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A Statistical Approach for Electric Taxiing Requirements for Regional Turboprop Aircraft

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Electric motorization of the landing gear appears to be one of the alternative solutions to reduce fuel burn, CO2 emissions, and noise during the taxi phase. Because turboprop aircraft operate on short routes, the taxi phase represents an important part of both flight time and fuel consumption. An Electric Taxiing System (ETS) sized to meet current operational practices could reduce the fuel consumption and remain near transparent to the pilots. This paper first presents a statistical approach to define the taxiing requirements for regional turboprop aircraft using 200 taxi phases of 77 aircraft. Requirements of 0.4 m/s^2 maximum acceleration until 15 kts, 25 kts top speed, and 13,000 ft distance (including taxi-in and taxi-out) are determined in accordance with the analysis, operational practices, and pilots' routines. For higher speed than 15 kts, the acceleration requirement is adjusted using the iso-power to limit the mass of the ETS. Then, an ETS with sufficient performance is sized to be integrated in the main landing gear of a regional turboprop aircraft (Dash 8-300). For a standard mission of 270 nautical miles, the expected fuel economy is 3.1 % for a payload loss of 2.2 % or 1.3 PAX due to the system weight.

Nomenclature

BAT = Battery
CDF = Cumulative Distribution Function
EM = Electric Motor
ETS = Electric Taxiing System
FDH = Frequency Distribution Histogram
GT = Gas turbine
INV = Inverter
PDF = Probability Density Function

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I. Introduction

According to the International Air Transport Association (IATA) forecast, the worldwide air traffic is rapidly regaining its pre-pandemic levels, and so is the air pollution due to aviation. In 2019, before COVID-19 pandemic, the worldwide aviation emissions accounted for 905 million tonnes of CO_2. The IATA estimation for 2021 was 547 million tonnes of CO_2, and the organization forecasts an augmentation of 40 % for 2022 [1]. A global objective of neutral carbon aviation for 2050 is planned [2] and the European vision for aviation 2050 is clear: aircraft movements must be emission-free when taxiing [3]. Indeed, the taxiing procedures at the airports contribute significantly to fuel burn and emissions.

Current solutions to reduce taxi fuel burn are the optimization of ground traffic flows and ground operations and the single-engine taxi [4]. However, taxiing with one engine is not recommended on slippery taxiways, with positive slopes, or when deicing operations are required [5]. Hybrid-electric configurations have been studied for turboprop aircraft where the electric motor would power the propeller during ground operation [6], but the propeller is inefficient during taxi, with high energy requirements involving high battery mass. External towing systems such as the hybrid-electric Taxibot [7] or the electric TowBots [8] are interesting alternatives to improve taxiing procedures, but they need infrastructures and could not be available at small airports. This approach also implies numerous vehicles on the ground, conflicting with the desire to optimize the ground procedures and traffic. On-board Electric Taxiing Systems (ETS) are intermediate potential solutions with motorization integrated in the landing gear wheels, at the cost of a heavier aircraft because of the additional components.

A primary investigation of taxi operation practices reveals that there is not a generally-accepted set of requirements for the taxiing speed and required acceleration. The *FAA ATC rules and regulations* affecting taxi operations only advocates that pilots should taxi to 'a safe taxi speed', involving speeds in the range of 15 to 20 kts but do not recommend a specific speed [9]. According to a private discussion with a Canadian airline, a maximum speed of 20 kts is recommended on asphalt surfaces. A limit of 15 kts must be used on gravel surfaces and taxiing speed must be kept under 10 kts on slush-covered surfaces. For this airline, the limitations apply to all their aircraft types in their fleet. The *B737 NG Flight Crew Training Manual* [10] reveals that taxiing top speed can reach 30 kts on long straight taxi routes. In [11], 30 kts is considered as a conventional taxiing speed. Also, the Pakistan International Airlines *ATR 42/72-500 Standard Operating Procedures* [12] indicates a maximum taxiing speed of 25 kts on straight taxiways. Concerning the taxiing acceleration, no written limitation was found but high acceleration implies greater jet blast, creating safety issues for vehicles or operators on the ground. However, an innovative study on taxiing requirements for single-aisle midsize aircraft was conducted by Maximilian T. E. Heinrich in [13]. Using four self-recorded taxi phases (two taxi-out and two taxi-in phases), the ETS requirement on acceleration is 0.445 m/s^2. For the taxi-out, a maximum speed of about 32 kts is needed. Using [14], which considers 20 taxiing procedures (10 taxi-out and 10 taxi-in phases), the speed requirements for an A321 are similar, with a required top speed of 31.4 kts. These studies could give a realistic idea of the ground requirements that an ETS has to meet for an integration in single-aisle midsize aircraft.

Numerous concepts of ETS emerged, with a focus on medium-range commercial jet aircraft. Long-range aircraft are not a target because an increase of the aircraft's weight would have an impact on in-flight fuel consumption [15]. WheelTug was the first company interested in electric taxiing, with a retrofittable and removable system [11]. Powered by the Auxiliary Power Unit (APU) and supplied by two induction motors, the system features a gearbox and is integrated into the nose gear. In 2010, a towing test was made at the Prague Airport with a B737-800, collecting data to determine the system requirements in various meteorological conditions, including snow, ice, and rain [16]. Finally, the WheelTug ETS provides a maximum taxiing speed of 9 kts and is useless on slippery taxiways, or if the center of gravity is aft (rear center of gravity limit) [17]. The performances of this system are widely under the speed limitations of the B737 and the requirements defined in [13] and [14]. DLR has designed an electric wheel hub motor that can be easily integrated into the nose gear of an Airbus A320 [18]. The designed system is powered by a fuel cell, features a gearbox and clutches, and is very compact because the rotor also forms the planet carrier of a two-stage planetary gear. The requirements were a maximum taxiing speed of 13.5 kts and the possibility to move the aircraft on a taxiway slope up to 1.5 %. The feasibility of the concept was demonstrated using the DLR A320 Advanced Technology Research Aircraft (ATRA) [19] at the Hamburg Finkenwerder Airport (Germany) [20]. However, the speed requirements are questionable because they do not fit the previous observations, and the integration in the nose gear will lead to skid issues in adverse conditions.

To avoid this limitation, other companies focused on integrating the ETS in the main landing gear. A synchronous motor, with direct-drive and not disengageable, was developed from a collaboration between Airbus, the German Aerospace Center (DLR), Safran, and the University of Nottingham [21], demonstrating the feasibility of such a system [22]. In 2011, Safran and Honeywell Aerospace Inc. joined forces into the EGTS (Electric Green Taxiing System) project. The system requirements were 20 kts in 90 seconds, 10 kts in 20 seconds for active runway crossing, and breakaway torque at 1.5% slope at Maximum Take-Off Weight (MTOW) [23]. In terms of acceleration, a brief calculation using the EGTS requirement shows that the system could reach a constant acceleration of 0.26 m/s^2, which is under the 0.445 m/s^2 found in [13] but increasing passengers' comfort. The maximum speed of the EGTS is still under the calculated requirements for single-aisle midsize aircraft with 20 kts top speed, but this system appears viable, fitting the FAA recommendations of safe taxi speeds. Despite its performance the project was aborted, but Safran stayed devoted to the electric propulsion through the Clean Sky 2 framework, but favored battery-powered propellers with the engine off for turboprop aircraft [24].

Although the previous studies demonstrated the feasibility of the concept, it is still unclear if the requirements used for the design would meet current airport operations. The primary objective of this paper is to conduct a statistical analysis of turboprop-powered aircraft taxi phase, determining realistic taxiing requirements for an ETS. The second objective is to use the previous analysis to determine sufficient performances of an ETS, and investigate the impact of its integration for a regional flight of a turboprop aircraft.

The paper is structured as follows: Section II presents the statistical analysis, including the methods of data acquisition and data processing. Section III determines the taxiing requirements for an ETS and Section IV is a case of design and integration of an ETS on a regional turboprop aircraft.

II. Statistical Approach

The main objective of this section is to determine the current taxiing operational practices of regional turboprop aircraft through a statistical analysis of real taxi data. Section II.A presents the methods of data acquisition, processing, and validation, and Section II.B shows the results of the statistical approach.

A. Taxi Data Acquisition

1. Method of Acquisition

The method consists of the acquisition of numerous taxi phases using the Flightradar24 tracking service [25], which combines data from ADS-B receivers, MLAT, and radar data. This network, together with government air traffic control and other data sources, is how Flightradar24 is able to track aircraft around the globe including on-ground operations at specific airports.

The data set used in this study contains 200 taxi-out phases of 77 regional turboprop aircraft (Bombardier Dash 8 and ATR 42 families), from 151 airports in 41 countries (see Table 5 for the description of the departure countries of the individual flights), from November 29, 2019 to February 7, 2022. A total of 26 flights were rejected as sparse taxiing data led to unrealistic taxi profiles (see Part II.A.3). The countries where the acquisitions were made are presented in dark blue in Figure 1.

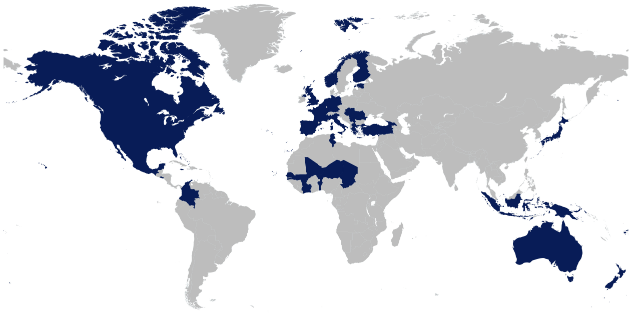


Fig. 1 Countries of taxi data acquisition

2. Data Acquired

The data collected from Flightradar24 are 1) timestamp, 2) UTC (Coordinated Universal Time), 3) aircraft registration, 4) GPS coordinates, 5) altitude, 6) ground speed, and 7) direction. Timestamp and UTC give date and time at each step of acquisition. GPS coordinates are longitude and latitude in degrees and altitude is given in feet. The aircraft ground speed is provided in knots and the track is in magnetic degrees. The taxi phase begins when the aircraft moves on its own power up to the start of the take-off acceleration.

3. Data Processing and Validation

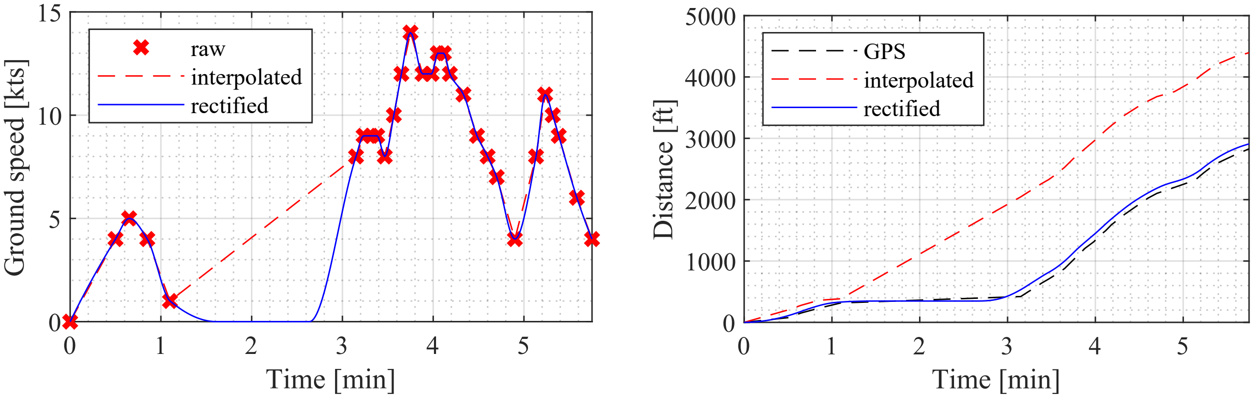
An automated approach was used to ensure data consistency of each taxi phase. Two independent methods to evaluate the taxiing distance were used:

1) Method A uses the GPS coordinates at each step of acquisition.
2) Method B is obtained by integration of the raw speed interpolation.

The total distances given by the two methods were compared to the distances measured directly on the airport taxi chart. This comparison revealed that, if the GPS coordinates give results nearly equal to the measurements, they could be directly used to obtain the baseline taxiing distance.

However, for 38 % of the flights (76/200), the deviation between the baseline (method A) and the calculated distance using method B is higher than 15 %, potentially highlighting a gap in the data set. This difference could be explained by the interpolation on the raw speed such as presented in Figure 2a, giving the interpolated dashed red line profile, while the actual taxiing speed was closer to the blue curve. To fit the baseline distance, a data processing was applied to adjust the taxiing speed to match the GPS taxiing distance. Figure 2b shows the raw GPS distance, speed-integrated distance, and rectified speed-integrated distance to match the GPS distance.

With this additional calibration method, only 13 % of the flights (26/200) still have a 15 % or more deviation on their rectified distances. These 26 flights were excluded and are not used for the next results.



(a) Speed profiles **(b) Distance profiles**

Fig. 2 Effect of the speed rectification on the calculated distance

B. Results

In this section, four taxiing parameters were targeted: total taxiing time and distance, top speed, and maximum acceleration. The maximum positive acceleration is calculated by the derivative of the speed and the distance with the Haversine formula [26]. These four parameters govern the sizing of an ETS, giving the kinematic requirements, and the power and energy demands.

The Frequency Distribution Histogram (FDH), the Probability Density Function (PDF), and the Cumulative Distribution Function (CDF) of the 4 targeted data parameters are presented and analyzed in the following results. The PDF calculates a continuous distribution, using the FDH which shows results in frequency, in percent, with the number of bins limited to 20. For the calculation of the CDF, a kernel density estimation with the MATLAB function *ksdensity* was used, with a kernel smoothing. The estimate used a bandwidth of 5 % of the total number of points.

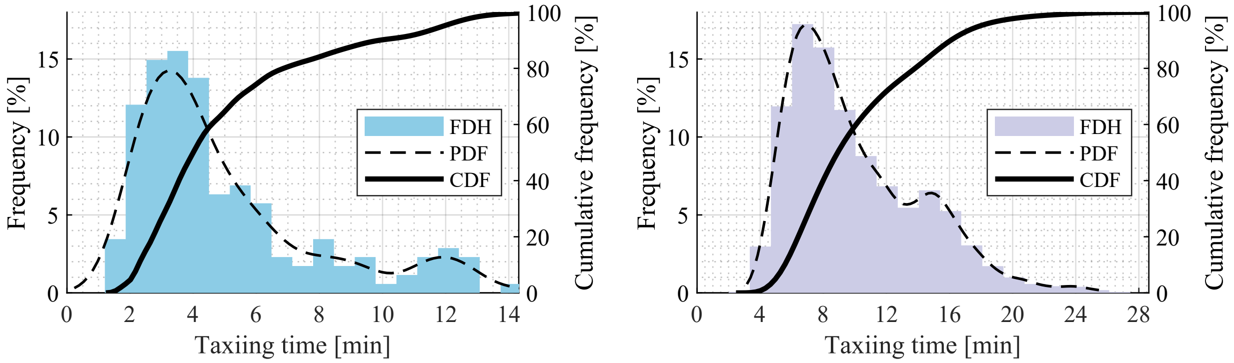
Two scenarios are considered for the analysis of taxiing time and distance. Although only taxi-out phases were acquired for this study, it is reasonable to statistically consider that the taxi-in phases would have similar duration, speed, and distance as taxi-out segments. In other words, the overall distribution of taxi-in profiles would be similar to the taxi-out profiles. No pre-determined routes (small to large airports for example) are favored, removing any correlation between "short" and "long" taxi-in and taxi-out phases. As a result, a total of 30,276 possibilities of total distances to complete both the taxi-out and taxi-in are generated from the data set.

1. Taxiing Time

In the acquisitions, the taxiing time is defined as the time between the first movement of the aircraft under its own power and the take-off acceleration. The time required to warm up the engines before taxiing is not recorded, meaning that a possible part of the fuel consumption will not be considered in further analysis. Indeed, a longer time for ground operations (warm-up of the engines and taxi) implies higher fuel savings with electric motorization but also requires a greater battery, impacting the in-flight consumption. Also, engine warm-up is still required before takeoff even with the ETS system.

For one taxi phase, the taxiing time varies between 1.4 minutes and 14.3 minutes. The average taxiing time is 5.0 minutes for a median time of 4.0 minutes. Figure 3a shows that the mode (main peak) is 3.2 minutes, with more than 50 % of the acquired taxis having a taxiing time between 1.9 minutes and 4.5 minutes. About 20 % of the taxi phases are longer than 7 minutes, but a second peak could be observed around 12 minutes. This second peak is correlated with large airports, where taxi distance and ground operation density is increased.

For two taxi phases derived from a random combination of two acquired taxis-out (Figure 3b), the mode is approximately 7 minutes, which is approximately twice the peak for one taxi. This analysis flattens the secondary peaks



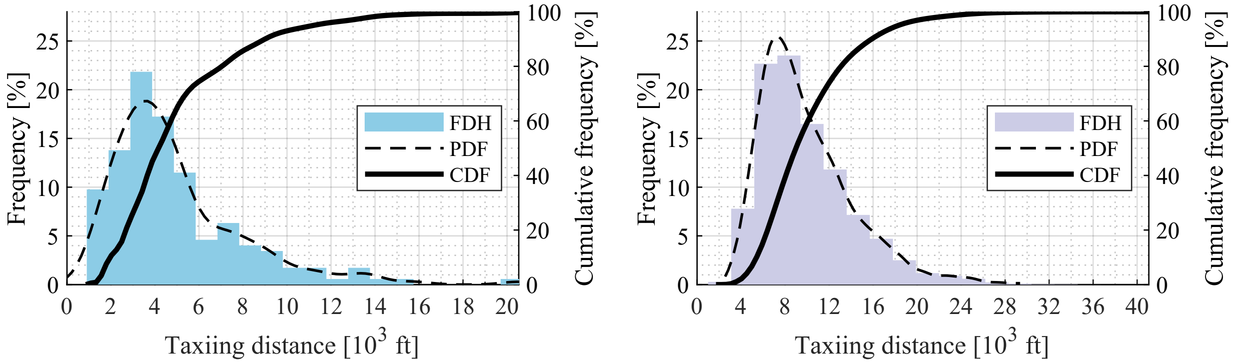
(a) Single taxi phase **(b) Two taxi phases (random combination)**

Fig. 3 Results for the taxiing time

but reveals a concentration of data around 14.7 minutes, result of the combination of all sized airports. After this value, the frequency highly drops, with longer taxis for only 15 % of the data. Approximately 80 % of the taxis combinations are shorter than 13.9 minutes.

2. *Taxiing Distance*

The analysis of the distance (Figure 4a) reveals a taxiing distance between 1,000 ft and 20,500 ft for a taxi-in or a taxi-out, with an average of 4,975 ft. The median distance is 4,150 ft. The mode is approximately 3,500 ft. About 20 % of the taxiing distances are longer than 7,000 ft and only 7 % of the taxi distances are longer than 10,000 ft. The maximum distance can be seen as an exception because only one taxi exceeds 15,750 ft.



(a) Single taxi phase **(b) Two taxi phases (random combination)**

Fig. 4 Results for the taxiing distance

Figure 4b presents the analysis combining both taxi-in and taxi-out phases. The concentration of distances is important between 5,000 ft and 10,000 ft with about 50 % of the data and the mode around 7,200 ft. The average distance for a combination of two random taxi phases is 9,950 ft, for a median of 8,980 ft. About 20 % of the combinations are longer than 13,000 ft and approximately 99 % of them do not exceed 24,000 ft.

3. Taxiing Top Speed

Figure 5 shows the worldwide results of the taxiing top speed analysis, where the mean and the median of the distribution are approximately 20 kts. Less than 20 % of the taxi segments reached a maximum speed higher than 25 kts, and less than 7 % exceeded 30 kts. This top speed fits with the requirements of 32 kts and 31.4 kts defined in [13] and [14] respectively. Even if approximately 2 % of the taxis reach a maximum speed of 40-50 kts, they could be seen as exceptions because the acquired speed limitations are all under 30 kts [9–12].

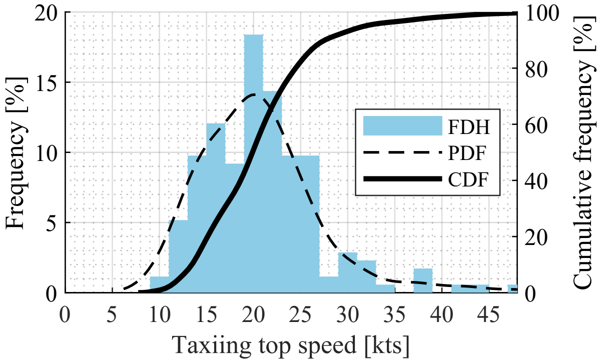


Fig. 5 Results for the taxiing top speed

It should be noted that the minimum top speed is 9 kts, which is the maximum performance of the WheelTug ETS. Because its performances do not meet the average of 20 kts, such driving system is questionable because it would affect the operational routines. The analysis also revealed that the top speed proposed by the EGTS would have been in the taxiing operational standards with a 20 kts top speed.

4. Taxiing Maximum Acceleration

Figure 6 presents the distribution of the peak acceleration observed on the taxi segments. The average maximum acceleration is 0.5 m/s^2, for a median of 0.45 m/s^2. On the FDH, a peak is emerging around 0.35 m/s^2, with 50 % of the maximum accelerations included between 0.25 m/s^2 and 0.5 m/s^2. However, the FDH presents a large panel of maximum accelerations, from 0.2 m/s^2 to approximately 1.2 m/s^2. It supports the idea that it exists no physical limit for the maximum acceleration since the motors can deliver a great amount of power but the engine jet wash could lead to safety issues at important accelerations, limiting the maximum values.

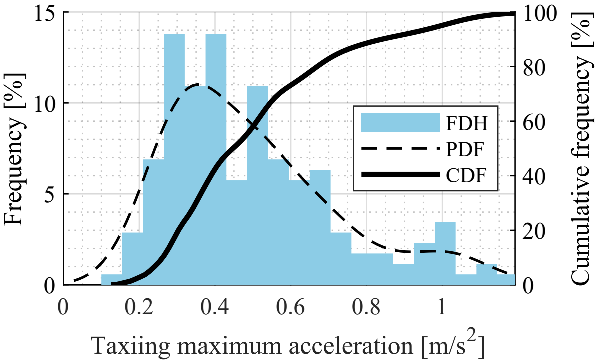


Fig. 6 Results for the taxiing maximum acceleration

III. Electric Taxiing Requirements

This section proposes requirements on total distance, top speed, and maximum acceleration for electric taxiing of regional turboprop aircraft. This will be used in Part IV to determine the potential of an ETS for such aircraft.

A. Requirements from Statistical Analysis

To ensure 80 % of the single taxi phases, the ETS should provide enough energy to complete 7,000 ft. The 80 % criterion appears reasonable because it represents a great part of the taxiing distances. The pilot could start the engine to cover the 20 % of longer taxi phases. Excluding 20 % of the data would save 65 % of the distance, highly reducing the size of the ETS, as explained in Part IV.C.2.

In the second case, to ensure 80 % of the random distance combinations (two taxi phases), the requirement on distance should be 13,000 ft, which is lower than double the first requirement made for one taxi phase only. It is explained by the combinations of the 174 taxi phases, with a greater proportion of short distances. With this distance requirement for the ETS sizing, more than 97 % of the single taxis would be possible. However, it means that the battery should be recharged after each taxi phases: on-ground and in-flight.

To meet the current operational routines, a realistic speed requirement would be 25 kts, which is after the PDF peak. Using the CDF, this requirement ensures that 80 % of the acquired taxis have lower top speeds. Moreover, 25 kts is exceeded for only 2.2 % (1,139) of the total acquired values (52,426), which represents 18.9 minutes of higher speed for a total taxiing time of 871 minutes for the 174 acquisitions. A maximum speed of 25 kts is lower than the ones found in [13, 14] but are in accordance with the FAA recommendations of safe taxiing speeds.

A maximum acceleration requirement of 0.4 $\mathrm{m/s^2}$ for the taxi is sufficient even if only 43 % of the taxis have a lower maximum acceleration. However, 0.4 $\mathrm{m/s^2}$ is exceeded for only 1.3 % (11.5 minutes) of the total recorded taxiing time. Hence, a maximum acceleration requirement of 0.4 $\mathrm{m/s^2}$ is following the operational practices and routines because a lower and more constant acceleration will not affect the taxiing procedures. It should be noted that 0.4 $\mathrm{m/s^2}$ is only 10.1 % lower than the requirement presented in [13].

B. Relation between Acceleration and Speed

As mentioned in the previous subsection, it is rare for the acceleration to exceed 0.4 m/s^2 but it would be of interest to determine the correlation between taxiing acceleration and speed to adapt the proposed requirements. As shown in Figure 7 by the colored points, the acceleration is higher at low speeds (high density of points) because the aircraft needs to reach its taxiing speed. For high speeds, it is rarer for the acceleration to reach high values, with a low density of acquisitions in the upper-right corner of the Figure 7. A great density of values is included in the proposed requirements of top speed and maximum acceleration represented by the red-limited area.

A self-recorded taxi-out phase of a Bombardier Dash-8 300 was used to determine if the maximum acceleration requirement is relevant for higher speeds than 15 kts. The app *Data Collection* was used by the pilot on a cellphone, for on-board acquisition of accelerometer (in g), gyroscope (in rad/s), magnetometer (in μT) and GPS data (latitude, longitude, altitude). The frequency of acquisition was set to 10 Hz. The speed profile was calculated by integration of the acquired acceleration. The black dots on Figure 7 refer to the values of acceleration and speed at each timestep of this on-board acquisition. Even if the self-recorded taxi has a maximum acceleration 6.7 % higher than the proposed requirement, a reduction of 0.03 m/s^2 to reach 0.4 m/s^2 would have almost zero impact. However, it shows that the acceleration tends to decrease for speeds higher than 10 kts. Finally, the acceleration could be reduced for speeds between 15 kts and 25 kts and the method used to adapt the acceleration requirement for such speeds is presented in Section IV.C.

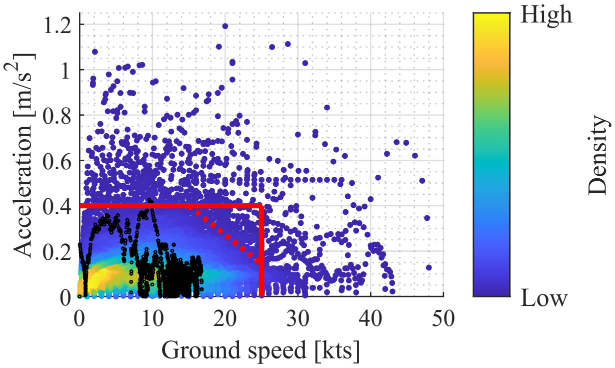


Fig. 7 Acceleration and ground speed of recorded taxi phases : on-board (black) versus radar (colored)

C. Conclusion

Table 1 summarizes the taxiing requirements of distance, top speed, and maximum acceleration for regional turboprop aircraft.

Table 1 ETS requirements for regional turboprop aircraft

Requirement	Single taxi phase	Two taxi phases[a]
Total distance	7,000 ft	13,000 ft
Top speed	25 kts	25 kts
Maximum acceleration (until 15 kts)	0.4 m/s^2	0.4 m/s^2

[a] Random combination of two taxi phases.

IV. ETS Design Case for Dash 8-300 Regional Turboprop Aircraft

This section presents the sizing of the ETS based on the statistically-derived requirements. Then, the fuel savings will be calculated for a specific mission, considering integration of the ETS in the MLG.

A. Case Description

The aircraft used for the purpose of this design case is a Dash 8-300. It is a regional aircraft powered by two turboprop engines (PW123). The mission of interest in this design case is a 270 nm flight, which is the distance between Montréal (CYUL) and Toronto (CYYZ) airports. This study assumes that the battery can be recharged during the flight only to simplify the technology introduction. The battery is therefore sized for both taxi-in and taxi-out phases.

1. Parameters and General Assumptions

For the baseline fuel burn calculation, it is assumed that the aircraft uses only one engine (single-engine taxi) for both taxi-in and taxi-out. During the taxi, the operating engine is at or near idle. For the taxi-out, a 2 minutes warm-up [5] is assumed for the other engine before take-off. Regarding the taxi using electric propulsion, both engines are warmed up for 2 minutes between gate departure and take-off. It is assumed that the GT can be used to fully recharge the battery during the flight to remove dependency on ground charging stations. Table 2 presents the aircraft parameters and assumptions used in this study, where the recharge efficiency represents the efficiency chain from the fuel to the battery.

Table 2 Aircraft parameters and assumptions for the application case

Parameter	**Notation**	**Value**
Aircraft mass	M	43,000 lb
Zero lift drag coeff. [27]	C_{d0}	0.0322
GT fuel flow at idle	f_{idle}	0.107 lb/s
Maximum payload [28]	$M_{PL,max}$	13,500 lb
Flight recharge efficiency	η_{rech}	0.3

International standard atmospheric conditions were used at sea level, on a longitudinal taxiway (no slope) with a constant rolling friction coefficient μ_{roll} = 0.025. This value is an average of the ones found in [29] and [30] for dry concrete taxiways.

The powertrain is equipped with a gearbox (GB), an electric motor (EM), an inverter (INV), and a battery (BAT). Figure 8 presents the powertrain architecture while Table 3 presents the components' specifications, based on current technologies.

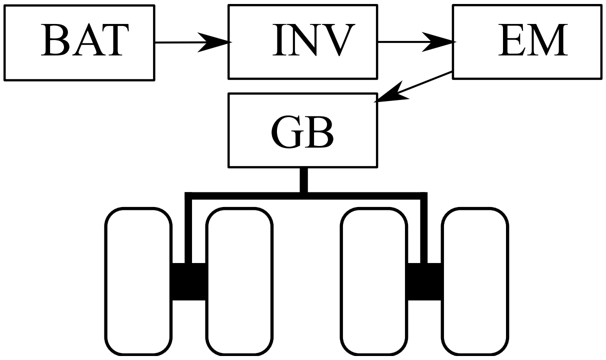


Fig. 8 Electric powertrain architecture

Table 3 Powertrain parameters and assumptions for the application case

Parameter	Notation	Value
BAT specific energy [31]	ϵ_{BAT}	115 Wh/kg
BAT max. C-rate (discharge) [31]	Cr_{dis}^{max}	70 h^{-1}
BAT efficiency [32]	η_{BAT}	0.99
INV specific power [33]	ϵ_{INV}	13 kW/kg
INV efficiency [34]	η_{INV}	0.97
EM specific power [35]	ϵ_{EM}	4.4 kW/kg
EM efficiency [35]	η_{EM}	0.95
EM max. RPM [35]	RPM_{EM}	4500
GB efficiency	η_{GB}	1.00

B. Calculation Method for Energy and Power Requirements

The total required power at the Main Landing Gear (MLG) wheels as a function of time is evaluated using

$$P(t) = \left(Mg\mu_{roll} + D(t) + M\frac{dV}{dt}(t)\right) V(t) \tag{1}$$

where no taxiway slope is directly considered. A relatively important upslope of 1 % would then translate to a reduction of the equivalent acceleration of 0.1 m/s^2 and thus, it is assumed that upslope operation would require a slight reduction in acceleration. The instantaneous aircraft drag force is represented by $D(t)$. It should be noted that no regeneration is considered during braking or deceleration, so if $P(t) < 0$ the power is maintained at zero. Then, the required power is defined as $P_{req} = \max(P(t))$. The energy consumed as a function of time is

$$E(t) = \begin{cases} 0 & t = 0 \\ E(t-1) + t_{step} P(t) & 0 < t \leq t_{taxi} \end{cases} \tag{2}$$

and the required energy is defined as the value of energy at the end of the taxi phase, $E_{req} = E(t_{taxi})$.

C. Impact of the Taxiing Requirements

1. Power

Realistic speed and acceleration requirements were previously proposed using the data (25 kts top speed and 0.4 m/s^2 maximum acceleration until 15 kts). Using Equation 1, the power requirement as a function of the taxiing acceleration and speed is evaluated for the baseline aircraft at gross weight.

By combining both the maximum acceleration and maximum speed (0.4 m/s^2 at 25 kts) the required power at the wheels would reach around 164 kW, as shown in Figure 9 by the red star.

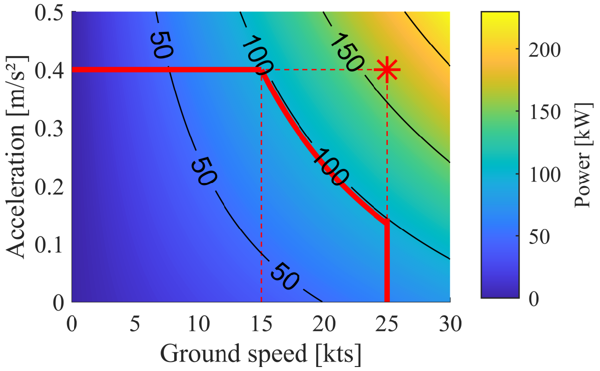


Fig. 9 Power requirements for different speeds and accelerations

However, a reduction in acceleration capability is acceptable as the taxiing speed increases as shown previously in Figure 7. To reduce the peak power requirement, it is suggested to reduce the acceleration capability upward of 15 kts following the iso-power at higher speeds. As shown in Figure 9 by the red-curved line, a total power P_{req} = 98 kW at the MLG wheels (49 kW by leg) would be enough to meet the adjusted requirement of maximum acceleration and reduce the maximum power by about 40%.

It should be noted that greater accelerations could be reached at a speed below 15 kts but the motor would be torque limited. Moreover, a total power of 98 kW at the wheels could allow the aircraft to reach approximately 35 kts, if needed.

2. *Energy*

An accurate energy calculation to cover both taxi phases depends on the aircraft acceleration, speed, and various losses associated with aircraft braking. However, a strong correlation exists between the taxiing distance and the energy required as shown in Figure 10, where the energy required for each of the 30,276 combined taxi-in and taxi-out phases were evaluated. A linear relation can be determined, $Energy[kWh] = 0.4351 \times Distance[10^3\ ft]$, with a coefficient of determination $R^2 = 0.99$.

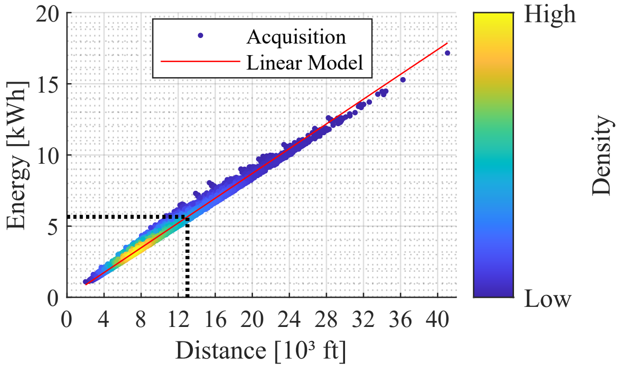


Fig. 10 Correlation between the taxiing distance and the required energy

The linear relation gives an energy $E_{req} = 5.7$ kWh at the wheels, as shown by the dotted black lines in Figure 10. As a reminder, the requirements are calculated to complete 80 % of the taxi-in and taxi-out distance combinations, meaning that 80 % of the combinations require at most 5.7 kWh for a total taxi distance of 13,000 ft.

D. ETS Mass Estimates

Table 3 presents a summary of the additional mass by an ETS, considering the various efficiencies.

Table 4 ETS components' masses and specifications

Component	Mass	Specification
Gearbox	98 lb	98 kW
Electric motor	52 lb	103 kW
Inverter	18 lb	106 kW
Battery	125 lb	6.5 kWh
Total	293 lb	-

The gearbox's weight is estimated using

$$M_{GB} = \frac{K \times hp^{0.76} \times (RPM_{EM})^{0.13}}{(RPM_{wheels})^{0.89}}, \tag{3}$$

based on current technology ($K = 72$) [36]. The masses of the electric motor, the inverter, and the battery are calculated using their specific power or energy. The masses of the components and their specifications are shown in Table 4 for a powertrain of 98 kW and 5.7 kWh at the wheels. This additional mass on-board would result in a maximum payload loss of 2.2 %, which also represents 1.3 PAX.

Projected technology growth in the years to come would result in an even more lightweight solution. For example, if battery specific energy were to double, as it did over the last decade [37], only 1.7 % of the total payload capacity would be lost (i.e., 1.1 PAX). Compared with today's technology, the cost in payload capability due to the ETS seems rather insensitive to technology growth as it is already of the order of only one passenger.

E. Fuel Savings

The main goal of an ETS integration in the MLG is to save fuel during the taxi phases, reducing CO_2 emissions. Its viability mostly depends on the relative payload loss versus the relative fuel savings for the entire mission. This section describes the method to evaluate the fuel savings.

The baseline fuel burn during single-engine taxi, $C_{taxi,base}$, is calculated by multiplying the taxiing time (t_{out} and t_{in} for taxi-out and taxi-in, respectively) by the idle GT fuel flow f_{idle}. There is also an additional time t_{wu} for the warm-up of the other GT after the taxi-out phase.

There are two different fuel consumption associated with electric taxiing. The first one, C_{e-taxi}, is the fuel used during taxi and warm-up. Even if a battery does not have enough energy to complete the whole taxi route, it still can achieve a part of it, which saves fuel. There is also the need to recharge the battery during the flight, leading to the second consumption C_{rech}.

After calculating the fuel consumption, Equation 4 provides the relative fuel savings c_{eco}, which is the absolute economy divided by the fuel used during the entire mission (including the flight). c_{eco} is in percent and given by

$$c_{eco} = 100 \times \frac{C_{taxi,base} - C_{e-taxi} - C_{rech}}{C_{flight,base} + C_{taxi,base}}, \tag{4}$$

where it is estimated that the Dash 8-300 burns 1,414 lb of fuel ($C_{flight,base}$) to complete the mission at maximum payload [27]. The proposed powertrain design is tested across the 30,276 simulated combinations. For every combination, the total taxiing time (in and out) can be deduced. Figure 11 represents the relative fuel savings for the proposed mission of 270 nm, including the taxi-out, the flight, and the taxi-in. It should be noted that the integration of an ETS always implies relative fuel savings.

Figure 11 shows that there is a high density between 1.3 % and 3.3 % of fuel savings, for taxiing times of 5 to 10 minutes corresponding to approximately 55 % of the acquired times (see Figure 3b). The red-limited area represents the maximum fuel savings for every taxiing time combination. The majority of the taxiing combinations are included in this area. Figure 12 shows the FDH, PDF, and CDF of the relative fuel savings for the proposed mission. About 68% of

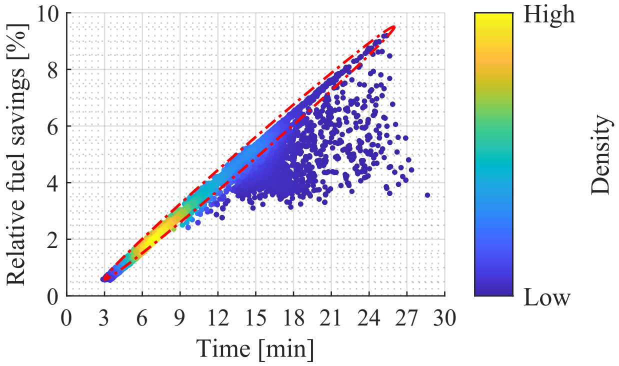


Fig. 11 Relative fuel savings for the 30,276 taxi phases combinations

the taxi combinations have higher fuel savings than the payload loss (2.2 %), corresponding to total taxiing times higher than approximately 7 minutes. Around 80 % of the combinations have fuel savings higher than 1.8 %, for an average of 3.1 %. Despite a maximum of 9.2 %, the fuel economy rarely exceeds 6 % (only for 3.5 % of the combinations).

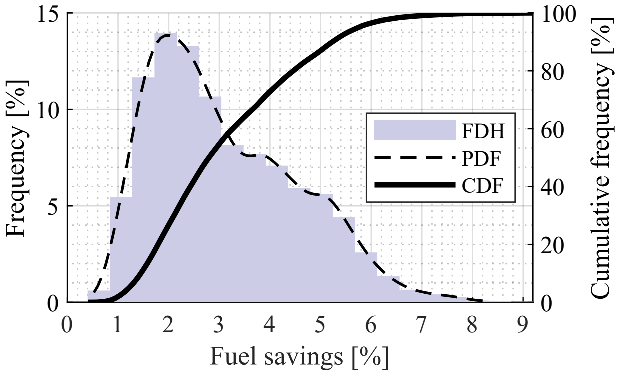


Fig. 12 Relative fuel savings for the 270 nm complete mission

Finally, Figures 11 and 12 confirm the high possibility to have fuel savings between 1.3 % and 3.3 % with a main peak of the PDF. In average, the expected economy of fuel is 3.1 % for a maximum payload loss of 2.2 % or a PAX loss of 2.7 % [28]. The average fuel economy is relatively low but allows to reduce fuel consumption, noise pollution, and reduced Foreign Object Damage (FOD) risks during the taxi. In a scenario where the battery would only be recharged on-ground, the aircraft would save an additional 2.5 lb (0.2 % of total fuel) per flight in average. Although this scenario would lead to further fuel savings, it would require the installation of charging infrastructure at each airport.

It is important to remind that the results presented in Figures 11 and 12 consider a 270 nm mission. A mission with a longer flight distance would burn more fuel, so the relative fuel savings c_{eco} would be smaller. At a certain distance, the fuel savings would not compensate for the payload and thus make the concept irrelevant.

V. Conclusion

In this paper, realistic electric taxiing requirements for regional turboprop aircraft were determined through statistical analysis of real flight data to better define the requirements of novel electric taxiing propulsion systems. This analysis aimed to fill the gap for future e-taxi systems as there are no generally-accepted set of requirements (speed and acceleration) for the taxiing phase to match current pilot operation.

The statistical approach revealed that a top speed of 25 kts appears to be a realistic requirement, with a maximum acceleration of 0.4 m/s^2 until 15 kts. These requirements are in accordance with the operational practices and pilots' routines. Distance requirements of 7,000 ft for one single taxi or 13,000 ft for two taxi phases were determined, representing 80 % of the acquisitions.

The second part of this article focus on the conceptual sizing of an ETS for the Dash 8-300 for a short 270 nm mission without ground charging capability. Using the speed, acceleration, and distance requirements for two taxi phases, a peak power capability of P_{req} = 98 kW and a total energy of E_{req} = 5.7 kWh are required at the MLG wheels. The integration of the designed ETS provides an average fuel savings of 3.1 %, for an additional mass of 293 lb, which represents 2.2 % of the maximum payload or 1.3 PAX (2.7 %).

Although this study demonstrates the benefits of electric taxi on regional transport aircraft, additional benefits could result from regenerative braking during taxi or landing to recharge the batteries [13]. Moreover, synergistic integration of such a system could be investigated, for example, with a replacement of the actual Ni-Cad batteries of the Dash 8-300 weighting about 115 lb. Finally, a smaller battery could be sized to complete only one taxi phase (in or out) and recharged in flight and on ground with a battery-powered ground power unit (eGPU), which would lower the payload loss.

Appendix

Table 5 shows the countries where the taxi acquisitions were made.

Table 5 Departure countries of taxi data acquisitions

Australia	Bahamas	Belgium	Benin	Canada	Cape Verde
Chad	Colombia	El Salvador	Estonia	Fiji	Finland
France	Georgia	Germany	Greece	Hungary	Indonesia
Italy	Ivory Coast	Jamaica	Japan	Maldives	Mali
Mexico	Netherlands	New Zealand	Niger	North Macedonia	Norway
Papua New Guinea	Portugal	Romania	Senegal	Serbia	Slovakia
Spain	Tunisia	Turkey	United Kingdom	United States	

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