OPERATION AND PERFORMANCE EVALUATION OF NOVEL ELECTRIC-WHEEL-DRIVEN HYBRID-ELECTRIC PROPULSION SYSTEMS ON STANDARD SHORT RANGE PASSENGER AIRPLANES

M.C. Schwarze, Munich, DE
renew.innovation@email.de

Abstract

In the scope of this technical paper a novel approach in the implementation of a hybrid-electric propulsion system is investigated on a standard short range airplane, in which the thrust of the aircraft engines is effectively combined with an electric-driven wheel propulsion system while the aircraft operates on the ground. The general system architecture, which could be effectively combined with Electric-Taxi systems, is shown both in principal and in detail with four sample architectures, including detailed weight estimation of the present and future system. Finally the impact of the E-Wheel system on the overall aircraft performance is evaluated. In this context the overall aircraft performance covers the field performance, mainly referring to the take-off and landing field-length, the accelerate-stop distance, the maximum payload capability and the impact of the system on overall fuel burn of the aircraft on standard short range missions.

1. INTRODUCTION

"Slightly a couple more than 100 years after the first successful powered flight the commercial aviation has become a pacesetter both of the globally cross-linked community and the international trade. Being aware of this key function as well as its responsibility for globalization, the aviation industry sector has committed to ACARE 2020 and Flightpath 2050 in order to dramatically decrease aircrafts' fuel consumption and emissions. These commitments however are in line with the particular and vital economic interests of the aviation sector, as profit margins has shown to be severely decreasing due to sustainable rising fuel prices. As a consequence motivation has been kept high to cut down fuel consumption and emissions of modern commercial aircraft thereby saving the sustainability of the aviation's business model as well as the environment.
One potential key element in an efficient strategy towards reduced emissions and fuel consumption could be the application of hybrid electric propulsion systems. The latter have already proven to be both feasible and beneficial widely on hybrid-electric road vehicles on the one hand and sporadically in today's General Aviation segment on the other hand."[1]

2. ELECTRIC TAXIING

"Electric driven wheel propulsion has silently entered the stage of commercial aviation by electric taxiing systems which are in discussion and under examination for standard short range passenger airplanes by companies like Airbus, Honeywell, Safran, Messier-Bugatti, L3, Lufthansa Technik and Wheel Tug.
The existing systems, some of them already tested in operational circumstances, enable the aircraft to taxi autonomously forward and reverse at low velocities by electrical motors while the main engines are kept shut down. Benefits of such a described taxiing system include significantly reduced or even no emissions, increased maneuverability, autonomous pushback and a significantly reduced fuel burn. Fuel savings on standard missions of a typical 150-seat short range aircraft, already considering the weight penalty of 400-750 kg of such a system, are within 3 to 7 % "…[2]" of the same order as modern winglets installations.
In this context two general technological architecture approaches for electric taxiing are shortly presented.
In the scope of the first principal architecture the wheels of the nose landing of the aircraft are driven by electric motors. For instance a test aircraft, ATRA (Advanced Technology Research Aircraft), of the DLR (German Aerospace Center), an Airbus A320, was equipped with a modified nose landing gear. Within the hub of each nose wheel an electric permanent motor assembly had been installed, driving the wheel via a two-stage planetary gear during taxiing by a gear ratio of 1:12 "…[3]". The taxi velocity at typically ramp operating weights of the aircraft was limited to about 15 kts by the power supply that was provided by an onboard high temperature fuel cell, which was hydrogen-fueled and stored within a special container within the cargo compartment. At a typically tricycle landing gear configuration of commercial transport aircraft the main landing gear supports about 90-95%
(WF: 90-95%) of the aircraft's weight while only 5-10% of the weight applies to the nose landing gear which limits the maximum transmissible traction at the nose wheels, especially when exposed to challenging surface conditions (for the Weight Factors please also see Fig. 1).

A second principal architecture therefore uses the main landing gear's wheels for electric wheel drive. In the scope of the "Green Taxiing" cooperation a Lufthansa Airbus A 320-200, registration D-AIZF, was retrofitted with two electric motors at the main landing gear of the aircraft. Each outer wheel both of the left and the right main landing gear was driven by a hub-mounted synchronous machine via a planetary gear with a transmission ratio of about 1:10, which was integrated in the rim of the wheel together with the electrical motors. The electrical motors were powered by the APU driven electrical generator of the aircraft. The maximum taxing velocity was limited because the off take from the aircraft's auxiliary power unit was restricted to 2/3 of the maximum electric off-take, featuring 90 kW, while the rest of the electrical power generation was foreseen for the aircraft's systems like avionics, control-systems and lighting."[1]

3. IDEA AND GENERAL ARRANGEMENT

"Once these electric taxi systems are installed and in use on standard passenger aircraft, enhancing the fuel and emission performance during taxi, but increasing their operational empty weight by 1-2 %, the question obviously arises, why these electric systems are not additionally used for further ground operation phases of the aircraft of higher velocity, especially during the take-off run and landing run.

of the main landing gear either directly or via a reduction gear, for instance a planetary gear. In contrast to aircraft using electric motors only for taxiing, the motors are of a suitable rated performance level, so that they can beneficially be used for the aircraft's operating phases of higher velocity and performance, especially during the take-off and landing run. " [1]

"To better quantify and evaluate the effects of said hybrid-electric propulsion system an appropriate performance-parameter should be defined to identify the proportion of electric thrust in reference to the conventional thrust of the main engines. As the conventional thrust lapses according to the specific by-pass ratio of the aircraft's engines with speed, increasing during the take-off run it is fundamental, to find a constant level of conventional thrust as a reference to refer to. Consequently the acceleration-effective electric thrust level during the aircraft's ground

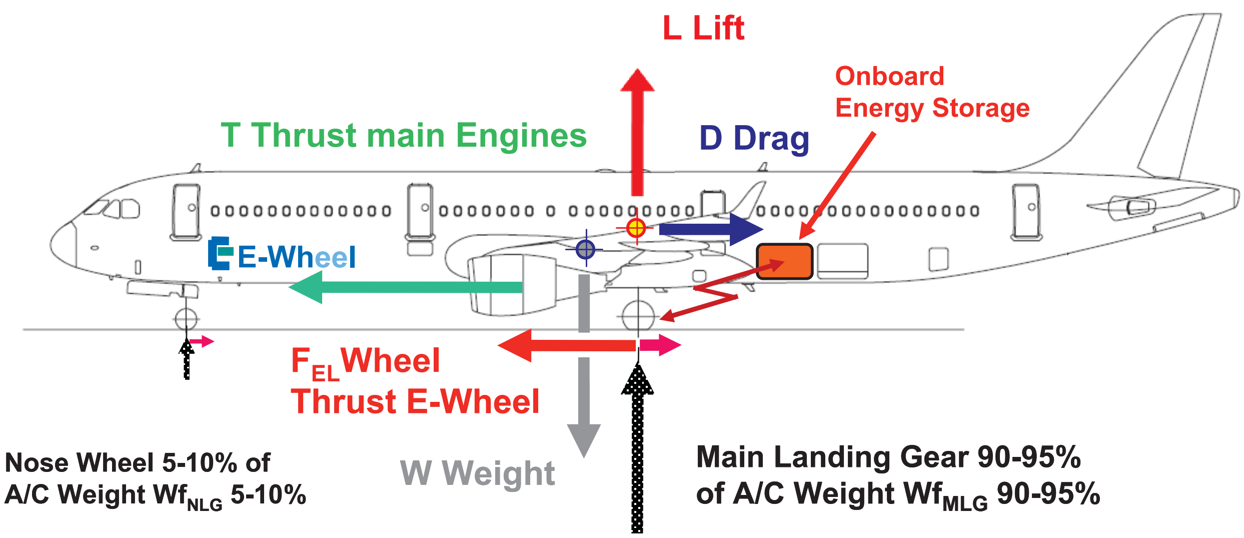

FIGURE 1. Forces and Weight Factors, affecting the E-Wheel system, here shown for take-off [1]

By this means the emission performance and especially the field performance of the aircraft can be significantly enhanced without relevantly adding weight. Hence this paper proposes a parallel hybrid-electric propulsion system (E-Wheel) to flexibly and efficiently combine the electric wheel drive with the trust of the conventional main engines at certain operating segments of the aircraft. This novel implementation of a hybrid-electric propulsion system is therefore investigated on a typical standard short range airplane with around 150 seats capacity. Besides improving the aircraft's overall efficiency on the ground, this hybrid-electric system enhances the field performance of the aircraft, optionally provides electric taxiing and enables to recover a certain share of the kinetic energy of the aircraft during landing corresponding to the function of a Kinetic Energy Recovery System. The electric energy used for take-off and recovered from landing run is stored in a high power electrical storage device, preferably consisting of super capacitors with high current ability. During taxing the electric wheel drive can be supplied by the APU.

Integrated in the aircraft the overall hybrid-electric architecture of the electric propulsion system comprises the energy storage device, power electronics and several electric motors installed at the main landing gear of the aircraft. Corresponding to the concept of distributed propulsion, each electric motor propels at least one wheel

run is chosen to be measured in reference to the maximum static take-off thrust level of both engines. The degree of hybridization (DH) in percent should therefore be defined as the integrated effective per wheels transmitted propulsive and electrically originated force, divided by the maximum static take-off thrust level of both main engines at standard conditions at sea level. If the electric thrust is a function of time respectively speed e.g. predetermined by the characteristic momentum-speed curves of the effective electrical motors, the propulsion-effective force level can be found by integrating the electric wheel thrust over time respectively speed for the entire time period of the acceleration ground run while the electric system is in use. The electric thrust level will be later on translated in a corresponding power level of the electric motors, taking into account the electrical drive train's efficiency, a potential reduction gear ratio as well as the speed momentum characteristics of the specified chosen electric motors.

The electrically generated thrust, transmitted by the motorized wheels, can be forward – facing e.g. during take-off run or for electric taxi. Contrariwise the electrically generated force can be reversed by providing suitable moments by the electrical motors, contributing to the effective braking force of the wheels during landing run or rejected take-off (RTO) or alternatively enabling the

aircraft to taxi backwards for instance during autonomous pushback.
Depending of the operation mode of the system the electric wheels can additionally contribute to the effective, overall thrust level as a sum of electric and conventional thrust. For example it can enhance the acceleration at the take-off-run or enable to accelerate a higher operating mass of the aircraft on a constant take-off distance. In a

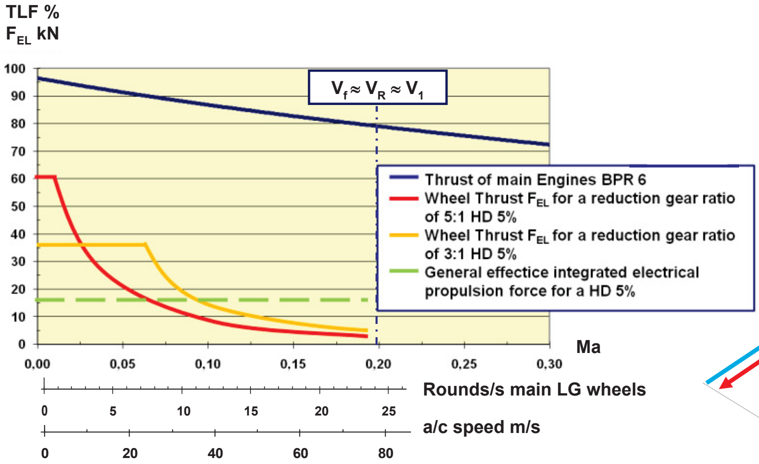

FIGURE 2. Thrust Lapse of the main engines BPR 6, the speed-dependant electrically generated forces are considered by an integrated effective propulsion force for a certain DH [1]

differing operating mode the electrical wheel drive can be used to substitute a proportion of the conventional thrust, permitting the aircraft to either take-off generally with de-rated conventional thrust or to further increase an already present derate-level on a fixed thus unchanged original take-off distance. For some employments of the hybrid-electric propulsion system further limitations, like climb requirements have to be taken into account.

For the take-off run the electrical wheel drive system will only be used during the ground acceleration segment $S_{G,TO}$ up to about a speed in the range of the characteristic decision speed v_1, and not for the following rotation ($S_{R,TO}$)- and transition section $S_{T,TO}$ of the take-off. The reason is that the lift of the aircraft is rapidly increasing with rising angle of attack during rotation, counteracting against the weight and therefore inadequately reducing the maximum transmissible wheel thrust, which is proportional to the normal force F_N. Additionally it will probably not be suitable to use the electric wheel thrust of the system beyond speeds approximately equaling the decision speed due to safety reasons. Thus at the time when a defect should occur within the electrical wheel propulsion system, the take-off can be aborted in any circumstance before exceeding v_1. As a matter of course the electric thrust can only be used in operation phases of the aircraft, in which the main landing gear is generally ground touching.
For the landing sequence the electrical wheel drive system will be used during the deceleration-run $S_{G,L}$ directly after derotation, starting optional brake-operation approximately when the nose landing gear touches the ground." [1]

4. REFERENCE AIRCRAFT

"As a Reference Aircraft an Airbus A320-214 with CFM56-5B4 engines, in total delivering 240 kN of static Take-off Thrust, was chosen. The MTOW of 77000 kg refers to the highest weight version of the aircraft currently available. The normal landing procedure can be applied up to a

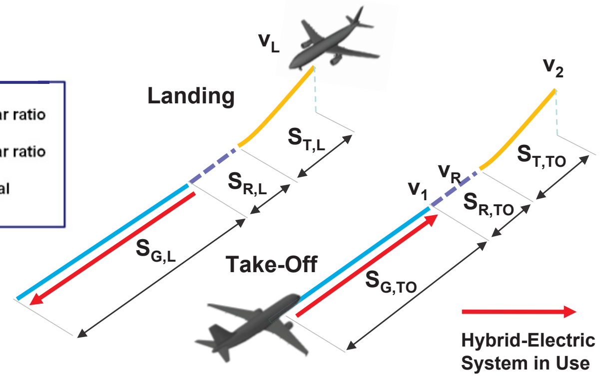

FIGURE 3. The E-Wheel System is used during ground acceleration/ deceleration segments of Take-Off TO and Landing L [1]

maximum landing weight MLW of 64500 kg. The original maximum payload capability equals 19200 kg." [1,12]

5. SYSTEMS ARCHITECTURE

"Figure 4 shows the general arrangement of the E-Wheel system in principal. The System consists of the onboard energy storage device, preferably made of super/ ultra capacitors or alternatively of Li-Titanat accumulators.

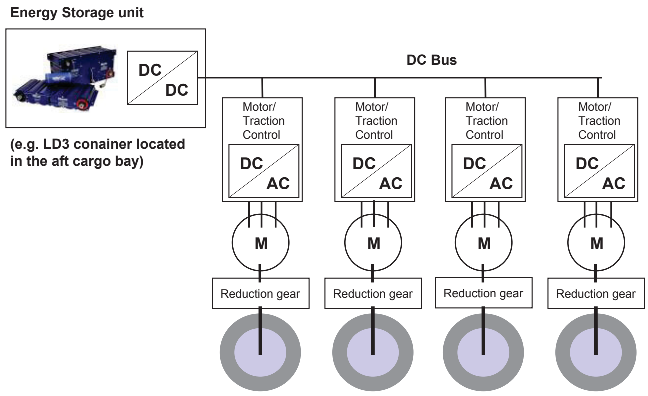

Figure 4: Principal system layout of the E-Wheel system (simplified)

The energy storage device can be advantageously stored in the aft cargo bay in direct vicinity to the main landing gear and can be loaded and unloaded according to demand. If capacitors are used there is a DC/DC converter which converts the variable voltage output of the capacitors to a certain stable voltage output level. It additionally organizes the charging process of the cell assembly when the system is run in energy harvesting

mode. The DC voltage is fed to the electric engine controllers, which internally might contain further advanced electronics like traction- and anti-skid control. The electric motors are driven by its engine controllers with AC-variable frequency and output voltage. The main landing gear wheels are propelled via a reduction gear unit, if no direct drive solution is foreseen.
While the DC/DC converter can be placed at the energy storage unit, the engine controllers might be also directly situated at the main landing gear or can be attached to the electric motors"[15].

6. THE ONBOARD ELECTRICAL STORAGE DEVICE

"The functionality of the onboard electrical storage device is to deliver sufficient power for traction to the electrical motors during the time period of the take-off acceleration run. The required electrical power as well as the resulting energy for the take-off run at MTOW depending on the degree of hybridization (DH) is shown in figure 5, already considering an efficiency of the electrical energy storage device of 0.9 as well as an overall electrical efficiency of the drive train of 0.74 [1]. An efficiency of 0.9 is a typical value for an energy storage device, obtained by high power, high capacity super and ultra capacitors [4], which might be preferably chosen as energy storage devices within this application. If electric energy should be harvested during the landing run, the electric storage device must at the same time be capable of absorbing high amounts of power from the electrical motors being run in generator mode during deceleration. This harvested energy could then be reused for energizing the electrical motors for the subsequent take-off run or for electric taxiing. The orange curve (with triangles) in figure 5 shows the minimum energy, which can be recovered from the landing run at MLW and which can be effectively reused for take-off at MTOW, taking already into account the electric drive train's efficiency for round trip use. The share of this energy, currently around 40 % [1]of the energy needed for take-off, could be enhanced in future up to values up to 60 %. The
combined requirements from take-off and landing lead to the main requirement of a high current respecting a high power capability of the electrical storage device. Stored onboard, the storage device should be of minimum weight, therefore requiring both advantageous gravimetric energy and power density as well as an acceptable volumetric energy density for occupying minimum volume on the airplane.
During the take-off run the power demand will be gradually rising with increasing speed up to a peak power value stated in figure 5. However the peak power is only reached for a few seconds, which bears the potential of minimizing the weight of the electric motors by accepting electrical overpowering of the motors for a certain short period of time. The amount of energy needed is the consecutive multiplication of power applied and time divided by the overall electric drive train's efficiency.
The requirements for the storage device for take-off can be already fulfilled with state-of the art high power accumulators like Li-Titanat types, which offer a high gravimetric power density of around 4 kW/ kg [6] together with high current capability. Compared to Lithium-Ion and Li-Po accumulators they offer a safe operation, without the hazards of over temperature, overloading, fire and explosions [6]. They are not sensitive to vibrations and do not loose electrical energy storage capability by increased cycle use. Furthermore they can be operated within the temperature range of -50 to plus 75° C [6] and can be reloaded to 90 % of its complete capacity in less than 10 minutes [6]. Their penalty of relative low specific energy is not relevant in this application, because due to the short time of take-off and landing run the power requirement is dominant over the energy requirement, which makes this accumulator type in general best fit for this application. Unfortunately one disadvantage remains. Although the loading time is significantly decreased compared to conventional battery types, charging time is not short enough to adequately receive and store the power and energy levels harvested from landing run.
Thus for enabling energy harvesting at landing enhanced energy storage devices known as super or ultra capacitors might be used. Super capacitors in general provide high power levels for a short period of time with the penalty of low specific energy, which makes them best fit for this application. As the ragone plot, Figure 6, shows, enhanced hybrid Lithium state-of the art capacitors reach specific gravimetric power densities of 3-6 kW with

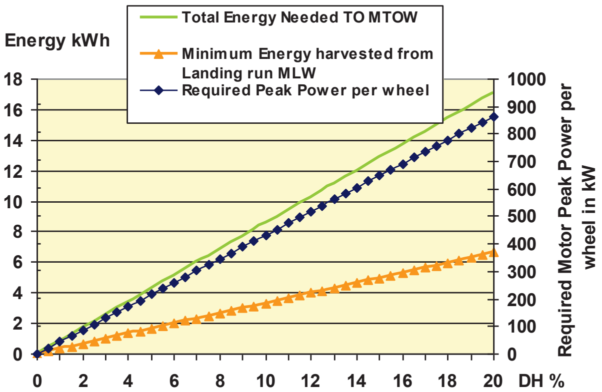

FIGURE 5. Power and Energy required for a take-off at MTOW depending on the DH and minimum energy recovered from landing deceleration run at MLW [15]

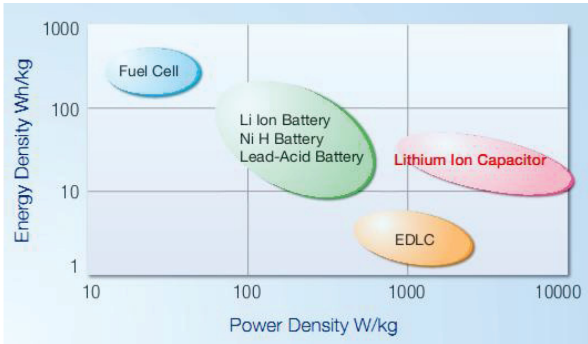

FIGURE 6. Ragone plot: typical values for specific power and energy obtained for modern hybrid super- / ultra capacitors compared to other storage technologies [5]

	Specific Energy Density	Specific Power Density	Volumetric Energy Density	Charging time	Storage duration time	Recuperation	Source
Near Future Super-/Ultracap	15 W h/ kg	3 k W/ kg	20 W h/l	Seconds to minutes	Hours to days	possible	[4,5,7,8]
Current Li-Titanat Accumulator.	80 W h/ kg	4 k W/ kg	-	around 10 minutes	Months	Impossible due to long charging time	[6]
Medium Future Super/-Ultracap	25 W h/ kg	6 k W/ kg	> 20 W h/l	Seconds to minutes	Hours to days	possible	[4,5,7,8]
Distant Future Super/-Ultracap	60 W h/ kg	100 k W/kg	> 20 W h/l	Seconds to minutes	Hours to days	possible	[4,5,7,8]
Current/ Future Advanced Flywheel	100 W h/ kg / up to 800 W h/ kg	1-5k W/kg / 5-9k W/ kg	-	Minutes/ seconds	Hours to weeks	Eventually/ possible	-

TAB 7. Characteristic parameters of present an future expected upcoming energy storage devices [15]

specific energy densities of 5-20 W h/ kg. However, significant improvement in both power and energy densities is expected for the upcoming future [4], as a consequence of intensive research. For the future specific energy density is expected to rise significantly, boosted by the research activities especially for automotive hybrid-electric engine architectures. In today's laboratories energy densities up to 85 W h/ kg [4] and power densities up to 100 kW/ kg [7] have been reached especially because of innovative electrode materials like new carbon- nano structures. For the future this indicates that significant weight decrease can be expected, resulting in an eventual drop of the weight of the energy storage device by a factor of 3 - 4. Hence, for the distant future the energy storage device's weight could be only have one quarter of today's weight.
Super cabs do have further advantages for airborne applications. They are not sensitive to vibrations, in contrast to accumulators they do not loose electrical energy storage capability by increasing cycle use and their efficiency stays stable independent from the current out- and intake levels [5]. Furthermore they can be safely operated under temperature conditions ranging from minus 30° C to 70° C [5] without remarkably loosing efficiency nor capacity, which is a further plus comparing it to a conventional accumulator. For a time about 4 to 5 years with permanent operation they do not need any maintenance nor replacement [4].
Above all their charging and recharging time lies in the area of seconds to minutes, which is ideal for high power applications during take-off and landing and which of course also guarantees complete recharge within the turn-around time or also during taxiing (e.g. by charging by the APU). Like Li-Titanant accumulators they are self-secure, which means that there is no danger of fire or explosion if they are protected against overloading, which is easily technically feasible. In comparison to batteries capacitors have no stable output voltage. The output voltages is depending on the charging status and reaches values of 2-4 V, which is in peak slightly higher than today's common single batteries cells (3.7 V). Because of their variant voltage output they need special energy management electronics, including a DC/ DC converter which converts the various DC voltage to a stable voltage output level and organizes the charging when the system is in energy harvesting or charging mode. The impact of the more complex power electronic is considered by doubling the power specific weight of the controller and power electronics
(see Table 13). Table 7 shows characteristic parameters of current and expected future energy storage devices, also including current and future advanced flywheels" [15].

6.1 Weight of the energy storage devices

"Figure 8 combines the information given in figure 5 and table 7 and shows the resulting weight of present and future expected energy storage devices depending on the degree of hybridization (DH) chosen. The black dotted line shows analogically to diagram 5 the capacity needed in kWh dependent on the (DH) chosen.

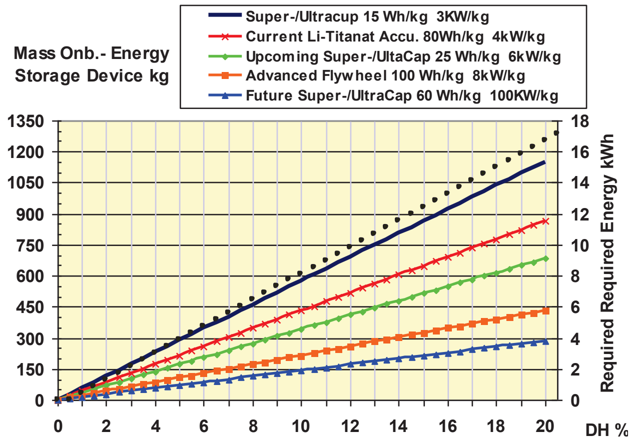

FIGURE 8. Resulting present and future weight of the energy storage device dependent on the type of energy storage device and DH chosen. The black dotted line shows in general the required energy to be stored depending on the DH chosen (right hand scala) [15]

The table also refers to Flywheel technologies. Flywheels store their energy mechanically by a flywheel with a certain moment of inertia which is kept in rotation at very high speeds. Energy can be extracted and added to the system, resulting in a droop respectively a rise in rotation speed of the fly wheel. If peak energy outtake and intake is high enough, the flywheel could also be used to harvest energy from landing run. This is currently realized in modern KERS Kinetic Energy Recovery Systems, used in Formula One. Future advanced fly wheels with high super conducting magnet levitation bearings and advanced hubless composite material architectures are expected to reach high specific energy densities, but eventually bear the risk of hazardous uncontained disk failure with potential effects at worst being approximately similar to uncontained engine failure" [15].

7. THE ELECTRIC MOTORS

"Corresponding to the concept of distributed propulsion, multiple electric motors propel the wheels of the main landing gear either directly or via a reduction gear, for instance a planetary gear. "In contrast to aircraft using electric motors only for taxiing, the motors are of a suitable rated performance level, so that they can beneficially be used for the aircraft's operating phases of higher velocity and performance, especially during the take-off and landing run."[1]

relevant for the safe operation of the system refers to the free wheel drive. In free wheel mode there remains a remarkable mechanical resistance due to the permanent magnets, still being active, eventually slightly affecting the aircraft's take-off performance if the systems is deactivated.
The second general motor type is known as the asynchronous induction motor ASM. It does not contain any permanent magnets which could demagnetize and therefore is easier to be integrated at the MLG for wheel propulsion. It normally tends to be slightly heavier than the PSM as well as it needs more volume. One relevant advantage is its natural free wheel drive. If the motor is de-energized, there is no relevant mechanical resistance left, except the resistance of the bearings which is negligible. The electronic control of an ASM is current

Figure 10: Tesla Electric Roadster Sport electric motor, peak power 225 kW, 32 kg, here shown with mounted flanges [15]

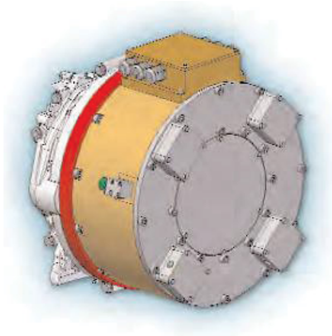

Figure 11:The L3 Magnet Motor G 35, peak power 280 kW, can with-stand accelerations up to 50g [10]

Figure 12: The Plettenberg Nova 150 reaches a peak power of 150kW with a weight of just 11.5 kg [11]

Electric Motor	Peak Power kW	Peak Moment	Specific Weight	Dimensions Diameter x Depth Volume l (dm^3)	Weight	Remarks	Source
Architecture I Tesla Electric Roadster Sport Electric motor	225	400 N m	7 K W/kg	Best estimate around 400 x 400 mm exact dimens. unknown 50.0	32 kg	Air cooled ASM	[9]
Architecture II L3 Magnet Motor G 35	280	1120 N m	2 K W/kg	444 x 231 mm 36.0	139 kg	Liquid cooled PSM torque motor	[10]
Architecture III/IV Plettenberg Nova 150	150	250 N m	13 K W/kg	310 x 105 mm 8.0	11.5 kg	Liquid cooled PSM torque motor	[11]

TAB 9. Characteristic parameters and performance of the specific used electric motors [15]

The motors' weight and characteristics are highly dependent on the specific type of engine chosen. Basically there are two suitable electric motor types. The permanent synchronous motor (PSM) offers the advantage of high volumetric specific power but demands costly lanthanide series for its permanent magnets. It can be easily electronically controlled but its permanent magnets can be demagnetized when exposed to overpowering or high temperatures, e.g. as a result of overload operation. This creates a challenge for integrating the motor at the main landing gear wheels, where the mechanical wheel brakes are situated within the rim, whereas modern carbon brakes are rated to temperatures up to 2000° C and heat up at normal landing up to around 300° C. A potential disadvantage

state of technology but in general requires more efforts for establishing and calibrating the motor control. Additionally the overall motor efficiency might be slightly less than with a PSM. An advantage results from the natural architecture of the ASM. The moment of the motor is dependent on the slip of the rotor, which makes it easier to implement traction control and anti skid solutions.
For modern highly efficient electric motors an efficiency of 90-95 % is reached both for traction and for energy harvesting in generator mode" [15].

8. WHEEL PROPULSION ARCHITECTURES

“In general for the installation of the electric motors at the main landing gear three different architectures are possible” [15].

8.1 Direct Drive

“With a direct drive the electric motor is directly coupled to the MLG wheel without a reduction gear. This solution is generally feasible because the system’s use for enhancement of the take-off and landing performance does not indeed require a high moment, because overcoming of the brake away operation for taxiing can be done by the aircraft’s main engines which are used in parallel. However if the E-wheel drive should additionally cover autonomous electric taxiing this demands for extremely high torque electric motors. For an Airbus A320-200 at maximum ramp weight for each of the four wheels an overall momentum of 5.3 k Nm is necessary to overcome the break away moment for electric taxiing. This value however appears extremely high. Nevertheless with current modern vehicle technologies the brake away moment could be overcome without reduction gears e.g. with the Siemens Syntegra technology at subway trains. In spite of that a large volume is to be expected to result either in a large required diameter or depth of the electric motor, complicating the engines’ installation. Hence this type of architecture is not further discussed in the scope of this paper”[15].

8.2 Single Electric Engine with reduction gear

“Corresponding to the concept of distributed propulsion this architecture means that one electric motor propels exactly one wheel. The reduction gear unit is e.g. formed by a planetary gear.
The electric motor can be placed in the vicinity of the wheel with variable orientation. Alternatively the motor can be placed within the MLG wheel’s rim, either on the inside (that means normally that the brakes have to be dismantled or an enhanced integrative solution has to be considered) or on the outside. Special attention has to be taken to avoid any unfavourable mechanical or temperature related interference of the mechanical brakes with the electric motors. For an unlikely but generally thinkable jam of the reduction gear an additional and optionally activatable free wheel drive solution should be foreseen” [15].

8.3 Multiple Electric Engines with reduction gear

“Within this solution multiple electrical motors are installed in a circular patter coaxial to the gear axis at every main landing gear wheel. The drives shafts of every single electric motor are coupled via a bevel pinion on a common gear ring with exterior or interior toothing. This gear ring is connected in a coaxial way to the rim of the main landing gear wheel. An optionally activatable free wheel drive solution should be foreseen. A free wheel drive would be a last option for an extremely unlikely but possible event that the geared drive shaft of one electric motor would be jammed in the gear ring or within an electrical motor an internal serious jam should occur. Being in free wheel drive e.g. the electric motor mounting assembly will rotate freely with the wheel” [15].

9. SAFETY CONSIDERATIONS

“The last discussed architecture not only implies distributed propulsion among the wheels of the main landing gear but also provides distributed propulsion by several motors at every single main landing gear wheel. This leads to several advantages, mainly affecting the operationabiliy and the safety of the E-Wheel system.
If an electric motor fails, with five motors per wheel (later described in architecture IV) this means only a negligible loss in wheel thrust thus aircraft performance. With one electric motor failure thrust droops by 2.0 kN which means a change in maximum overall thrust level of the aircraft of - 0.7 %. With the unlikely case of a double failure of two electric motors at the same time thrust decreases by only - 1.5 %. If one of the four tyres of the main landing gear bursts during the take-off run the overall thrust decreases by - 3.7 % in reference to the maximum static thrust. Take-off can than be optionally aborted if needed, which will be the normal case also for an aircraft without an E-Wheel system encountering this conditions. But in view of the resulting thrust droop it would be also possible to continue the take-off in most cases.
In view of the thrust droop asymmetric wheel thrust could be handed on the runway at any time, because asymmetric thrust resulting from an engine failure of a twin aircraft is required to be safely hand able at any time by regulations (see also v_{MCG} speed for minimum ground control for details) and the trust of one main engine is around 2.5-10 times higher than the complete wheel thrust applied by all wheels.
If a serious failure occurs within one of the components of the E-Wheel systems, the take-off run can be aborted at any time because the wheel thrust will only be applied until shortly before reaching v_1, the decision speed. Additionally advanced electronics like traction control, anti-skid and ESP functions could be combined with real time health and integrity monitoring of the system as well as wheel thrust asymmetry detection.
A further benefit of the discussed architecture refers to the weight–efficient utilisation of material, especially for the gear. The distributed generated moments of the five motors are introduced to the gear ring well distributed over its total circumference, meaning that five times every 72 ° a moment of just 250 N m is brought into the structure of the gear ring and the rim. With a single motor a corresponding momentum of 1 k Nm would be introduced to the gear at one single point of the structure, which would be certainly mean more weight and also creates a single point of failure” [15].

10. SAMPLE WHEEL PROPULSION ARCHITECTURES

“In this section four sample wheel propulsion architectures are studied in principle, ranging from a degree of hybridization of 5 % to values up to 17 %. For these architectures table 9 gives information on the characteristic parameters of the motors being used. Figure 10-12 shows photos of the chosen motors.
The take-off and landing run at corresponding maximum weight of the aircraft only lasts about 35 s.

Hence the peak power of the electric motors is only encountered at a minimum share of this time and just at maximum speeds of the aircraft, which reach up to 280 km/ h at take-off. Therefore it is expected that the electric motors do not need any further cooling than by the surrounding air flow, which is just effective at higher speeds. This might also account for electric motors which are originally designed for liquid cooling.

	Motor best efficiency	moto rmax rpm	Number of motors used Total Peak Power	Installation / Compatibility with E-Taxi	Overall Motors' mass	gear ratio	DH reached
Architecture I Tesla Electric Roadster Sport Electric motor	88-90 %	1400 0	4 - one per wheel 900 k W	To the outside within the ouside main landing gear wheel's rim / E-Taxi with additional auxiliary Nose Landing Gear Motor	128 kg	10.8 :1	5.2 %
Architecture II L3 Magnet Motor G 35	n.a. around 96%	4400	4 - one per wheel 1120 k W	Within the main landing gear wheel's rim / E-Taxi with additional auxiliary Nose Landing Gear Motor	139 kg	3.4 :1	6.5 %
Architecture III Plettenberg Nova 150	95 %	6000	16 - four per wheel 2.4 MW	In a circular matrix attached to the outside of the MLG wheel's rim / E-Taxi with additional auxiliary Nose Landing Gear Motor	184 kg	4.6 :1	13.9 %
Architecture IV Plettenberg Nova 150	95 %	6000	20 – five per wheel 3.0 MW	In a circular matrix attached to the outside of the MLG wheel's rim / Full autonomous E-Taxi with current architecture	230 kg	4.6 :1	17.3 %

TAB 13. Details and characteristics of the four five E-Wheel Propulsion architectures, as well as DH reached [15]

The following table 13 gives details on each of the four sample wheel propulsion studies examined at the Airbus A320-200.
The gear ratio of the reduction gear is adjusted according to the maximum rated speed of the electric motors to prevent overpowering. The electric wheel thrust will thereby be applied up to a speed, approximately equalling the speed of V_{EF} (speed of engine failure recognition) which is slightly less than the decision speed v_1 and around 72 m/ s equalling 260 km/ h at MTOW conditions. If electric taxiing is additionally desired, the architectures I-IV need an additionally small electric auxiliary motor at the nose landing gear wheel to overcome break away moment also under critical conditions. Architecture V in contrast is fully capable of electric autonomous taxiing without auxiliary taxi motor" [15].

11. WEIGHT OF THE REDUCTION GEAR, POWER ELECTRONICS AND ACCESSORIES

"For the E-wheel system's overall weight, additional weight due to the reduction gear, the power electronics and engine control and the accessories has to be taken into account. The accessories should here cover all remaining parts like cabling, clamps, engine mountings and the structural casing of the energy storage device. It also contains the weight of a LD3 container for the housing of the energy storage device, which equals 80 kg. The electronic energy storage system which has the function of a battery management system is included in the weight of the power electronics which has been effectively doubled, also because of the necessary DC/ DC voltage converter. Table 14 gives an overview about the masses and specific masses of the components used for estimating the weight of the system's for the present, medium and distant future. While for the energy storage device significant reduction in weight is expected for the future, the masses of the electric motors and the reduction gear are kept unchanged because they nowadays already present a high degree of optimization with rather minor potential of future enhancement" [15].

	Current System's Mass	Medium Future System's Mass	Distant Future System's Mass
Reduction Gear	6.5 kg/ N m	6.5 kg/ N m	6.5 kg/ N m
Electric motors	13 kW/ kg [11]	13 kW/ kg [11]	13 kW/ kg [11]
Controller/ Power Electronics	2 times 0.0425 kg/ kW → 0.085 kg/ kW [13]	2 times 0.0175 kg/ kW → 0.035 kg/ kW [13]	2 times 0.0175 kg/ kW → 0.035 kg/ kW [13]
Accessories	220 kg	200 kg	200 kg

TAB 14. Current and medium and distance future (specific) weights of further E-Wheel components [15]

12. OVERALL SYSTEM'S WEIGHT

"By adding the components weight of energy storage device, electric motors, power electronics, reduction gear and accessories the overall system's weight can be now

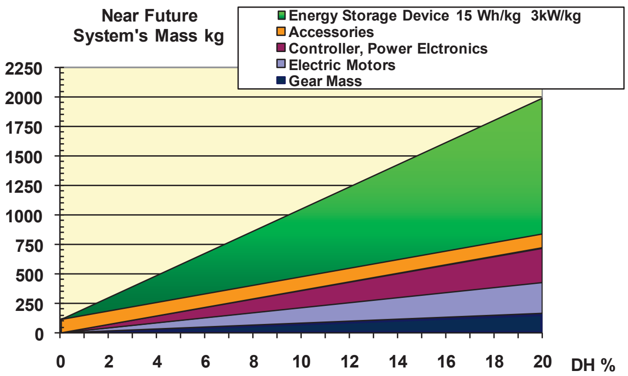

FIGURE 15. Mass of the E-Wheel System with near future super capacitors depending on the DH chosen [15]

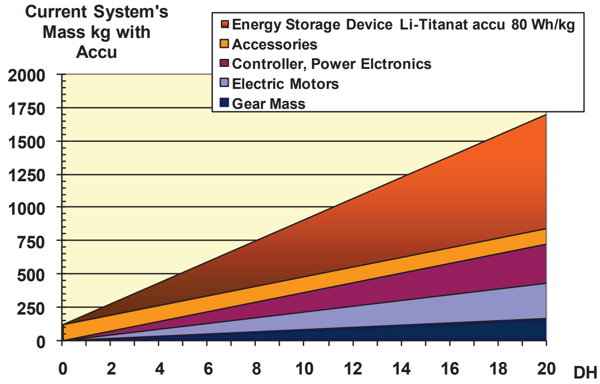

FIGURE 16. Current mass of the E-Wheel System with state-of the art Li-Titanat accus depending on the DH chosen, no energy harvesting capability [15]

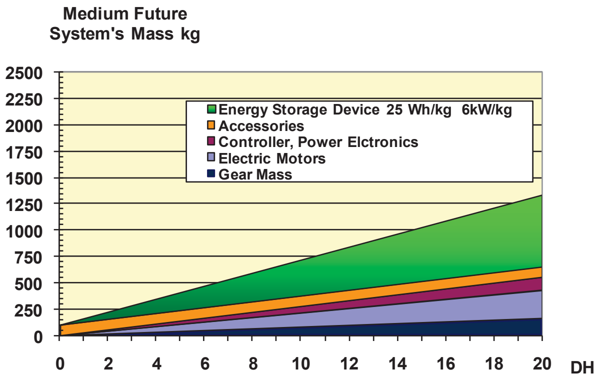

FIGURE 17. Mass of the E-Wheel System with medium future super capacitors depending on the DH chosen [15]

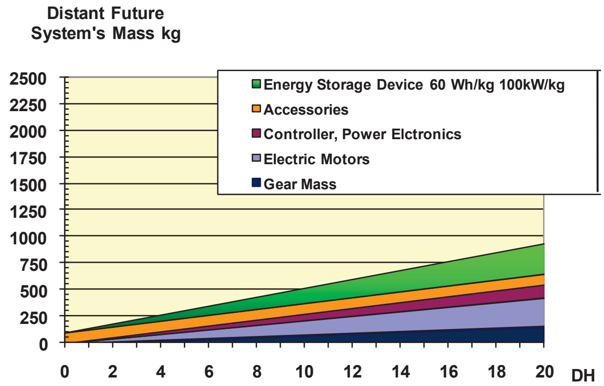

FIGURE 18. Mass of the E-Wheel System with distant future super capacitors depending on the DH chosen [15]

estimated for the present, the medium and distant future dependent on the degree of hybridization chosen" [15].

13. IMPACT OF SYSTEM'S WEIGHT ON FUEL BURN

In the following the impact of the extra weight of the E-Wheel system on the fuel burn of the aircraft should be evaluated, especially for climb and cruise, as well as for some complete example standard missions. Furthermore the fuel gain due to electric taxiing on the ground should be figured out.

13.1 Climb

The extra fuel needed for uplifting the E-wheel system's weight on cruise altitude depends on the cruise altitude chosen and can be computed with data taken from the Flight Crew Operating Manual [16] for excess loading of the aircraft at MTOW. Table 19 shows an overview of the amount of fuel, which is needed for uplifting one ton excess weight, at MTOW conditions.

Climb to Cruise Flight Level 250kt /300kt/ Ma 0,78	Extra fuel needed per 1000 kg excess weight
FL 370 *	60 kg
FL 330	52 kg
FL 310	43 kg
FL 290	35 kg

TAB 19. Extra Fuel for uplifting excess weight at MTOW conditions (* performance limit: no direct climb at MTOW)

13.2 Cruise

During cruise the extra fuel needed for the excess loading per one ton at high cruising weights and Ma 0,78 can be calculated with data from the FCOM [16] depending on the cruise altitude. Results are stated in table 20.

Cruise Flight Level Ma 0,78	Extra fuel needed per 1000 kg excess weight and 1000 nm
FL 370	80,5 kg
FL 330	74,0 kg
FL 310	54,4 kg
FL 290	43,5 kg

TAB 20. Extra Fuel in cruise due to excess weight, M 0,78

13.3 Take-off, Descend, Approach, Landing

The extra fuel for one ton excess weight at high aircraft's weights during descend, approach and landing is generally negligible [16], but apart from that will be respected in the mission calculations. At Take-off the engine run at maximum thrust conditions anyway, therefore not causing additional fuel burn.

13.4 Fuel gain due to electric taxing

The E-wheel system should also enable the aircraft to autonomously taxi on the ground without the aircrafts' engines running. The electric power is provided by the Auxiliary Power Unit (APU). According to Airbus the fuel flow of the APU at maximum electric output and average ECS outtake is 2 kg/min [17]. In contrast to the APU both engines need 11,5 -12,5 kg/s [17,2] for powering the aircraft at ground during taxi. A value of 11,5 kg/s is chosen for the calculations. The overall fuel saving strongly depends on the taxi time. For the following calculations a TTT Total Taxi Time of 15 [18], 20 [2] and 26 (LTO cycle) minutes are chosen with view to standard missions. According to Airbus from these values another 8 minutes [2] have to be subtracted. This is because of the necessary procedure of warming up the engines before take-off (5 minutes) and for cooling down the engines after landing (3 minutes). This results in an ETT Effective Taxi Time of 7, 12 and 19 minutes. Fuel due to electric taxiing can only be saved during the effective taxi time.

13.5 Mission Fuel and Deltas

Table shows the fuel needed for three different missions in kg of typical stage lengths of 500 – 800 nm without the E-Wheel system onboard, calculated from FCOM data [16]. It additionally states the amount of fuel, which could be potentially saved by electric taxiing.

Fuel kg or %	500 nm	670 nm	800 nm
Taxi TTT 20 min	230	230	230
TO and climb	1261	1582	2067
Cruise	2106	2481	3640
Descend	115	115	115
Fuels saved due to E-Taxi ETT 12 min	114	114	114
Fuel saved E-Taxi ETT of total mission fuel %	3,1 %	2,6 %	1,9 %
Total Fuel Consumed	3706	4408	5869

TAB 21. Mission Fuel and fuel saved by E-Taxi

The fuel, which can be saved by the E-wheel system due to Electric taxi can be set in relation to the additional fuel needed for carrying the system's weight on a certain mission. Diagram 22 shows the fuel saved from E-Taxi depending on the Total Taxi Time and the extra fuel needed for the system`s weight depending on the degree of Hybridization DH and the stage length in nm. If the amount of fuel saved from E-taxi is higher than the amount of fuel for the extra weight, the E-wheels system will additionally lead to slightly less enhanced fuels and will therefore save fuel. This is the case on short mission and on long taxi times. If the both amounts of fuel are equal, it will only enhance the field performance of the aircraft and enable E-taxi without fuel penalties on the missions. With increasing sector length on longer mission the addition fuel due the extra weight overcomes the fuel savings of E-Taxi. Then the system means a fuel penalty. The higher the degree of hybridization DH the heavier will be the weight of the system due to the electrical onboard storage and the shorter will be the critical stage length, in which the resulting fuel saving is zero.

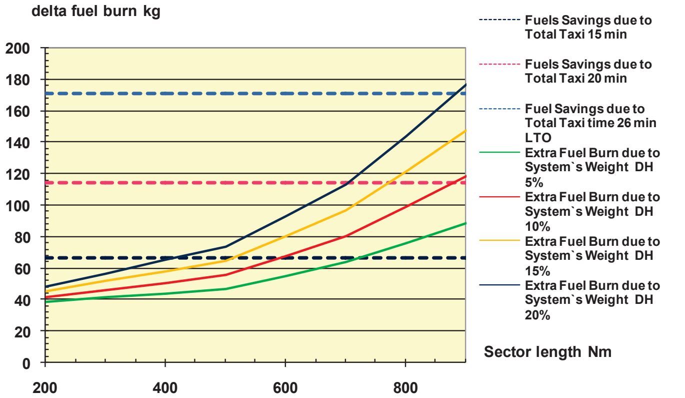

FIGURE 22. Delta fuel in kg for the extra weight of the system and fuel saved from E-Taxiing depending on the stage length

Figure 23 shows the percental delta in fuel burn due to the extra weight and the fuel saved by E-taxi depending on the Total Taxi time and stage length.

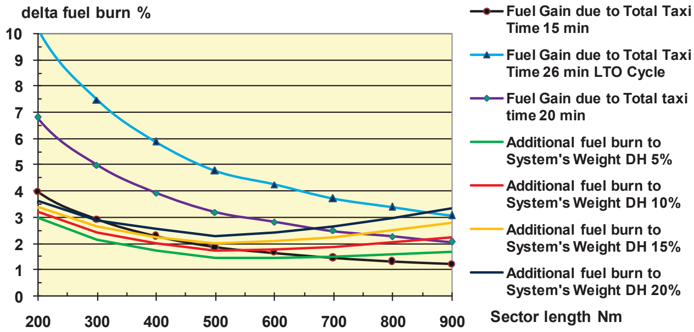

FIGURE 23. Delta fuel in kg for the extra weight of the system and fuel saved from E-Taxiing depending on the stage length

Figure 24 shows the overall delta in fuel burn in percentage depending on the Total Taxi Time and stage length. For a DH of 10% at a total taxi time of 15 min the critical stage length is 550 nm. For missions, which are shorter, the E-Wheel system will save fuel, for missions longer it will result in a fuel penalty. For higher taxi time the critical stage length increases. The stepped curved graphs in the figures are due to changes to higher flight levels because of increased stage lengths.

For typical A320 mission between 500- 700 nm the E-wheel system can be fuel neutral, eventually slighty save missions fuel, if the total taxi time is around 17 min or higher. The total taxi time however contains 8 min for starting up the engines and cooling them down, which is at least partly done at the parking position. Subtracting this time the E-wheel will be of benefit in terms of fuel savings - additionally to enhancements of the field performance - if the effective rolling taxi time is at least 9 min, which is a realistic value for most missions.
The figures apply to the system's weight of the present. If they are calculated for the medium and future system's weight the critical stage length however will further

beneficially increase due to less extra fuel needed for the system's weight.

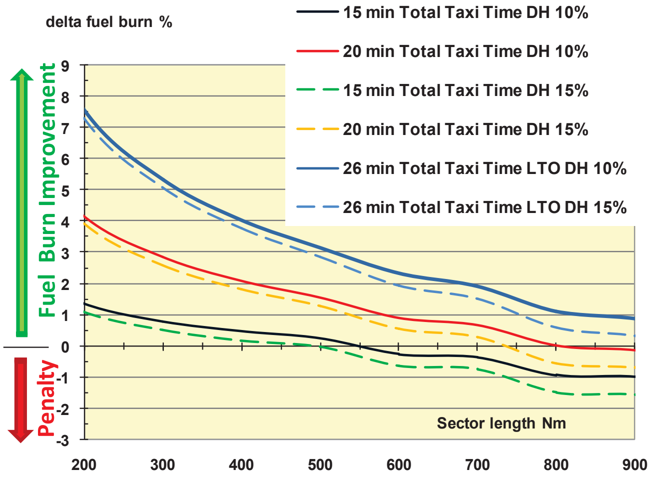

FIGURE 24. Relative change in fuel burn due to the E-Wheel System depending on the DH and stage length

14. E-WHEEL EFFECTS ON TAKE-OFF PERFORMANCE

"During the take-off run the electric Wheel-drive System (E-Wheel) works in cooperation with the main engines as a parallel hybrid-electric propulsion system, providing additional thrust in this case via four motorized wheels of the main landing gear. The thrust lapse of the conventional main engines is respected in the calculations by a thrust lapse factors TLF as a function of aircraft speed (see Figure 2).

The propulsion-effective electrical thrust level is initially considered to remain constant for the complete period of ground acceleration run. This electrical thrust level is seen as the integrated propulsion-effective force, integrated over the whole period of the take-off run. The efficiency of the electric wheel drive (well to wheel) of about 74 % is competitively high compared to the efficiency of the main engines of approximately at best 20 % - 30 % during the take-off run (well to wake), enhancing the overall efficiency of the aircraft, contributing to lower emissions and slightly decreased fuel burn and noise emissions according to the hybridization degree chosen." [1]

14.1. Shortening the take-off distance (TOD)

"With the use of the hybrid-electric system the electrical wheel drive additionally contributes to the overall thrust level during take-off." [1]

"The system will be operated during ground roll up to a speed approximately equaling the decision speed v_1 "…". The rotation and transition distances are not affected by increased thrust and remain unchanged." [1]

Figure 25 "…shows the absolute reduction in take-off safety distance in m against the degree of hybridization (DH), for the mode of TOD reduction. It becomes clear that the absolute reduction in take-off length rises digressively. For a DH of 10 % a reduction in TOSD of 210 m is archived, for a DH of 15 % the reduction equals 290 m. Figure "…26" states the relative reduction in TOSD against the DH. For a DH of 10 % the abbreviation in TOSD compared to the reference at MTOW conditions is 9.4 %, for a DH of 15% TOSD is reduced by 13.2 %. The ASD is also shortened, but less, as no safety factor has to be applied "…[9]."

These results show the effects of an enhanced E-Wheel system for aircraft of a moderate by-pass ratio of around 6 :1. As the thrust lapse of the main engines main engines while the electric thrust remains constant, the hybrid-electric propulsion systems will generate higher performance gains in terms of TOSD and ASD reduction for modern aircraft with high by pass ratio including potential future aircraft with UHB engines, propfan-driven aircraft, as well as generally propeller-driven aircraft."[1]

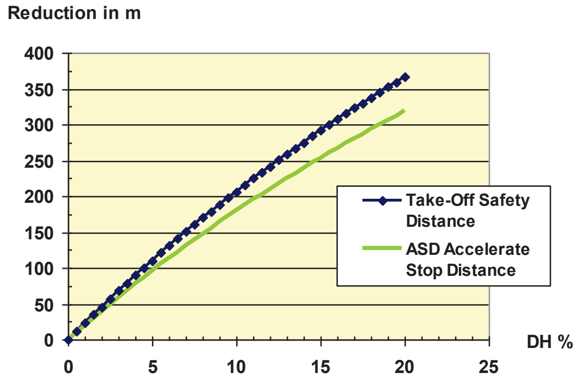

FIGURE 25. Absolute reduction of Take-Off Safety Distance TOSD and Accelerate Stop Distance ASD [1]

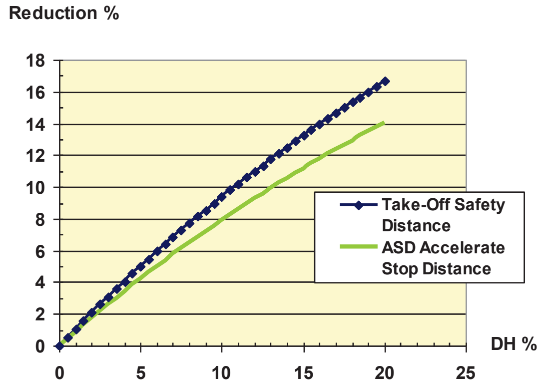

FIGURE 26. Relative reduction of Take-Off Safety Distance TOSD and Accelerate Stop Distance ASD [1]

14.2 Comparison of the E-Wheel system with an advanced high lift system regarding TO-performance

The specific effects of the E-wheel system in reducing the TOD could alternatively be reached by an advanced high lift system. Figure 27 shows the incremental C_L which must be added to the existing lift coefficient C_L of the take-off configuration with a C_L of 1,4 to reach a certain reduction in take-off distance. This increment hence

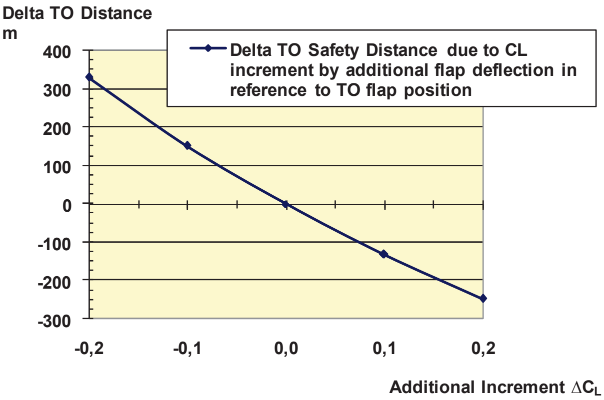

FIGURE 27. Delta in TOD due to an increment in lift coefficient as a consequence of flap deflection with reference at take-off configuration of the aircraft ΔC_L=0 comes

additionally comes to the existing increment of the take-off flap position of ΔC_L 0,2, at approximately 10° flaps setting, building on the clean configuration with C_L of around 1,2. In this context the take-off flap position is chosen as a reference with delta ΔC_L=0.

Figure 28 does the same like Figure 27, but states the percental reduction in TOD as a result of increased or decreased C_L due to flap deflection. Furthermore it additionally presents the penalty in maximum L/D, thus in

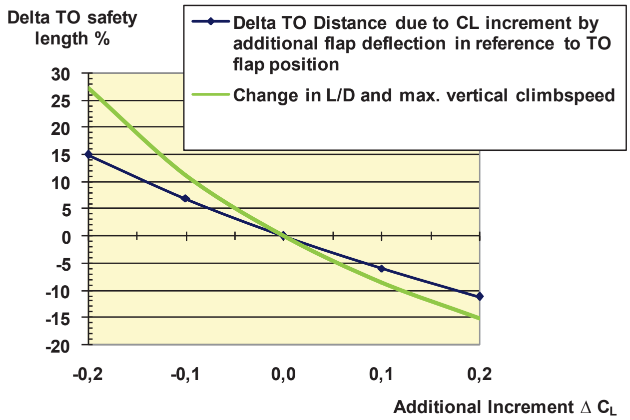

FIGURE 28. Percental change in TOD and L/D (climb performance) due to an additional increment in lift coefficient as a consequence of flap deflection with reference at take-off configuration of the aircraft ΔC_L=0

initial climb performance of the aircraft, due to flap extraction. It shows, that with an additional increment of ΔC_L=0,2 TOD, is reduced by 10% and maximum L/D and climb performance is diminished by 15%.
The E-wheel system however will not reduce L/D and climb performance. Its effect on the TOD is linked with the corresponding effect of an advanced high lift system in Figure 29. For the reduction in TOD of around 200 m a DH (degree of hybridization) of 10% is necessary. As an alternative the same reduction in TOD can be reached with an additional increment in C_L of 0,16 of an advanced high lift systems in reference to the take-off flaps position, but unfavorably this reduces the L/D and maximal initial climb performance of the aircraft by 13% in reference to the take-off configuration with a max. L/D of approximately 13-14. Hence a high lift system can reach the same effect but with significant penalty in climb performance.

On the other side with the help of the E-wheel system, e.g. namely with a DH of only 6,1%, it becomes possible to lower the flap setting by an increment of ΔC_L=0,1 or around 5° to reach the same and changed TO distance but with decreased flap deflection. As a result L/D and

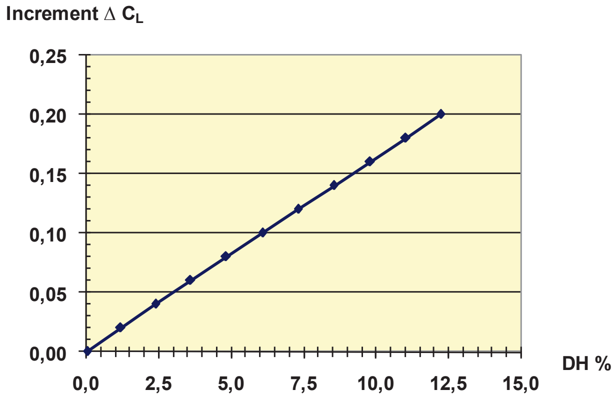

FIGURE 29 Same effects in change in TOD for the E-wheel system and an advanced high lift system with reference at take-off configuration of the aircraft ΔC_L=0

initial climb capability would be raised by 12% with positive impact of perceived noise at the ground hence reducing the noise foodprint Additionally flight safety is enhanced by improved obstacle and ground clearance at initial climb. The increased climb capability could also be used to boost up the take-off weight at constant climb performance in reference to the original aircraft, but requires adapting certain aircraft specific constraints like the maximum tire speed. Altogether the E-Wheel system helps to reach the same TOD at reduced flap deflections, resulting in significant better climb capability and thus lower ground noise levels

14.3. Take-off with derated conventional thrust

“In a further operation mode a certain proportion of the conventional thrust could be replaced by the electric thrust. In the calculations it is determined how much the thrust level of the conventional main engines could be derated by the pilot to reach the constant safety TOD of 2200 m with the E-Wheel system being active, here shown for MTOW conditions. Thereby it is considered that the electric thrust can replace or even exceed the conventionally usual thrust during the ground acceleration run, however due to the lowered conventional thrust the transition segment is slightly stretched up to 15 m.
Derated thrust take-offs account for the majority of take-offs worldwide in today’s commercial airline operation, beneficially reducing the highly thrust-related engine maintenance costs as well as elongating the time, both

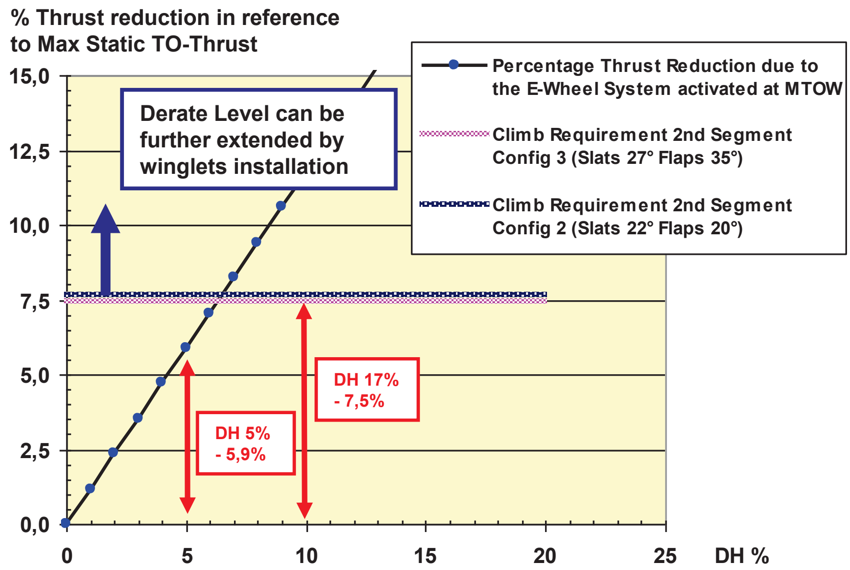

FIGURE 30. Possible reduction (derate) of Take-Off Thrust at MTOW for a fixed original TOSD dependent on the DH [1]

the engines can stay on the wing and the aircraft can generate revenues. Today a derated take-off is possible, whenever the available take-off distance is remarkable longer than the take-off distance needed for a certain operating weight, the climb requirements are still met with reduced thrust, especially during the 2nd segment, and the runway is not contaminated by snow or slush "…[14]". With the E-Wheel system activated, the thrust derate levels could be either significantly extended or will become also available for higher take-off weights, including MTOW, as well as on shorter runways.

For guaranteeing same and constant take-off performance the TOD has to be equal to the original TOSD of 2200 m, conventionally being reached with maximum TO thrust and without E-wheel system at MTOW. By solving the equitation numerically the thrust Reduction Factor TRF (%) could be figured out dependent upon the Hybridization Degree DH (%) chosen. The TRF as percental value states the maximum derate thrust level of the main engines in reference to their maximum static TO thrust level." [1]

15. E-WHEEL EFFECTS ON LANDING PERFORMANCE

15.1 Shortening the landing distance

"The E-Wheel system will additionally contribute to the overall deceleration level in the scope of hybrid-electric braking for reaching a shorter landing safety distance LSD, compared to the original LSD of 1890 m at MLW" [1].

15.2 Brake Relief

"During the ground deceleration run the hybrid electric system can be alternatively operated in a diverse mode to relief the mechanical wheel brakes. As figure "…33 " shows, according to the DH chosen, "…here shown for a DH of 10 % ..." in this way the mechanical brakes could be relieved by up to 11.2 % for normal braking and 8.9 % at RTO. As the mechanical brake converts kinetic into thermal energy, the relief significantly lowers the braking temperature and therefore shortens the time needed for cooling down the brakes, which is normally equal or shorter than the turnaround time. In certain conditions, for instance with low cost carriers, which demand a very short turnaround time, braking temperature is critically and undesirably extend the ground time. This is why brakes are required by regulations to have a certain maximum temperature before initiating the next take-off, respecting the case that they have to be eventually activated in RTO maximally to abort take-off.

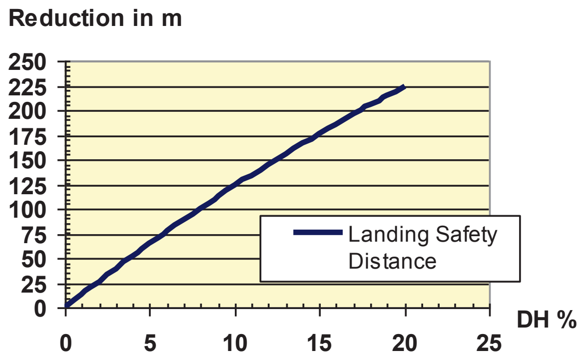

FIGURE 31. Absolute reduction of Landing Safety D.[1]

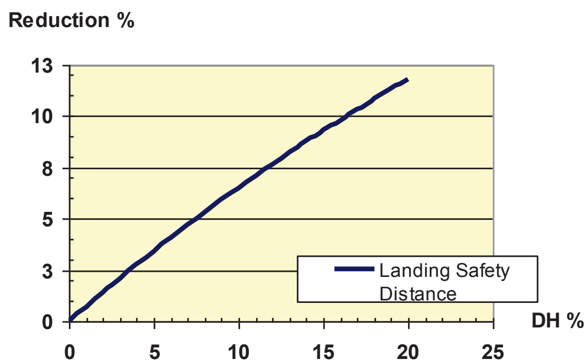

FIGURE 32. Relative reduction of Landing Safety D.[1]

When the electric motors are running in generator mode during the landing run, they can recover a certain share of the kinetic energy, acting as a Kinetic Energy Recovery System. According to the system architecture of the hybrid-electric system the recovered energy will be stored on board by super capacitors, whereas finally at least "...40 % (see figure 5).." of the maximum capture-able energy can be efficiently reused e.g. to energize the system at the next take-off, weather to shorten the TOD, to accelerate a higher take-off mass or to decrease the conventional thrust." [1]

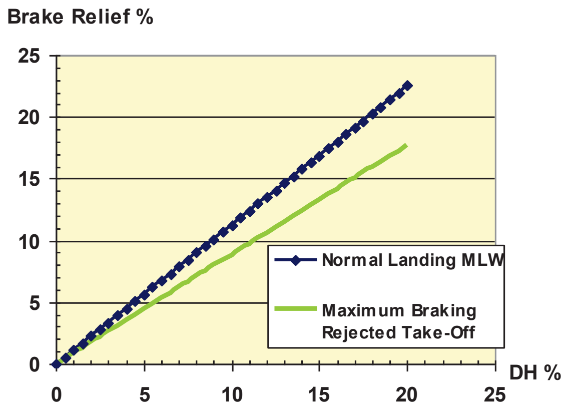

FIGURE 33. Percental Brake Relief due to the E-Wheel system for normal Landing at MLW and for RTO at MTOW according to the DH [1]

16. OPERATION (TAKE-OFF AND LANDING) WITH HIGHER OPERATING MASS

"The additional available electrically generated wheel thrust can also be used for the aircraft's operation with higher mass, thus, for accelerating a higher take-off mass on a fixed and unchanged take-off distance and similarly decelerating an increased landing mass on a constant and unchanged landing distance. Figure "…34 " shows the possible mass increase with the hybrid-electric system in operation for reaching the original and unchanged take-off distance of 2200 m. Figure "… 35 " does the same for the landing safety distance with the system in braking mode. As the E-wheel only works during the ground segment the rotation sequence is slightly elongated due to generally higher operation- and lift off speeds as a consequence of the increased mass. At the same time the transition segment at TO is also extended mainly due to the decreased T/W ratio in response to the higher mass. " [1]

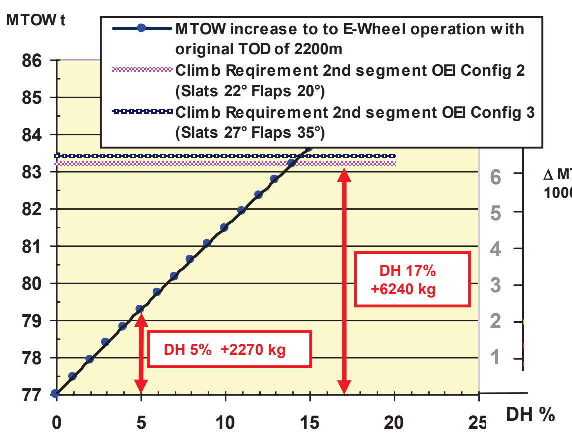

FIGURE 34. showing the possible increase in MTOW with the E-Wheel system dependent on the DH and the OEI climb requirements [1]

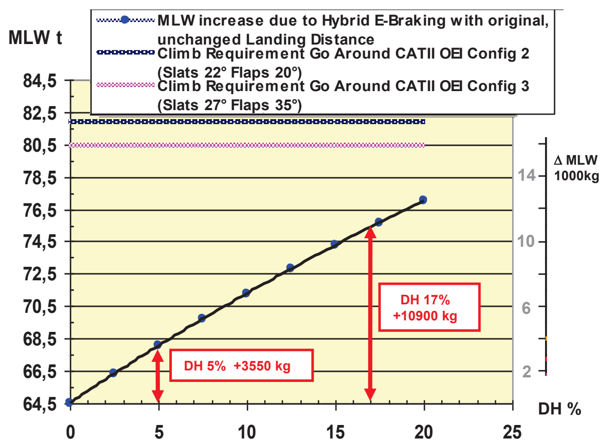

FIGURE 35. showing the possible increase in MLW with the E-Wheel system dependent on the DH and the go around OEI climb requirements [1]

"Furthermore the subsequent climb requirements, mainly for the 2nd segment in One Engine Inoperative OEI conditions have to be still fulfilled with decreased T/W ratio due to the higher mass. Figure "…34" shows these supplementary limits for the MTOW, depending on the aircraft's specific configuration, especially the flap setting.

Recapitulatory in view of all these limitations for take-off, a take off mass increase of 4480 kg, respectively a MTOW increase of 5.8 % becomes available for a DH of 10 %. It appears probable, that the increase in TO mass could be nearly completely applied for enhancing the payload mass capability, as many parts and components of the A320 aircraft family are also used for the A321 up to a MTOW of 93.5 t and a MLW of 74.5 t.

Figure 36 shows again the relevant overall system's weight for the present, medium and distant future but as well shows the net payload increase for an unchanged and original field performance. It includes all mentioned limitation from take-off and landing, including take-off and landing distance, acceleration stop distance, 2 nd segment climb and landing OEI climb requirements. That means although the weight of the aircraft is increased there is no longer take-off and landing distance necessary due to the additional acceleration and deceleration forces of the E-Wheel system available. The system's weight has been already deducted, so that the real net payload increase is shown. It becomes clear that with a DH of 14 % a maximal payload increase of 4660 kg (+24.3 %) in the present and 5400 kg (+28.1%) in the distant future becomes available with the system, if no further structural enforcement is necessary on the plane. This however in view of the Airbus A321-200 is an appropriate approximation for low to medium net payload increases up to around 3.5 tons. But also comparing the original A320 versions with the current ones, MTOW has been continually been raising from 68.4 t to 78.4 t or by around 10 tons without remarkably increasing the OEW.

Further increasing the DH higher than 14 % does not make sense from the payload perspective as the 2nd segment climb limitation becomes active, which could be seen in the buckling of the curves in the diagram. But increasing of the DH keeps enhancing the field performance of the aircraft. With a degree of hybridization of 17 % a decrease in take-off safety distance of 330 m is reached (- 15 %), while the landing safety distance necessary droops to 1690 m (-200 m).

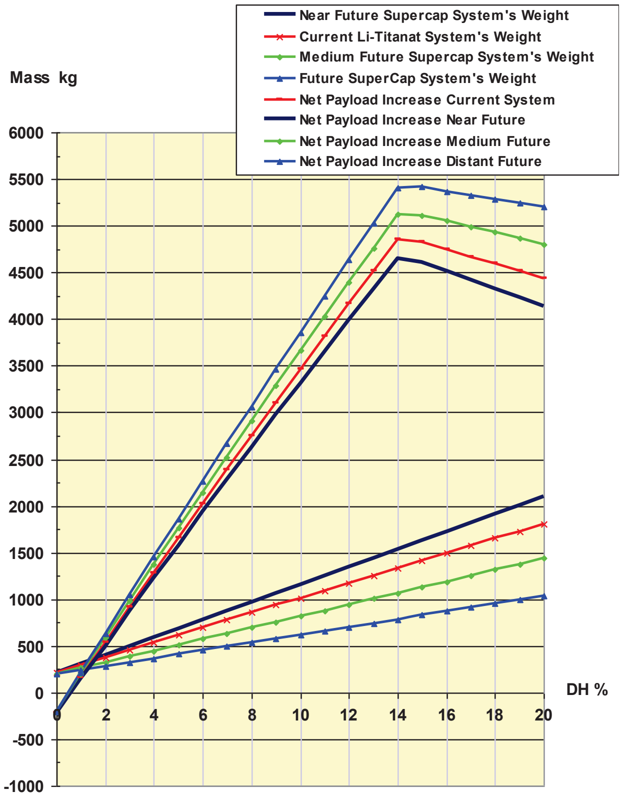

FIGURE 36. System's mass for the present, medium and distant future and net payload increase due to the system depending on the DH. Calculating the net payload, the system's weight has already been deducted [15]

The accelerate stop distance, important as a requirement which states, whether an aircraft is allowed of being operated on a certain runway and if yes with which operation mass, is affected by - 290 m. The systems weight for a DH of 17 % becomes 1570 kg in the medium and 910 kg for the distant future, which equals or is even less than the weight of current inflight entertainment systems, installed within this class of aircraft.
However on standard passenger aircrafts for the upcoming future degrees of hybridization of around 10 % seems both interesting and realistic. The E-Wheel system can be built on existing e-Taxi systems as a further evolution or enhanced embodiment.
Therefore for a hybrid electric system of DH 10 % subtracting the initial system weight of around 1015 kg a net payload increase of 3300 to 3450 kg depending on the energy storage technology becomes available, meaning a maximum payload boost of 17.7%.
If the maximum take-off weight is significantly increased by payload e.g. by 4.5 t, from an operational perspective it would be furthermore appropriate to also increase the MLW absolutely by the same value to allow higher payload operation of the aircraft. Figure "…35" shows the maximum increase of landing weight for the E-wheel system being active in braking mode for reaching the original landing safety distance of 1890 m depending on the DH. For landing additional climb requirements for go around in OEI conditions apply by a climb gradient of 2.5% for low visibility CAT II approaches with a minimum decision height of 200 ft, limiting the MLW depending on the flap setting (configuration). Summing up, in view of all TO and landing constraints for instance an E-wheel system with DH of 10% will enable an MTOW increase by 4.48 t and an MLW increase by also 6.78 t on the original and unchanged take-off and landing safety distances.
Already respecting the weight of such a system of presently 1015 kg with a DH of 10 %, a net payload increase of 3.35 tons will become possible, boosting the maximum payload capability of the Airbus A 320-214 from 19.2 to 22.5 t or by 17.7 %. This can be further enhanced by winglets or sharklets installation as they effectively affect the 2nd segment climb performance and thereby the maximum payload capability" [15].

17. COMPARISION WITH INCREASED THRUST LEVEL OF THE MAIN ENGINES

The following of the described effects can alternatively be reached by simply increasing the thrust level of the main engines:

- reducing TO distance
- take-off with higher mass
- shortening accelerate stop distance by better acceleration
- derated take-offs with higher derate level

But with increased thrust level there is no or even a negative effect on:

- shortening the landing distance (even slighty longer due to higher idle thrust)
- landing with increased landing mass (Overall brake energy of mechanic brakes have to be adapted to higher landing weight and slightly increased idle thrust, might have a negative impact of turn around time due to cooling down of the hotter brakes)
- no E-Taxiing, therefore no savings in fuel burn

If the thrust level of the main engines is raised on an existing plane, the dimensions of the nacelles and especially the fan diameter remain the same. Regarding the A320 family the thrust level of the A321 is around 20% higher than with the A320 (nearly similar, if A319 is compared to A320). However the dimensions of the engine, nacelle and fan (diameter 1,73m) are still the same. For increasing the thrust level the air flow through the engine has to be raised. But with constant engine dimension this results in an increased specific thrust. According to [19] a higher specific thrust F_S results in an decreased specific fuel burn of the engine B_S (if specific heat value of the fuel H_u, thermal efficiency η_{TH} and flight speed c_0 remains constant)

$$B_S = \frac{2 \cdot c_0 + F_S}{2 \cdot \eta_{TH} \cdot H_U} \quad (1))$$

Table 37 shows some members of the CFM-5 engine family, which are applied on the A320 family, and their specific data concerning thrust level, specifc thrust and estimated change in specific fuel burn due to (1). The thrust level is increased by approximately 10 and 20 %, which is also in the same range like the E-wheel system's impact on overall thrust level. The fan diameter of the engines is constant [20]. It becomes clear, that the by pass ratio droops with increased thrust level, too, which hints to also a lower specific performance in cruise. For raising the thrust level by 10% this results in an estimated increase in sfc of 2,4%. If the thrust level is raised by 20% sfc raises by 3.7%. It is possible that this increase in sfc can be lowered by adapted, special methods of the engine manufacturer. However the tendency will remain, that there is an slight increased sfc and therefore a higher amount of mission fuel burnt.

CFM 56	5B4	5B1	5B3
max take-off thrust lb	27000	30000	33000
Increase in max thrust %	100	111	122
Air flow lb/s	897	943	968
Specific thrust lb/(lb/s)	30,10	31,81	34,09
Fan diameter m	1,73	1,73	1,73
BPR	5,7	5,5	5,4
Estimated change sfc %	100,0	102,4	103,7

TAB 37. Changes in specific thrust, BPR and estimated changes in sfc due to an increase in thrust level at constant engine dimensions, here shown for TO [20]

Additionally, there will probably more weight of the engine if a higher thrust level is applied. At the A321, which has a thrust level 20% higher than the A320, the additional weight for engines, nacelle and pylons becomes around 350 kg.
Altogether it is very probable, that the raising of the thrust level results in a slightly increased sfc, resulting, together with extra weight, in higher amounts of mission fuel burnt. In contrast, the E-wheel system can save fuel, despite of its extra weight, at low till standard mission's ranges with average taxi time.

18. FUTURE POTENTIAL OF THE E-WHEEL SYSTEM

"The E-Wheel system, with electric motors of a suitable performance level directly installed at the main landing gear might open up a fundament for further future innovations apart from electric taxiing. As the electric motors can easily measure important parameters in real time like applied wheel thrust, asymmetries, distance remaining and already covered and could be easily coupled to lightweight enhanced electronics further automotive inspirited applications become available like active track stabilization, active cross wind compensation, ESP applications and maybe once autopilot guided or assisted take-off runs. The take-off and initial climb is the last part of the a/c mission, not being able to be guided by the autopilot. So maybe one day the system might help to enable automatic or guided distance-, speed- and acceleration controlled take off runs, might assist in the detection of a take-off rejection necessary or even itself can initiate RTOs.
Furthermore the advantages of the E-Wheel systems in terms of field performance can be considered in early preliminary aircraft design which means that performance gains can be transferred to another area, for example from field performance to cruise performance – also meaning fuel burn - , as the field performance is held stable with the help of the system while e.g. the wing area is being decreased.
Another aspect reveals within the calculations, stating that a DH of 12 % means effectively to have a landing gear without effective rolling friction. This also means that the system can be operated to reduce the friction at the wheels without needing traction respectively positive wheel slip, which might be also relevant in terms of safety and future certification.
Furthermore a DH of 12.6 % exactly equals the gap between maximum TO and max continuous thrust, eventually allowing an advanced aero-engine matching with the engines run on more or less ideally stable and effective conditions with potential significant positive impact on fuel burn.
The E-Wheel System at a DH of 10 % in hybrid-electric braking mode is as effective as the thrust reverses which weight around 800 kg in total and are complex and costly, but presently seem to be necessary for safe operation of the aircraft in difficult conditions.
Altogether it becomes clear that exactly a DH of around 10 % of this class of aircraft is both interesting and realistic and might open up new possibilities for an effective integral approach in aircraft design." [15]

19. CONCLUSION

„The application of the E-Wheel electric hybrid propulsion systems on a standard short range passenger aircraft leads to a variety of flexible operational advantages. The system can be generally built on an electric taxiing system as an advanced future embodiment.
For instance, applied on an Airbus A320-214, for a degree of hybridization DH of 10 %, meaning that 10 % of the maximum engines' static thrust is additionally applied as electric wheel thrust at the main landing gear, the take-off distance can be shortened by 210 m. Alternatively the thrust can be derated by -7.5 % at MTOW or the MTOW can be raised by 4.48 t on the original and unchanged take-off safety distance of 2200 m."[1] This equals a net increase in maximum payload capacity of 3.35 t or a relative net increase in the aircraft's maximum payload mass capability of 17.7 %. At the same time the landing safety distance is decreased by 120 m or landing is feasible with an increased MLW of plus 3.18 t or more on the same landing distance of 1980 m. Alternatively the mechanical wheel brakes could be relieved by 11.2 %, eventually shortening the turn-around time ".. by brake temperature."The system's weight will be in total 1015 kg presently (820-620 kg in the future), whereas around 430 kg presently applies to the onboard electrical storage device, loadable in a standard container on demand in the aircraft's aft cargo bay. The current weight of the system will be less than present inflight entertainment system installed in this type of aircraft…", but will affect the aircraft's performance in positive way."[15]
It is shown that the E-wheel system behaves at least fuel neutral or can slightly save fuel on short to standard missions at an effective E-Taxi time of 9 minutes or more at the present system's weight.
Some of the effects of the E-Wheel system can alternatively been reached by raising the thrust limit of the main engines, but without the capability of saving fuel by E-taxi and with the additional penalty of an increased sfc, which results in a higher amount of block fuel needed.

References

[1] Schwarze, M. C. 2013. *Novel Electric-Wheel-Driven Hybrid-Electric Propulsion Systems on Standard Short Range Passenger Airplanes*. CASI AERO 13, 60th Aeronautical Conference. Toronto, Canada

[2] Airbus S.A.S. Jan 2013. *Flight Airworthiness Support Technology, Fast 51*. Airbus S.A.S. Blagnac.
(last accessed April 2013)obtainable: http://www.airbus.com/support/publications/?eID=dam_frontend_push&docID=28153

[3] Schier, M., Rinderknecht F., Brinner A., Hellstern H. 2011. *High Integrated Electric Machine for Aircraft Autonomous Taxiin.*, EVER Conference 2011 Monaco, Ecologic Vehicles Renewable Energies. Recited by the Institute of Vehicle Concepts, German Aerospace Center, Stuttgart, Germany

[4] Wikipedia Deutschland. May 2013. Website, *general info, super- and ultra caps* (last accessed May 2013) obtainable: https://de.wikipedia.org/wiki/Doppelschichtkondensator

[5] JM Energy. May 2013. *Company website, product presentation Li supercab , brochure Ultimo.*
(last accessed May 2013) Obtainable: http://www.jmenergy.co.jp/pdf/ULTIMO%20Brocure-en.pdf

[6] Mobile-Power.info. May 2013. *Website, general info, Li-Titanat accumulators* (last accessed May 2013) Obtainable: http://www.mobile-power.info/d/batterielexikon/akkus-lithium-titanat.html

[7] Signorelli, Schindall, Kassakian. 2009. *Carbon Nanotube Enhanced Ultracapictor*. LEES Labatory for Electromagnetics and Electronic Systems, MIT Massachusetts Institute of Technology, website, poster presentation,
(last accessed May 2013) Obtainable: http://lees.mit.edu/lees/posters/RU13_signorelli.pdf

[8] Khare, E. April 2013. *Design and Synthesis of Hydrogenated TiO2-Polyaniline Nanorods for Flexible High-Performance Supercapacititors.* University of California Santa Cruz (last accessed May 2013) Obtainable: www.usc.edu/CSSF/Current/Projects/S0912.pdf

[9] Tesla Motors. May 2013. *Company website, product presentation, electric motor.* (last accessed May 2013): Obtainable: http://www.teslamotors.com/roadster/technology/motor

[10] Magnet Motor. May 2013. *Company website, product presentation, G 35 datasheet.*(last accessed May 2013) Obtainable: http://www.magnet-motor.de/uploads/media/MM_G35_datasheet_low_01_2_.pdf

[11] Plettenberg Motoren. May 2013. *Company website, product presentation, Industrieanwendungen, Nova 150,* (last accessed May 2013) Obtainable: http://www.plettenberg-motoren.net/index.php/de/antriebsserie-nova/antriebsserie-nova-150

[12] Airbus. May 2011. *A320 Airplane Characteristics for Airport Planning*. Airbus S.A.S., Blagnac.
Customer Services. Technical Data Support and Services.

[13] Plettenberg Motoren. May 2013. *Company website, product presentation, Industrieanwendungen, Motorsteuerung,* (last accessed May 2013) Obtainable: http://www.plettenberg-motoren.net/index.php/de/motorsteuerung/motorsteuerung-mst-400-400

[14] Airbus. January 2002. *Getting to Grips with Aircraft Performance*. Airbus, Blagnac. Customer Services,
Flight Operations Support & Assistance

[15] Schwarze, M. C. 2013. *Integration of Novel Electric-Wheel-Driven Hybrid-Electric Propulsion Systems on Standard Short Range Passenger Airplanes*. EUCASS 2013. 5th European Conference for Aeronautics and Space, Munich, Germany

[16] Airbus. January 2002. *A 319/A320/A321 Flight Crew Operating Manual*. Volume 3 Flight Operations. Airbus, Blagnac. Customer Service Directorate, Technical Documentation Services (AI/SE-D)

[17] Airbus. July 2004. *Getting to Grips with Fuel Economy*. Issue 4. Airbus, Blagnac. Customer Services,
Flight Operations Support & Assistance

[18] H. Khadilkar and H. Balakrishman, January 2011. *Estimation of Aircraft Taxi-out Fuel Burn using Flight Data Recorder Archives*. Masters Thesis, Massachusetts Institute of Technology, Cambridge, USA

[19] W. J. G. Bräunling. 2004. *Flugzeugtriebwerke. Springer Verlag, 2. Auflage.*

[20] CFM company website 2013. *The Technology behind the CFM56-5B Turbofan Engine*. (last accessed August 2013) obtainable: www.cfmaeroengines.com/engines/cfm56-5b