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IMPACT OF ELECTRIC TAXIING ON HYBRID-ELECTRIC AIRCRAFT SIZING

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Abstract

Turboelectric, serial and parallel hybrid-electric and universally-electric aircraft seem to be a potential key technology to allow for synergistically integration of new technologies within the airframe. This is enabled by the separation of the thrust generation devices and the power and energy supply system. This novel integration capability is potentially required to fulfill the ambitious environmental targets set by the European Commission with the Strategic Research and Innovation Agenda (SRIA) or the National Aeronautics Space Administration (NASA) with the NASA N+3 goals. SRIA is aiming a reduction of CO_2 by 75% up to the year 2050 compared to the year 2000 and an emission-free taxiing capability for future aircraft concepts. For the purpose of electric taxiing different ground-based and aircraft onboard options are available. In this paper the focus is set on the aircraft systems. Hybrid-electric propulsion systems are already intrinsically enabling electric taxiing in some cases such as electric driven fans. In the presented studies the impact of the so-called in-wheel electric taxiing system is investigated for hybrid-electric and also for a conventional solely kerosene powered aircraft. For these concepts the electric taxiing capability and the potential block fuel saving impacts are identified. Furthermore, the potential usage of the installed system assisting the take-off ground acceleration phase is discussed.

NOMENCLATURE

ASM	Asynchronous Motor
DH	Degree of Hybridization
EDF	Electric Ducted Fan
EIS	Entry-Into-Service
ElTaS	Electric Taxiing System
ETV	Electric Towing Vehicle
IWETS	In-Wheel Electric Taxiing System
GB	Gear Box
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics Space Administration
OEI	One-Engine Inoperative
PMSM	Permanent Magnet Synchronous Motor
SLST	Sea Level Static Thrust
SRIA	Strategic Research and Innovation Agenda
TOC	Top-of-Climb

1. INTRODUCTION AND OBJECTIVES

The European Commission with the Strategic Research and Innovation Agenda (SRIA) [1] or the National Aeronautics Space Administration (NASA) with the NASA N+3 goals [2] are yielding ambitious emission reduction targets for future transport aircraft. As an example SRIA aims a reduction of CO_2 by 75% and NO_X by 90% up to the year 2050 compared to the year 2000. Additionally an emission-free taxiing capability is required for future transport aircraft. One potential solution for emission free taxiing is electric taxiing. There are several ground-based and aircraft onboard concepts available. A ground-based solution is for example represented by an electric towing vehicle (ETV). The advantage of this concept is that no additional equipment has to be installed on the aircraft, which has to be carried over the entire mission. The disadvantage of this concept is that the infrastructure at the airport is strongly influenced by occupying the taxiways with additional vehicles. Another option to provide electric taxiing capabilities is to propel the aircraft with electrically supplied propellers or fans on the ground. Electric power trains are under investigation in turboelectric [3], serial and parallel hybrid-electric [4] and universally-electric aircraft [5], [6]. The advantage of an aircraft onboard Electric Taxiing System (ElTaS) is that no infrastructure at the airport is influenced. A disadvantage of an onboard ElTaS is that the system weight has to be carried for the entire mission although it is only used for a short period of time.

The influence of an ElTaS for today's conventional aircraft has been already investigated. A positive impact of an ElTaS could be a possible fuel reduction despite its additional weight. For example, for an assumed flight distance of 1000 nm and 30 minutes of ground time a blockfuel saving of 3% is possible [7]. Also, a positive impact on maintenance cost, especially for the engines, is often mentioned. However, the positive impact of electric taxiing depends strongly on the utilization of the aircraft and especially taxi time and fuel price are crucial parameters to obtain a cost benefit when using an ElTaS [8]. Chakraborty et al. [9] presented a preliminary sizing of an ElTaS, which was mounted on both main landing gears. Several speed requirements were defined that the ElTaS has to fulfill, such as acceleration for runway crossing and maintaining speed. A simple approach for the friction forces was assumed. For an aircraft with a Maximum Take-Off Weight (MTOW) of 79000 kg a power requirement for each electric motor of 50 kW at a mechanical efficiency of 0.8 was calculated. This power requirement was in good agreement with published data from first tests conducted by Honeywell and Safran [10]. The electric motors used by Honeywell and Safran had weight of 150 kg for each main landing gear.

Different options of an ElTaS in a hybrid-electric propulsion system are available. One option could be to use electric fans to generate thrust during taxiing. Another option is to use electric motors embedded within the wheels of the landing gear providing the necessary taxiing force. For the purpose of this paper these two options are compared on a short range aircraft featuring a parallel hybrid-electric propulsion system. The expected advantage of the In-Wheel Electric Taxiing System (IWETS) is the higher propulsive efficiency during taxiing compared to an electric

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fan system operated at low Mach numbers. In this speed ranges the propulsive efficiency is usually lower than 10% depending on the fan pressure ratio [11]. Furthermore, the different systems are compared to ground-based ElTaS and a conventional reference aircraft.

For the purpose of this paper, these two aircraft onboard ElTaS are compared on a hybrid-electric aircraft platform accommodating 180 passengers at 1300 nm. Additionally the IWETS is synergistically used as a take-off assistance system to identify the sizing effects on the hybrid-electric power train. These investigations include for take-off different normal and abnormal modes of operation such as one-engine inoperative, one electric ducted fan inoperative, IWETS inoperative.

2. ELECTRIC TAXIING SYSTEMS

As mentioned in the introduction section there are several options available realizing electric taxiing capability. The most promising ones on the aircraft system side are the generation of a taxi force via the thrust of a fan or via the traction force with the help of the wheels. Both concepts and their modelling approach are described in more detail in the following. In general the necessary minimum taxi force, $F_{Taxi,min}$, is equal for both concepts and can be determined with the Equation (1).

$$F_{Taxi,min} = MTOW \cdot g \cdot \mu \qquad (1)$$

It is a function of the aircraft MTOW and the friction coefficient, μ. For the scope of this paper, μ is used to be 0.8 for static and 0.03 for moving conditions. As required taxi speed 5 m/s (10 kts) is used.

For an airport emission-free taxiing system several supply options are possible such as fuel cell or battery supply. This paper will analyze battery supply only. In contrast to a fuel cell supply no radical changes of the airport infrastructure are required e.g. through provision of liquid hydrogen to allow for CO_2 and NO_X free emission ground operation.

2.1. Electric Fan

The propulsion system of an aircraft is sized in a way that it fulfills the thrust requirements in critical flight phases such as Top-Of-Climb (TOC) or take-off. In case of a hybrid-electric aircraft at least two different energy sources are combined in combination with the corresponding chemical and electrical energy conversion devices to generate the necessary thrust. An example of an electric supplied thrust generating propulsor is represented by an Electric Ducted Fan (EDF) as sketched in Figure 1. It consists of a reduction planetary Gear Box (GB) system, an electric motor, a power management and distribution system including a cooling system and a battery supply system. The GB is required to convert the higher rotational speed of the electric motor to a lower rotational speed of the fan. This has been identified as a potential method to decrease motor mass and dimensions. The flow path sizing of the EDF is usually performed in TOC conditions. The sizing point of the electrical system is depending on the degree of power hybridization, H_P, which defines the electric portion to the entire required propulsive power for a specific flight state. The calculation of the propulsive efficiency is based on a zero-dimensional performance model covering design and off-design characteristics to estimate the maximum thrust capability and the propulsive efficiency according to [12]. The ducted fan model is based on standard compressor theory and basic gas-dynamic relationships [12].

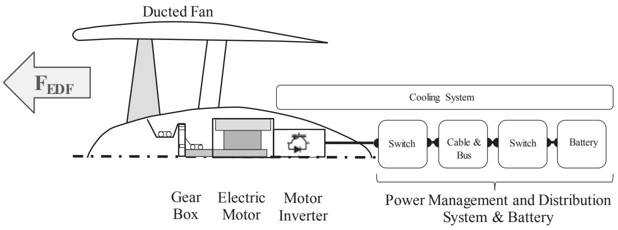


Figure 1: Sketch of the electric fan supply architecture adapted from [13]

If sizing an EDF in TOC conditions provides normally enough power to generate the necessary taxi force. However, depending on the design HP this also implies that the EDF is running in deep part load conditions during taxiing. The required taxi power can be determined with Equation (2)

$$P_{EDF} = \frac{F_{Taxi} \cdot v_{Taxi}}{\eta_{Prop,EDF} \cdot n_{EDF}} \qquad (2)$$

It is a function of the required taxi force according to Equation (1), the taxi speed, v_{Taxi}, the propulsive efficiency of the EDF, $\eta_{Prop,EDF}$, and the number of fans, n_{EDF}, that contribute to the taxi force. With the required taxi speed of 10 kts or about 0.01 Mach the propulsive efficiency is in the range of 10%. The electric system from battery to the electric motors including the GB has an efficiency of 95% according to [14].

2.2. In-Wheel Electric Taxiing Motor

In case of an IWETS, the electric motors are integrated in the wheels of the landing gears. There are two different possibilities: installing the electric motors into the nose landing gear [15] or into the main landing gears [10]. The weight on the main landing gears is up to 92% of the aircraft weight. This offers the advantage that there is more weight on the wheels to transfer a larger range of torques of the electric motors to the ground, also in advert conditions such as wet or icy taxi ways. If the torque exceeds the static ground force the wheels cannot transfer the torque to the ground. This has to be avoided and is one boundary that defines the size of the electric motors. Therefore, in this work electric motors installed in the wheels of the main landing gears are considered.

For the design and sizing of the ElTaS it is important to identify the acting forces that have an effect on its performance. Figure 2 displays the system design of the taxiing system with the electric motor installed in the wheel of the landing gear and the forces. The friction force between the wheel and the ground depends on the weight of the aircraft. To accelerate the aircraft on the ground, the motors of the ElTaS have to have enough power and provide sufficient torque on the ground to overcome rolling friction and especially the breakaway forces to set the aircraft into motion. Experiments showed that these forces are approximately 6 kN for an Airbus A319 with an electric motor installed in the wheels of the nose landing gear [16].

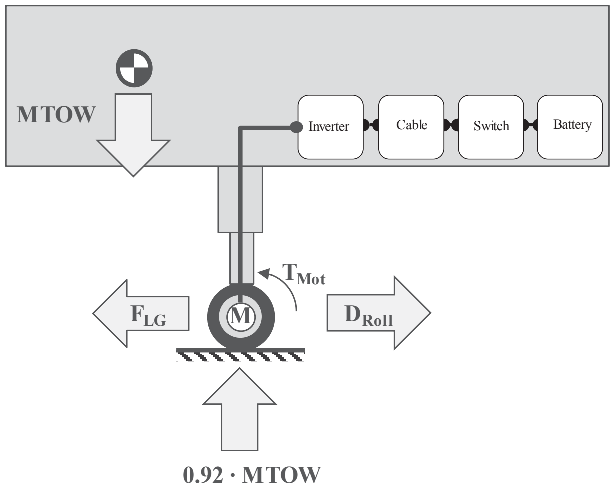


Figure 2: Forces of the in-wheel electric taxiing system

The electric motor is responsible for the generation of the required torque. There are several eligible electric motor types available for the aviation sector such as permanent magnet synchronous motors (PMSM), asynchronous motors (ASM) or switch reluctance motors [17]. From an efficiency and mass point of view the PMSM has been identified as the most promising electric motor type for propulsion systems [17]. However, considering the surrounding environment of an IWETS the PMSM is not a suitable motor type according to [18]. The brakes are also located in the main landing gears, which can generate heat loads of up to 300°C. This temperature is above the critical temperature of normal permanent magnet materials. The common Neodymium-Iron-Boron permanent magnets have a demagnetization temperature of around 200°C according to [19]. An advantage of the ASM compared to the PMSM is that it allows for a lossless operation during a failure case. This is beneficial for take-off conditions.

For the energy and power supply of the electric motor a battery system is used. The battery is connected via cables and protection switches to the inverter-controller unit of the electric motor. For that purpose the battery has to be sized for the maximum power demand of the electric motor including the losses of the other involved components and the required energy demand to fulfill the taxi times. As thermal management system a passive air cooling system is used. Therefore, in the first instance no additional system mass or drag penalty has been accounted for this system. During the sizing process a case-by-case analysis has to be performed if the battery power or the battery energy requirement is the sizing case for the required battery system mass. This can be checked with the specific power and specific energy, respectively. Furthermore, the installed battery mass should provide enough energy that after the taxi procedures a residual energy of at least 20% state-of-charge is available. For lithium based batteries this is a typical value to avoid damage of the electrodes [20].

An overview of the used electric component parameters to determine the overall systems efficiency and mass is given in Table 1.

Table 1: Component parameters used for the design of the in-wheel electric architecture

Component	Sizing Parameter	Efficiency	Source
Electric Motor	20 Nm/kg* 4 kW/kg	90.0%	[18]
Inverter	20 kW/kg	99.5%	[14]
Converter	20 kW/kg	98.0%	[14]
Cable	1 – 19 kg**	~100.0%	[14]
Battery	1000 Wh/kg 1500 W/kg	90.0% - 99.0%***	[21]

* projection to EIS 2035+

** 540VDC transmission voltage using 6 m cable length per electric motor

*** Efficiency depending on power or energy sized battery system

3. SYSTEM METHODS FOR IN-WHEEL ELECTRIC TAXIING

The following section describes the modelling approach of the IWETS and the extension of existing handbook methods to cover an in-wheel traction force assistance during take-off.

3.1. Sizing Method of the In-Wheel Electric Taxiing System

A central part of the design of the electric architecture is the design point of the electric motor for the IWETS. The mass, volume and performance of an electric motor is defined by the design torque to be transmitted and the design rotational speed defining together the overall design power [17]. With the minimum required taxi force according to equation (1) the necessary electric motor torque, T_{Mot}, per wheel can be calculated using the number of electrically powered wheels, n_{Wheels}, and the radius of one wheel, r_{Wheel}, as shown in Equation (3)

$$T_{Mot} = \frac{F_{Taxi,min}}{n_{Wheels}} \cdot r_{Wheel} \tag{3}$$

Schwarze has introduced the degree of hybridization (DH) for IWETS [17]. The DH is defined as the ratio of the total transmitted wheel force to the sea level static thrust of the propulsion system as shown in Equation (4). Substituting the wheel force with Equation (1) it can be seen that the DH can be expressed as a function of the load distribution, μ and the reciprocal of the thrust-to-weight ratio. Depending on the friction coefficient the possible values of DH ranges between minimum 2.8% and maximum 79.6% for a given landing gear load distribution of 92%. The parameter c can be used to design the electric motor for higher forces than the friction force.

$$DH = \frac{MTOW \cdot g \cdot \mu \cdot 0.92}{F_{SLST}} = 0.92 \cdot \mu \cdot \frac{W}{F} \cdot c \tag{4}$$

The design rotational speed of the electric motor, n_{Mot}, can be determined with Equation (5).

$$n_{Mot} = \frac{v_{A/C}}{2 \cdot \pi \cdot r_{Wheel}} \tag{5}$$

It is a function of the aircraft's speed, $v_{A/C}$, and the wheel's radius, r_{Wheel}. The minimum required speed is given by v_{Taxi}

for an ElTaS. Finally, with these parameters the design power of the electric motor can be determined. This design approach is visualized in Figure 4. It can also be recognized that for a given torque demand or DH the required motor power is determined by aircraft speed. If the electric motor is operated above the design speed, the output torque and in turn traction force has to be reduced to accelerate the motor further. This is also called flux weakening [17].

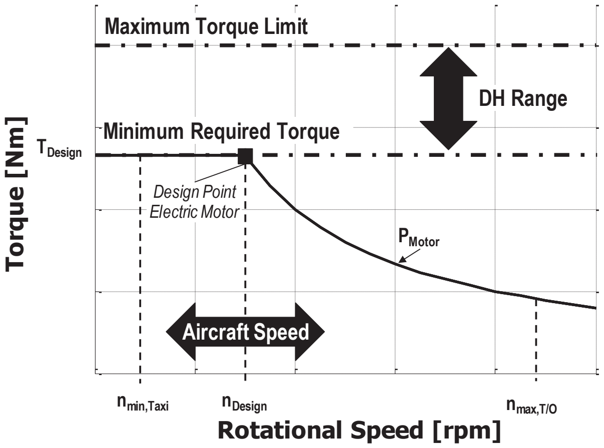


Figure 3: Sizing chart of the electric motor for in-wheel taxiing and take-off assistance system

According to Table 1 the main sizing parameter of the electric motor is the specific torque. One design option to reduce the torque requirements of the electric motor may be performed with the help of a GB. Equation (6) is used for the estimation of the required GB mass taken from [22]. It is based on a planetary GB system and is only a function of the maximum output torque, T_{max}.

$$m_{GB} = 0.1127 \cdot T_{max}{}^{0.772} \cdot \qquad (6)$$

The efficiency of a planetary gear box can be assumed to be around 99% [23] at a gear ratio of 4. The mass of the other electric components are calculated with their individual sizing power including the efficiency losses of the power train chain. The total electric system mass with four installed electric traction motors can be expressed as a function depending on the total required electric landing gear power in kilowatt, $P_{LG,Tot}$, and the design motor torque, T_{Mot}, in Newton-Meter using the component data given in Table 1. For the mass estimation a case-by-case analysis has been performed distinguishing if the electric motor system is sized for the maximum torque (cf. Equation (7)) or power demand (cf. Equation (8)) represented by the specific torque and specific power, respectively. The maximum value out of this approach is defining the overall system mass as given in Equation (9). The other components are sized for the maximum power demand. The cables are designed for 540 VDC, the next step for future subsystems [24].

$$m_{El,IW,T} = 0.05 \cdot P_{LG,Tot}{}^{1.1} + T_{Mot}{}^{0.49} + 0.025 \cdot T_{Mot} \qquad (7)$$

$$m_{El,IW,P} = 0.38 \cdot P_{LG,Tot} + 0.014 \cdot T_{Mot} + 43.82 \qquad (8)$$

$$m_{El,IW} = \max(m_{El,IW,T}, m_{El,IW,P}) \qquad (9)$$

3.2. Extension of Take-Off Field Length Calculation

A potential synergy effect using an IWETS is the potential usage of the installed traction force to assist the acceleration phase of the ground based part during take-off. For a better assistance the motor system can be sized for higher aircraft speeds, $v_{A/C}$, than the taxi speed limited by the rotation speed of the aircraft. To determine the required balanced Take-Off Field Length (TOFL) normally the three cases all-engine operative, one-engine inoperative take-off (OEI) and OEI stop are considered visualized in Figure 4. The maximum length out of these cases are finally defining the TOFL.

The ElTaS is only affecting the ground based part of the take-off phase. It has to be ensured that the propulsion system is capable to deliver the specific thrust demand after the take-off speed to reach defined obstacle height of 35 ft according to EASA CS25 [25]. Furthermore, it has to be ensured that the required second segment climb gradient of 2.4% for a two engined and of 3% for a four engined aircraft is at least reached during OEI according to FAR and EASA CS25 [25]. For the calculation of the OEI case an operative ElTaS is assumed, because it is unlikely that two systems at the same time are failing.

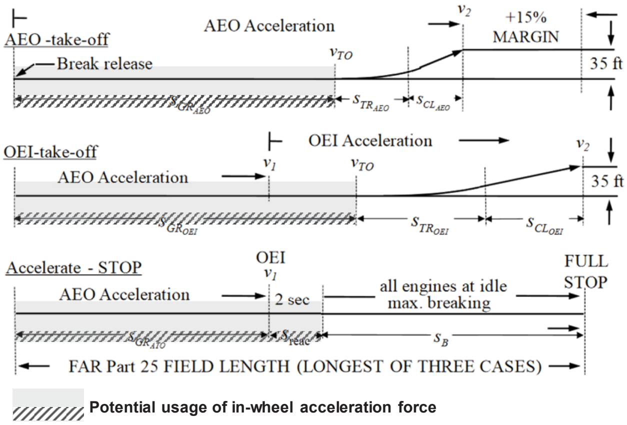


Figure 4: Simulation cases and marked impact of an in-wheel electric taxiing system used to determine the balanced field length. Adapted from [26].

For the determination of the required TOFL there are several handbook methods available such as Torenbeek [27] and numerical methods such as Gologan [26]. For the scope of this paper the handbook method of Torenbeek is used to estimate the impact of the ground roll based field length shown in Equation (10)

$$s_{T/O,Gnd} = \frac{v_x{}^2}{g \cdot \sigma} \cdot \frac{1}{\left(\frac{F_{Prop} + F_{LG}}{MTOW \cdot g} - \mu\right)} \qquad (10)$$

It is based on the reference speed, v_x, defined by Torenbeek, the gravity constant, g, the local air density ratio, σ, the thrust-to-weight ratio extended by the average traction force of the landing gear, F_{LG}, and μ.

Schwarze [18] has analyzed for an ElTaS at different DH of an Airbus A320 class aircraft a reduction in TOFL of up to

350 m. This reduction potential is reached at a DH of 20% or 48 kN wheel force assistance. Because the DH has an impact on the necessary motor torque and in turn mass, for the scope of this study the IWETS is sized to just eliminate rolling friction of the main landing gear as suggested by [9].

4. REFERENCE AIRCRAFT PLATFORMS

The emission-free taxiing capability is required for an EIS in 2050. However, from a technical point of view the realization of such a concept is already possible with current technology. For that reason the following section describes the reference aircraft platforms for an EIS year of 2035+. Beside a parallel hybrid-electric aircraft also a conventional kerosene supplied aircraft is considered to identify the impact of an IWETS on different aircraft platforms.

4.1. Mission Profile

Figure 5 shows a typical mission profile including the definitions for the single flight phases and mission parameters such as block and trip fuel and time. In the following case the total taxi times are around 25 min or 12% of the total block time for a 1300 nm mission. For the following studies a taxi-out time of 20 min and a taxi-in time of 6 min are assumed. The taxiing numbers are based on [7] stating that the average taxi-out times are above 15 min in the United States with increasing trend. In Europe the taxi times account for 10% to 30% of the block time [7].

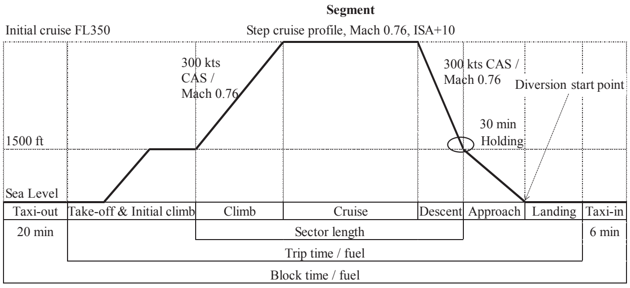


Figure 5: Flight profile of the 1300 nm short range mission used for both reference platforms based on [28]

Additionally, when focusing on the IWETS also the push back capability is considered that such a system offers. For that purpose the IWETS includes a 30 second push back procedure in the performance calculation. During taxiing it is assumed that the gas turbines are not running.

4.2. Conventional Reference Aircraft

The reference short range aircraft is based on an Airbus A320 class aircraft that has been downsized to a design range of 1300 nm for 180 PAX and is based on [29]. The selected design range covers 90% of the cumulative stage lengths in a narrow body class according to [29]. The cruise Mach number is set to 0.76. For the projection of technology developments for the targeted EIS year different enhancements are considered such as advanced structural and aerodynamic improvements, an all-electric subsystems architecture and advanced geared turbo fans (GTF). The subsystem architecture is designed for an overall transmission voltage of 540 VDC. Table 2 summarizes the most important parameter of this reference aircraft based on [29].

Table 2: Overview of relevant aircraft parameter of the kerosene supplied aircraft

Aircraft Parameter	Value
MTOW	60361 kg
Release Fuel	6187 kg
Block Fuel	4834 kg
Taxi Fuel	204 kg
Wing Area	94 m²
TOFL	max. 2200m

4.3. Parallel Hybrid-Electric Power Train

The parallel-hybrid electric aircraft is a derivative of the conventional reference aircraft. The propulsion system has been replaced by a discrete parallel hybrid-electric architecture as sketched in Figure 6 also referred to as “BHL Quad-Fan” [29]. It consists of two battery supplied EDFs and advanced kerosene supplied GTFs. These propulsion systems are completely segregated. The advantage of this configuration is that the H_P can be nearly independently chosen without effecting operational margins of other components such as turbo components. This hybrid-electric configuration only covers the hybridization on propulsion level without using any synergy effects offered by the new propulsion type such as additional improvements in aerodynamics.

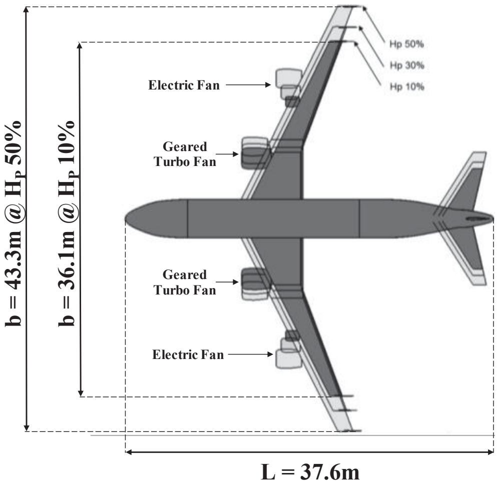


Figure 6: Top-view of the discrete parallel hybrid-electric aircraft platform for different design degree of power hybridization values adapted from [29]

The electric power train consists of advanced electric motors using high temperature superconducting technology, multi-level power electronics with Silicon Carbide as semiconductors and advanced lithium based batteries cooled via a liquid thermal management system. The system architecture is based on [14], [30]. An optimum system voltage with regard to system efficiency and mass has been identified at 1500 VDC. For the considered battery technology a specific energy target of 1000 Wh/kg is assumed. The batteries have been sized in a way that the residual state of charge is above 20% at the end of the design mission. The optimal design H_P was identified at 20% during top-of-climb conditions. These investigations included for the set H_P also different operational hybridization strategies for the mission performance. The most promising hybridization strategy was identified by taking full advantage of the installed electric power during all flight phases while the conventional GTF are providing the residual thrust. In this hybrid mode the EDF are also providing the required taxi thrust. For the overall aircraft level assessment the aircraft preliminary design tool PaceLab APD has been used [31]. Table 3 summarizes the basic parameters of the baseline parallel hybrid-electric power train.

Table 3: Overview of relevant aircraft parameter of the hybrid-electric aircraft sized for a design degree of power hybridization of 20% based on [14]

Aircraft Parameter	Value
MTOW	82026 kg
Release Fuel	5695 kg
Battery	12601 kg
Block Fuel	4728 kg
Taxi Energy Mass	880 kg
Wing Area	127 m²
TOFL	max. 2200m

4.4. In-Wheel Electric Taxiing System Integration and Assessment

For the provision of the IWETS capability different options are available for the considered aircraft platforms. Figure 7 gives the implementation strategies for the conventional and the hybrid-electric aircraft.

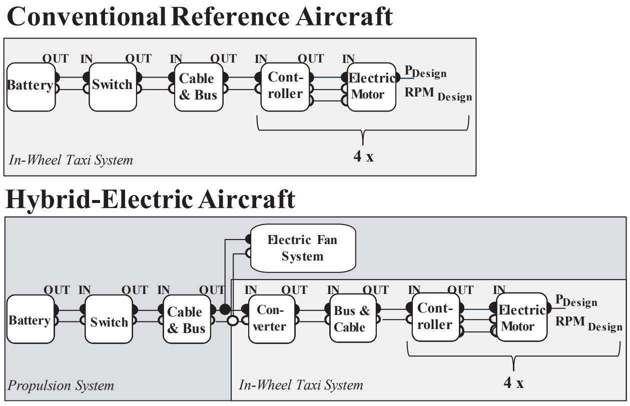


Figure 7: Integration of the in-wheel electric taxiing system in different aircraft platforms

For the conventional aircraft, the in-wheel system architecture has been designed as a standalone system that has a dedicated battery supply. Using the battery system for an operating time below 1h implies that the standalone battery system is sized for discharge rates or C-rates greater than 1. The C-rate is defined as the amount of electrical current the battery delivers based on its nominal capacity [20]. Normally high C-rates cause also high voltage drops within e.g. lithium battery cells and is proportional to an efficiency decrease. For that reason the standalone IWETS results in a mean electric transmission efficiency from battery to the motor shaft of 80.2%. The hybrid-electric aircraft platform has already a battery system installed for the main propulsion system. For that purpose the IWETS can be connected to the available infrastructure. The difference to the standalone system is the additional required step down converter (see bottom Figure 7). The converter transforms the 1500 VDC main power train voltage down to the subsystem voltage of 540 VDC. The considered battery system of the hybrid-electric propulsion system is sized for the provision of the necessary energy demand. For the hybrid-electric reference aircraft more than 12 tons of batteries are installed. This results in very low discharge rates of the battery cells during the taxi-phase and in turn enables high discharge efficiencies of more than 99% [20]. For that reason the integrated IWETS can achieve a higher transmission efficiency than the standalone system of absolute 83.8%. This higher battery efficiency is also overcompensating the additional required converter.

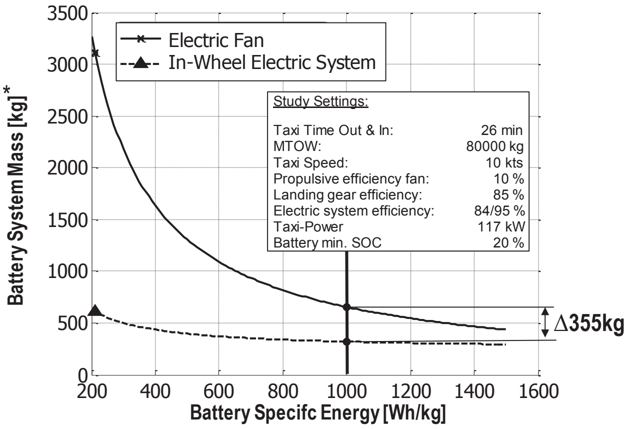
With a battery system the emission free-taxiing capability can be only locally achieved at the airport, if renewable electric energy is assumed. However, if not using renewable electric energy also a conventional electric energy generation causes a CO_2 footprint. This equivalent CO_2 is assumed to be 0.39 kg/kWh for an averaged global electric energy mix based on a projection to the year 2035 according to [32]. Beside the pure electric energy generation also the production process of the necessary batteries causes a CO_2 footprint. According to [32], a lithium battery designed for 3000 charging cycles emits an equivalent CO_2 of 69.20 kg/kWh. Combined with the electric energy production the equivalent CO_2 of a battery system can be assumed to be 69.59 kg/kWh according to [32]. For comparison the equivalent CO_2 of kerosene (well-to-wake) is 3.73 kg/kg_{Fuel} [32] assuming a CO_2 neutral tank system.

5. RESULTS

Based on the described methods the different electric taxiing options are compared on system and aircraft level with regard to overall system mass impact, MTOW change, block fuel and CO_2 reduction potential.

5.1. System Level Results

This section covers the comparison of the potential aircraft onboard ElTaSs on system level used for a hybrid-electric aircraft configuration. Figure 8 shows a trade study of different battery specific energies impacting the battery mass of an EDF ElTaS and an IWETS. For the EDF system only the required battery mass for taxiing is considered. The required component mass of the EDF system is already included in the MTOW. In contrast to the EDF, the IWETS includes the additional required component masses in the battery system mass to identify the reasonable system mass delta for electric taxiing capability.



** Includes additional required component masses of in-wheel electric taxiing system*

Figure 8: Comparison of the electric fan and the in-wheel electric taxiing system for different battery specific energies (reference 1000 Wh/kg)

The specific energy ranges from 200 Wh/kg representing today's battery technology level up to 1500 Wh/kg for potential future developments [33]. The IWETS shows a lighter overall system weight than the EDF option. This is mainly driven by the battery mass influenced by the overall system efficiency. The EDF system with an overall efficiency of 9% has a battery demand of 3300 kg at 200 Wh/kg and 650 kg at 1000 Wh/kg. The IWETS with an overall efficiency of 68% has a battery mass including the required system of 610 kg at 200 Wh/kg and 320 kg at 1000 Wh/kg. It is obvious that with increasing specific energy the battery demand is decreasing. The impact of the battery specific energy is higher for the EDF due to the more inefficient overall system than for the IWETS. But it can be recognized that an in-wheel electric system including the battery for current technology weighs around 600 kg for an Airbus A320 class aircraft.

A potential synergy effect of IWETS is the assistance during take-off using the installed traction force of the wheels. Figure 9 shows the impact of different design points of the electric motor on the resulting maximum and average traction force and overall system mass for the given aircraft parameters used for Figure 8.

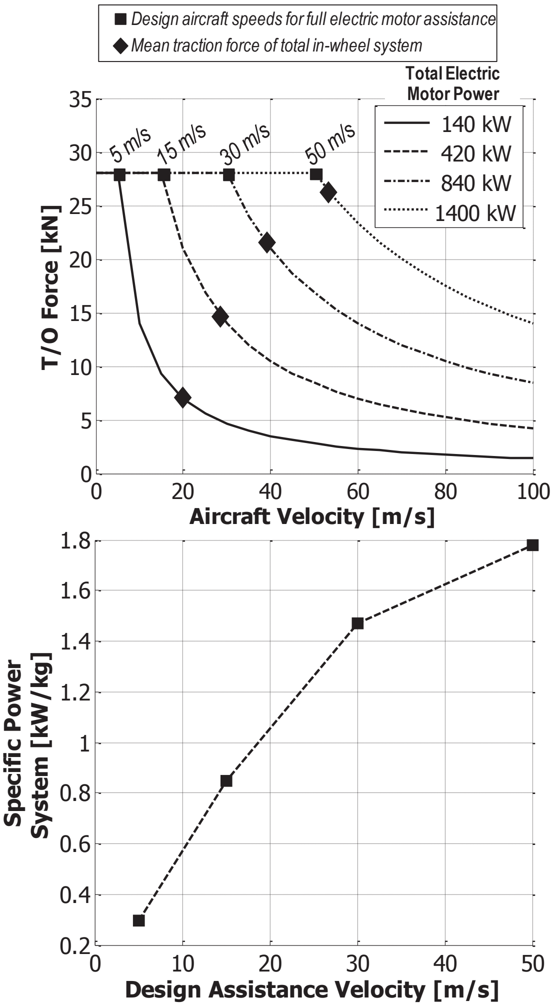


Figure 9: Impact of different design electric motor power and corresponding full traction force assistance speeds at constant DH for the total in-wheel electric system. Top: Force assistance for different design motor powers; Bottom: Specific power of the in-wheel electric taxiing system

As mentioned above, the required breakaway forces of an Airbus A319 are around 6 kN for an electric motor installed in the wheels of the nose landing gear. Therefore, the here calculated forces are large enough to set the aircraft into motion. When using the design point for taxiing as assistance power the maximum available traction force can be only used up to 5 m/s. Afterwards the system is limited by the maximum installed power. In this operation case the electric motor is operated in the flux weakening area. This can be also recognized by the average available traction force that is for this case 7.7 kN. For the present investigation a take-off speed of 75 m/s is assumed. Increasing the electric motor power results in a longer availability of the maximum traction force. Installing 1400 kW total power results in an average traction force availability of 26.3 kN equal to a DH of 11%. From a mass point of view the system shows an advantage by installing higher system power represented by the increasing specific power over the design assistance speed. This effect is mainly driven by the GB and the electric motor sized for maximum torque requirement in this operating area. However, the gradient reduces at 30 m/s caused by the sizing strategy change of the electric motor from torque to power. The total electric system mass increases by 320 kg from 140 kW to 1400 kW.

5.2. Aircraft Level Assessment

Based on the system level results, the different electric taxiing options have been analyzed on overall aircraft level focusing on possible aircraft onboard ElTaS options. Beside the hybrid-electric aircraft also the conventional kerosene supplied aircraft has been analyzed for a better comparison of the different options. As technology standard a battery specific power of 1000 Wh/kg has been set as technology target. This battery technology is also considered for the parallel hybrid-electric main power train. Table 4 (overleaf) summarizes the results of the different aircraft types and electric taxiing options. It can be recognized that an IWETS can already improve the aircraft performance of a conventional supplied aircraft. In this case a block fuel reduction of 2.3% compared to a conventional taxiing system can be achieved. However, this improvement comes along with a 1.3% higher MTOW. Due to the higher efficiency during ground roll the required taxi energy can be reduced by 97.2%. Assuming a non-renewable electric energy source the emission-free taxiing requirement can be not fulfilled. Nevertheless, the CO_2 generation can be reduced by 96.6%. However, this result is only valid if the production of the battery is neglected. Otherwise this additional CO_2 impact completely overcompensate the reduced taxi energy. Table 4 also includes the sizing effect of the conventional and the hybrid-electric aircraft when using a ground-based ElTaS in form of an ETV. With an ETV the block fuel of the conventional aircraft can be reduced by 4.1%. The hybrid-electric derivative shows a block fuel reduction of 2.8% compared to the onboard ElTaS.

In the baseline configuration the parallel hybrid-electric BHL Quad-Fan is generating the required taxi force with the help of the EDF. Due to the high part load conditions of the EDF during taxiing and the higher MTOW the required taxi energy is only reduced by 64.1% and the generated CO_2 by 54.9% compared to the reference aircraft. This impact can be improved by using an IWETS. With this system the required taxi energy demand can be reduced by 89.7%

Table 4: Results of different electric taxiing options for conventional and hybrid-electric aircraft for an entry-into-service year 2035, a specific energy of 1000 Wh/kg and design range of 1300 nm

	Conventional Aircraft			**Hybrid-Electric Aircraft**		
Taxi System	*Conventional (Reference)*	*In-Wheel Electric Taxiing*	*ETV*	*Electric Fan (Baseline)*	*In-Wheel Electric Taxiing*	*ETV*
System Mass [kg]	n/a	319	n/a	n/a	454	n/a
Taxi Energy [kWh]	2448	68	n/a	880	91	n/a
Taxi-Energy Mass [kg]	204	158*	n/a	880	91	n/a
MTOW [kg]	60361	61158	60331	82026	80466	79284
Block Fuel [kg]	4834	4728	4638	4728	4652	4595
Release Fuel [kg]	6187	6134	6031	5695	5603	5533
Battery Demand [kg]	n/a	158*	n/a	12601	11438	11221
Mission Energy [kWh]	74244	73608	72372	80941	78674	77617
Equivalent CO_2 Taxi [kg]	761	27	n/a	343	36	n/a
(with battery production)	n/a	10995	n/a	61239	6333	n/a
ΔMTOW [%]		(+1.3)	(-0.1)	(35.9)	-1.9 (33.3)	-3.3 (31.3)
ΔBlock Fuel [%]		(-2.3)	(-4.1)	(-2.2)	-1.6 (-3.8)	-2.8 (-4.9)
ΔTaxi Energy [%]		(-97.2)	(n/a)	(-64.1)	-89.7 (-96.3)	n/a (n/a)
ΔTaxi CO_2 [%]		(-96.5)	(n/a)	(-54.9)	-89.7 (-95.3)	n/a (n/a)

* battery mass sized for power requirements
brackets show delta to conventional reference

compared to the EDF option. In turn, the required battery mass reduces significantly that has to be carried through the entire mission and overcompensates the additional system mass of about 450 kg of the IWETS. Therefore, the MTOW of the hybrid-electric variant reduces by 1.9% and the block fuel by 1.6%. The equivalent generated CO_2 for taxiing can be reduced by the same amount as the energy saving. The main effect on the decrease of the energy demand is forced by the higher efficiency of the IWETS taxi option.

The in-wheel electric system can be used as synergy effect by assisting the aircraft during ground acceleration of the take-off phase. Figure 10 shows the result of the parallel hybrid-electric aircraft using the installed IWETS for different installed power demands indicated by the aircraft assistance speed. This study has been only performed with the maximum taxi traction force (DH 4.2%), which is equal to the elimination of the ground friction of the main landing gear during take-off as proposed by [9].

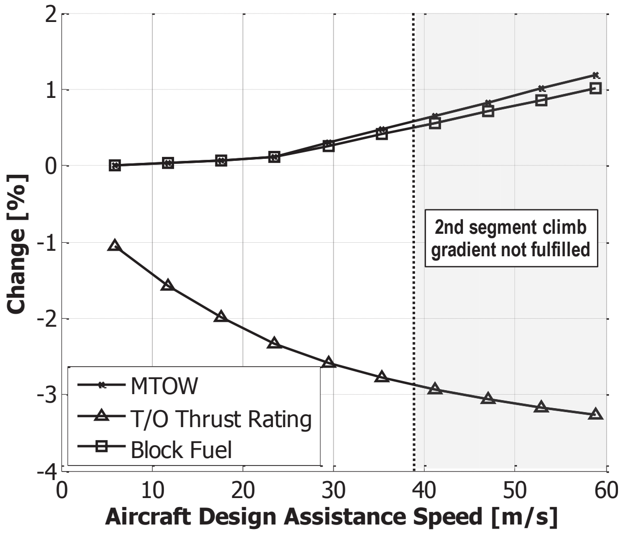


Figure 10: Impact of the usage of the in-wheel electric taxiing system during take-off ground acceleration on thrust rating, MTOW and block fuel for the parallel hybrid-electric aircraft configuration

In this study the assisted in-wheel electric power is used to decrease the thrust rating of the propulsion system during take-off by keeping the TOFL constant at 2056 m. This can be performed up to a maximum assistance speed of 39 m/s and a down rating of the propulsion group by 2.9%. A further increase in the assistance speed or force does not further improve the aircraft performance, because otherwise the installed take-off thrust is not sufficient anymore to fulfill the 2nd segment climb gradient during OEI. However, with this additional assistance option results in a MTOW increase of 0.6% and a block fuel increase of 0.5% when not redesigning the propulsion system. The increased MTOW is driven by the installed system mass. The kink in the chart at around 25 m/s indicates the sizing change of the motor system from torque to power sizing. Another possibility could be the reduction of the TOFL instead of reducing the take-off thrust. For a maximum speed of 60 m/s the TOFL could be reduced by up to 3.2%, however, resulting in a 1.2% higher MTOW and 1.0% higher block fuel.

6. CONCLUSION AND OUTLOOK

In this paper a detailed investigation of an in-wheel electric taxiing system has been analyzed motivated by an emission-free taxi requirement. The main focus has been set on the influence of such a system on a discrete parallel hybrid-electric aircraft concept powered by kerosene supplied geared turbofans and battery supplied electric fans for a year entry-into-service of 2035+. The design mission was set to 180 PAX and 1300 nm. It could be identified that for the present hybrid-electric topology the installation of an additional taxiing system including all necessary components is advantageous with regard to overall maximum take-off weight reduction of 1.9% and block fuel reduction of 1.6% compared to a baseline hybrid-electric aircraft platform using electric fans for taxiing. This is mainly driven by the higher efficiency of the in-wheel electric taxiing system during ground operation compared to an electric fan supply. Even a conventional kerosene powered aircraft would already benefit from an in-wheel electric taxiing system with 2.0% block fuel reduction, although an additional system has to be installed.

An initial estimation using the in-wheel system also for take-off assistance shows that the balanced take-off field length can be reduced by 3.2% or the required take-off thrust can be reduced by 2.7%, respectively. However, this additional effect comes along with a higher maximum take-off weight and block fuel. This use case can be a design option when balanced take-off field length requirement is a design driving parameter. For the more relevant case of downsizing the propulsion group the assistance system is limited by the one-engine inoperative case and has to be taken into account when sizing such a system.

For further work it has to be identified how an in-flight recharge of the battery system via generators at the engines can further increase the overall system performance. This recharging process can reduce the installed battery mass by sizing the battery system only for taxi-out. The recharge process would also not be sizing critical. However, this recharge process is just shifting the emission generation from ground to in-flight. During this study the in-wheel system is also used as push-back option at the airport. This capability will have an impact on the cash operating costs, because a push-back vehicle at the airport is not required anymore. Furthermore, this system can increase the lifetime of the tyres via using the installed system to pre-rotate the wheels before touch down during landing. These design options in combination with a higher maximum take-off and landing mass have to be considered in future work to fully identify the potentials of an in-wheel electric taxiing system on a cost basis. For medium and long range aircraft onboard systems may not be a suitable solution, because the portion of the taxi phases are significantly reduced in contrast to the overall mission length.

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