4. Discussion

We estimate that the turbojet aircraft types considered in this study consumed a total of 8851.6×10^3 kg of fuel for conventional taxiing plus MES and warm-up at Zurich Airport between May 1 and September 30, 2024. Over the 46,419 observed taxi movements of turbojet aircraft, this results in an average taxi fuel consumption of 190.69 kg per departing flight. Compared to conventional taxiing, the results of our study suggest that towing departing turbojet aircraft to the runway with external AGPS promises a considerable reduction in total taxi fuel consumption, supporting the findings of Camilleri and Batra [3]. For example, for Airbus A320 family aircraft we arrived at a fuel consumption reduction of 83.85 kg per departure, which is in line with 110 kg per movement reported by [13].

At the airport level, towing all departing turbojet aircraft to all runways at Zurich Airport could reduce taxi fuel consumption by up to 58.5 % according to our estimates. This result is consistent with the 53.5 % reduction potential reported by Fleuti and Maraini [12] for the same airport. Our results further indicate that restricting external AGPS-based towing to turbojet aircraft departing from runway 16 could achieve an airport-wide taxi fuel consumption reduction of 18.7 %.

In absolute numbers, towing all departing turbojet aircraft to all runways in the observation period from May to end of September 2024 could have saved 5178.6×10^3 kg of fuel, while limiting towing to runway 16 departures would have resulted in savings of 1574.0×10^3 kg. Assuming a CO_2 equivalent (CO_2e) of 3.16 kg CO_2 per kg of jet fuel [23], the consistent use of external AGPS could have saved emissions of up to 16.36 million kg CO_2e or 4.97 million kg CO_2e, respectively. A conservative extrapolation of our results to an observation period of a full year suggest a maximum emission reduction potential of approximately 30 million kg CO_2e through the use of external AGPS. This figure is striking, particularly considering that Zurich Airport Ltd. reported Scope 1 and 2 CO_2e emissions of 23.86 million kg for the year 2024 [24].

Our results emphasise that the taxi fuel reduction potential of an airport strongly depends on the selection of the aircraft to be towed to the runway. If aircraft to be towed are selected on the basis of their taxi duration, it can be deduced from Figure 4 that the reduction potential of Zurich Airport starts to decreases if only flights with taxi durations t_{taxi} greater than 5 min are towed to the runway. Similarly, if towing is limited to aircraft departing from runway 16, the reduction potential starts to decline when movements with taxi durations t_{taxi} exceeding 7.5 minutes are exclusively selected. As the fuel consumption of taxiing aircraft is highly dependent on the duration of the taxiing process, towing flights with with short taxi durations does not contribute much to the overall fuel-savings of an airport. Therefore, the use of external AGPS is especially suitable for airports where aircraft experience long taxi durations. These are airports which, due to their size, have long taxi distances, e.g., Amsterdam Schiphol Airport, as well as airports prone to congestion and delays.

Our results further indicate that the fuel-saving potential of an aerodrome depends on the number of external AGPS units available for towing. For the example of Zurich Airport presented in this study, almost the maximum possible taxi fuel reduction potential can be realised with 20 external AGPS units, see Figure 5. However, the use of so many external AGPS units is associated with high capital and operational expenses, which may not be justified. However, as shown in Figure 5, a significant part of the fuel-saving potential can still be realised with a much smaller number of external AGPS units in use, making it a more cost-effective approach. If all turbojet aircraft are considered for external AGPS towing, a taxi fuel reduction of 34.8 %—more than half of the maximum achievable reduction potential of 58.5 %—can be attained with just four external AGPS units. Similarly, if only turbojet aircraft departing from runway 16 are eligible for towing, more than half of the maximum achievable fuel reduction potential of 18.7 % can be realised with just two external AGPS units. Since flights departing on runway 16 are predominantly long-haul aircraft handled at the Midfield Terminal of Zurich Airport, this result is particularly promising for the following reasons: (i) these flights do not need to cross other runways on their way to runway 16, simplifying the communication between pilots, air traffic control, and the AGPS ground crew, (ii) the taxi distance from the midfield terminal to the runway is relatively short, which limits operational expenses on the AGPS units, and (iii) there are several flight operation areas where the AGPS could be decoupled from the aircraft, e.g., the de-icing area or the multiple line-up positions of runway 16. Particularly at large international airports such as Zurich Airport, the provision of only this many external AGPS units should be within the realms of possibility, especially if conventional pushback tugs are also considered for use as external AGPS. Indeed, large airports typically maintain an *operational reserve* of pushback tugs to ensure smooth operations, allowing for the replacement of vehicles experiencing technical issues or to manage periods of high demand and congestion. At times when the operational reserve is not required for pushback duties, these vehicles could be repurposed and deployed as external AGPS units.

The methods used and results presented in our study do have limitations worth mentioning. The surface trajectories used to estimate taxi fuel consumption are predominantly of very high quality. Occasionally, however, we observed noisy data, such as latitude and longitude values changing abruptly from one location to another. There are also rare cases of trajectories with gaps. These gaps usually occur on areas of the apron of Zurich Airport which have poor or no line-of-sight to the ADS-B receivers of the OpenSky Network. Another source of error is that pilots sometimes do not switch on their transponders until they have started taxiing, resulting in incomplete trajectories. Noisy trajectories, gaps in data, and incomplete trajectories can result in either overestimation or underestimation of a flight's taxi duration, directly affecting the accuracy of the taxi fuel consumption estimates presented in our study. To mitigate the influence of noisy trajectory data and trajectories with gaps in future studies, one could apply certain filter algorithms such as a Kalman filter aligning trajectories with the geometries of taxiways and runways [25] or match-making techniques making use of open-source geospatial airport data [26].

Our fuel consumption estimates for taxiing turbojet aircraft are based on the assumption of idle thrust settings, as commonly referenced in the literature [3, 5, 12, 14, 15]. These thrust settings may not fully reflect reality, particularly during acceleration phases of taxiing. Additionally, we assumed that each aircraft type is equipped with one single engine type. In reality, however, aircraft are fitted with multiple engine variants, each with slightly different idle fuel flow rates. Furthermore, based on discussions with subject matter experts, we assumed that for all aircraft types, the MES takes $t_{\mathrm{M}} = 60$ seconds per engine and the overall warm-up phase takes $t_{\mathrm{W}} = 120$ seconds. In practice, MES and warm-up times vary significantly depending on a number of different factors and may thus differ from our simplified estimates. For instance, newer generation aircraft with geared turbofan engines often require significantly longer MES durations than assumed in this study. Consequently, the actual fuel consumption for MES and warm-up is likely to deviate from the values reported here.

There are also limitations to the results of our study. The fuel reduction potential of external AGPS presented in this study should be understood as maximum values. In practice, lower values are likely to be achieved due to operational inefficiencies, such as those that may arise through coordination between air traffic control, pilots, and the AGPS ground crews. For this reason, we consider the 36.5 % fuel-saving potential reported by Ithnan et al. [15] for Amsterdam Schiphol Airport to be a realistic target that could also be achieved in day-to-day operations at Zurich Airport.

It is also worth noting that we have assumed a fairly simple taxiing procedure to estimate the potential fuel-savings of external AGPS. For conventional taxiing, we assumed that the actual taxiing of an aircraft begins only after the engines have completed the warm-up phase. Provided it is long enough, however, the taxiing process can effectively serve as the warm-up phase in practice. For taxiing with external AGPS, we assumed that the AGPS disconnect from the aircraft shortly before line-up, allowing pilots to initiate take-off immediately after the warm-up phase. Yet, this assumption may not be realistic for all airports, as suitable flight operation areas are required for the separation process. Optimal locations for external AGPS separation purposes include multiple runway line-up positions or de-icing pads, which provide adequate space and enable parallel taxiing operations. These flight operation areas allow aircraft to be uncoupled from their external AGPS without interfering with other taxiing movements. In addition, aircraft that are already disconnected from their external AGPS and ready for take-off can continue to taxi independently without being affected by the uncoupling process of other aircraft.

Finally, we have not further examined certain operational aspects of external AGPS in this study. Firstly, after disconnecting from an aircraft, external AGPS units must be able to exit the flight operations area and return to the stand area via a road. This requires the flight operations areas to have road access, which may not be available at all aerodromes or could necessitate construction activities. Furthermore, we have not taken into account the fuel consumption of pushback tugs and external AGPS but assumed (somewhat optimistically) the use of solar-charged electric vehicles.

5. Conclusion and Outlook

In this study, we addressed the question of whether and how potential fuel-savings resulting from the use of external AGPS at a large aerodrome can be estimated on the basis of surface ADS-B trajectories obtained via the OpenSky Network. To this end, we have presented a method that can be used to detect both take-off and pushback events from surface trajectories. This allows the determination of the taxi duration of departing aircraft, on the basis of which their taxi fuel consumption can be estimated. In order to quantify the fuel-saving potential, we have considered two modes of taxiing: conventional taxiing, in which turbojet aircraft taxi under the power of their own engines, and external AGPS taxiing, in which turbojet aircraft are towed from the stand to just before the runway.

Our results show that a widespread use of external AGPS for departing turbojet aircraft at Zurich Airport would reduce taxi fuel consumption by up to 58.5 % compared to conventional taxiing. In the observation period of this study, which is May 1 to September 30, 2024, 5178.6×10^3 kg jet fuel could have been saved, which corresponds to emissions of 16.36 million kg CO_2e. Conservatively extrapolated to an observation period of an entire year, external AGPS might enable the reduction of approximately 30 million kg CO_2e at Zurich Airport, which is considerably more than the Scope 1 and 2 CO_2e emissions of the aerodrome of 23.86 million kg for 2024 [24]. Our results further suggest that with limited external AGPS resources, the choice of the *right* aircraft for towing is crucial. It is particularly worthwhile to tow those aircraft to the runway that have long taxi durations. We were also able to show that considerable fuel-savings can be realised with a fairly manageable use of resources: If only four external AGPS units are used, which perform one tow per 30-minute interval, up to 34.8 % of Zurich Airport's total taxi fuel consumption could be saved.

Our study has shown that the fuel-saving potential of external AGPS can be quite substantial. However, it must be emphasised that the goal of emission-free taxiing mentioned in *Flightpath 2050* [1] cannot be achieved by relying on this system alone. Nevertheless, we consider it a good first and feasible step into the right direction. We therefore recommend that airports, airlines, and handling agents integrate external AGPS into their daily operations. However, the implementation of external AGPS in practice will impact ground operations at an airport, requiring adaptions of existing processes. In addition to the need for designated flight operation areas for AGPS decoupling, several key operational issues must be addressed. These include questions of responsibility and communication during AGPS-assisted taxiing, such as how air traffic control, pilots, and AGPS ground crews will communicate, as well as how and to whom taxi or runway crossing clearances will be issued. Additionally, technical reliability concerns must be considered: What procedures are in place if an external AGPS experiences a technical issue on the taxiway, or if a towed aircraft encounters a defect, such as an inability to start its engines? How will such aircraft be removed from the taxiing sequence, and how will disruptions be managed?

If solutions to these questions can be found that ensure the safety of air traffic at all times, airports, handling agents, and airlines will need to conduct a cost-benefit analysis to determine if and how external AGPS units should be deployed. In this context, the following trade-off must be considered in detail: Costs and benefits are not experienced by the same stakeholders. While airlines may experience cost benefits from reduced fuel consumption due to the use of external AGPS, airports and/or handling face additional costs associated with the investment in and operation of external AGPS units. Subsequently, to ensure a successful future for external AGPS, stakeholders are required to find a collaborative solution allowing all parties to reap the benefits while sharing the costs.

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Author Contributions

- Manuel Waltert: Conceptualization, Methodology, Data Curation, Software, Validation, Visualization, Writing (Original Draft and Editing), Project Administration
- Benoit Figuet: Methodology, Software, Writing (Review)
- Michael Felux: Conceptualization, Writing (Review)

Open Data Statement

The software code used to download the OSN-data employed in this study is available on the following repository: https://github.com/m-waltert/osn24_agps

Reproducibility Statement

The software code used to generate the results presented in this paper is available on the following repository: https://github.com/m-waltert/osn24_agps

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