

Estimation of energy consumption and emissions in aircraft operation and potential for savings

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Aircraft emissions and fuel consumption are a double issue for companies and authorities. Fuel represents a big share of airlines operating costs, and carbon dioxide emissions are directly related to them; on the other hand, pollutant emissions are a concern for local authorities in terms of public health for airports near cities. In this regard, both airlines and aviation authorities join together in an effort to reduce costs and reduce environmental impact of air transportation. Reducing pollutant emissions and fuel consumption during taxi phases (taxi in and taxi out) is an attractive option due to the increase of air traffic and the congestion at airports that leads to longer taxi times and the related extra fuel consumption and generated emissions. In Europe, this is a key issue as taxi phases represent a significant amount of the total time of medium-haul flights. New emerging systems and the development of power sources, as well as new technologies, provide ways to reduce fuel consumption and pollutant emissions; in this document, a study of the potential savings of some of these systems is developed. In particular, on board motor actuators powered by batteries, a fuel cell or the aircraft APU, along with the study of the usage of conventional push back tractors to move the aircraft during taxi phases. On board systems show good results for short routes, reduction in LTO emissions and overall fuel consumption. NO_x emissions for overall operations show small increases for shorter routes, and even reductions in some cases, but increase for long routes. Dispatch towing with conventional tractors shows savings in fuel and some emissions but worse results than on board systems.

1. INTRODUCTION

Air transportation has become a useful link between countries and a fast way to travel. Its growth has been increasing within last decades¹. Revenue passenger kilometres set a record in 2011, and it is expected to grow about 5% several years from now². Fuel consumption is linked to aviation activities and so is expected its growth as well in emissions related to it. Emissions come from combustion occurring at turbojet engines, as CO₂, CO, VOC (HC), NO_x, and SO₂, (which depends on the sulphur level in the fuel); there are also combustion product species emitted at relatively low concentrations (PM, N₂O and CH₄)³. These emissions can be organised in two categories, greenhouse gas emissions (mainly CO₂ and water, but also others as N₂O) and criteria pollutants (HC, NO_x, SO₂, lead, CO, PM). Aircraft emissions of CO₂ are proportional to fuel consumed by a factor of 3157 g/kg fuel³, NO_x emissions are related to high power settings and high pressure ratios and temperatures⁴. HC and CO emissions are important in low efficiency performances⁵. NO_x emissions from aviation represent 4.5% of total emissions in Europe, while CO₂ represent near 3%. There is a strong correlation between jet fuel and crude oil price, and so there is a interest of airlines to try to reduce the costs while a

reduction of the environmental impact is also envisaged. Governments and international authorities, worried on climate change and air pollution, are making serious efforts in order to reduce CO₂ emissions and air pollutants. Although international aviation emissions are currently excluded from the targets of the main international protocol on this matter (Kyoto Protocol), ICAO's Environmental Protection Strategic Objectives are to limit or reduce the impact of aircraft engine emissions on local air quality. This local concern is focused on effects created during the landing and take-off (LTO) cycle as these emissions are released below 3,000 feet. In this regard, limits and recommendations are included in ICAO annex 16, and emissions limits are related to engine characteristics for CO and HC and also year of manufacturing in the case of NO_x (Committee on Aviation Environmental Protection, CAEP, standards). Goals for 2030 in emissions for European Union are 40% cut in greenhouse gas emissions, 27% increase in energy efficiency and 27% of total consumption from renewable energy (compared with 1990)⁶. The Advisory Council for Aviation Research and Innovation in Europe (ACARE) has a goal of 75% CO₂ emissions reduction per passenger kilometre and 90% reduction in NO_x emissions in its Flight Path 2050 program⁷. NO_x emissions reduction are the focus of most international efforts for pollutant emission

reduction, and goals for 2016 and 2026 are 45% of CAEP/6 and 60% of CAEP/6⁸.

Emission goals can be achieved by improving aircraft performance in several ways, from engine improvements (CAEP regulations), to operational methodologies change. Besides LTO, rest of flight, the en-route phase, is where most of the emissions are produced due to its length, but LTO cycle still has significant emissions (figure 1). Fuel burned and emissions during taxi phases depends on taxiing times, as well as on the number of active engines. Because the cruise phase is the longest one, aircraft engines are designed to be more efficient in this phase, resulting in worse performance during taxi phases; this leads to higher emission index of certain pollutants (CO, HC). Taxi time is also affected by the congestion problems and delays. In Europe, aircraft spend long portions of its flights in land; this means relevant amounts of fuel spent in taxi phases⁹ (table 1, end of section 3)

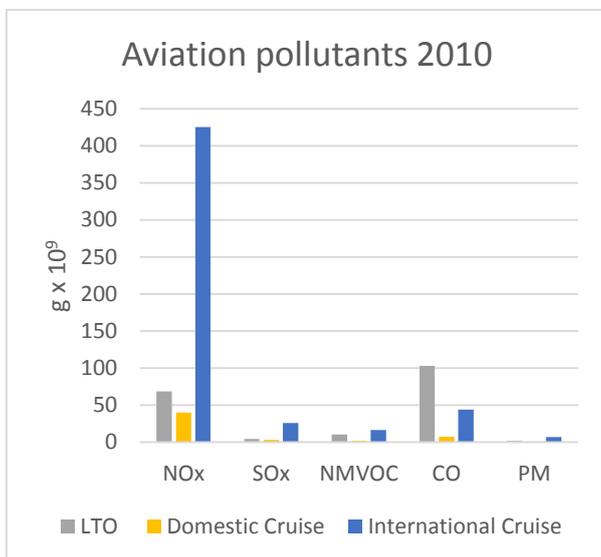


Figure 1-Aviation pollutants (2010) in Europe¹⁰

In this regard, a study from Instituto Superior Técnico shows several alternatives for fuel consumption and emissions reduction in Lisbon airport for all movements during a year¹¹, showing the benefits of several alternatives (dispatch towing, single engine, taxi times reduction and an innovative system based on a rail system). In this study, as will be mentioned in next paragraph, the aim is the comparison between dispatch towing and three on board system alternatives (as well as the feasibility of these alternatives) in several routes.

Based on the need of cutting emissions and jet fuel consumption in aviation, the objectives for the thesis are to study ways of reducing emissions (CO₂, NO_x, CO and HC) and fuel consumption in LTO cycle. More in particular, during taxi operation, by considering several alternatives: electric motor assistance with different power sources (batteries, fuel cell, and aircraft's auxiliary power unit (APU)), towing alternatives (use of a pushback type tractor to perform taxi) and compare those possible solutions with today's conventional procedures. The aim for this text are fuel consumption, CO₂, NO_x, CO and HC emissions, more in particular during aircraft ground movement.

2. STATE OF THE ART

Biojet fuels are a promising alternative for lowering fuel consumption and emissions, despite its limited availability¹²⁻¹⁴. In addition, evolution of aircraft technologies during last decades has led to a significant improvement in fuel efficiency regarding passenger air traffic¹⁵. Advances until now and expected for the future include weight reduction, aerodynamic improvement, engines higher efficiency, future aircraft concepts and operating improvements that could lead to a more 'eco-friendly' aviation.

As for taxi alternatives, taxi phases are a source of pollutant emissions for local air and with the increase of air traffic and taxiing times in airports comes the consequently concern about fuel costs and emissions. One simple way to reduce the emissions, and fuel burnt, is the single engine taxi¹⁶. The use of only part of the engines during taxi would reduce emissions, despite some constraints for its usage⁹. Studies made in the USA showed potential air pollutant emission savings of 27% and 45% without reducing taxiing time in Orlando and New York- La Guardia¹⁶.

Several options to avoid engine use during taxi phase can be compared in terms of fuel consumption and emissions to the conventional taxiing procedure. When considering alternatives for taxiing procedures, they must include push-back from gate (except from particular cases, as no nose-in parking, use of reverse thrust, etc.), moving the aircraft from still with enough force and driving it during the taxi in the taxiway. Taxiing alternatives to engines can be separated in tractor type equipment (external, also called dispatch towing), and in electric motor on wheels (on-board system), which can be on the nose gear or in the main wheels. On board systems can be powered by different sources. In this research three sources will be considered: batteries, fuel cell, and aircraft's auxiliary power unit (APU). Apart from complete electrified taxi solutions with on board systems, there is also studied the only substitution of conventional pushback.

External systems for taxiing are vehicles (tractors or 'tugs') that are attached to the aircraft in order to tow it along the taxiway (dispatch towing). The power required for the taxi phase does not come from the aircraft, but the tractor. These tractors are those used as conventional vehicles used for pushback or towing the aircraft, despite acceleration forces supported by the nose gear and the command of the procedure (pilot, tug driver) have to be studied¹⁷. Taxibot is a representative dispatch towing system from the Israel Aerospace Industries, developed with French manufacturer of ground-support TLD Group. With a version for narrow body (NB) aircraft and another for wide body (WB) (TaxiBot International), it consists of a semi-robotic, hybrid tractor (towbarless), controlled by the pilot. This means that the pilot is in control of the movement, using the same controls that are used in conventional taxiing. This system has been tested extensively, and now it is being used by Lufthansa (NB version) LEOS in Frankfurt airport. Its speed is reported to reach 42 km/h¹⁹.

On board systems considered are those in which an electrical motor moves the aircraft. In this particular case, closest to market alternative are a nose gear system and a

main gear system. WheelTug e-taxi system is a solution developed by WheelTug and Chrous Motors and consists of a nose wheel motor powered by aircraft's APU (no modifications required on the APU). It is an on-board system designed to perform a part of the taxi phase for narrow body aircraft. The device is an electric motor installed in the nose gear (one on each wheel), and the weight of the system is around 136 kg²⁰. However, this system does not allow to reach usual taxi speeds. The speed limitations only allows the WheelTug to be useful in taxiing situations where the aircraft has to stop and move.

Born by the union of Honeywell and SAFRAN, EGTS (Electric Green Taxiing System) is not certified yet¹⁹. The idea is similar to the nose gear system, but in the main one. The EGTS consists of an electric actuator driven by APU, but in this case there are also modifications needed in the APU. EGTS has been demonstrated in the Paris Air Show 2013 in an A320, and is expected to enter into service in 2016 with a maximum speed of 33 km/h²¹. The company expects to reach important savings in emissions²². These on board systems have been tested on A320 aircraft.

Regarding on board systems, power sources available considering examples of electric vehicles are a generator (in this case aircraft's APU), fuel cells and batteries. A battery consists of two or more electric cells connected together. These cells convert chemical energy into electrical energy, and they consist of electrodes and an electrolyte; the reaction between them generates electricity. Performance criteria are specific energy and power, energy density, voltages, efficiency (Ah, capacity and energy), availability, operating temperatures, life cycles, recharge rates.... Performance also depends on temperature, state of charge..., which also influence life and efficiency. Even when the chemistry is the same, not all batteries are equal. It is important to control carefully the current and the voltage, and maintain the battery in a state of charge over 20%, to avoid a drop in efficiency²³. Characteristics from available batteries extracted from literature²⁴⁻²⁷; high energy batteries show low power settings, and high power batteries show low specific energy compared to others. In this regard, lithium ion batteries are the most promising option, but its price is still high.

Fuel cells convert chemical energy from fuel into electricity, but unlike batteries, chemicals are not stored inside; fuel cells require a constant source of oxidant and fuel to maintain the energy supply. The origin of the hydrogen will determine its emissions in the place of production, but using hydrogen as a fuel does not produce emissions (tank to wheel), as reaction product is water²⁸. The environmental impact of a fuel cell is low and its electric conversion rate is high, and these are advantages compared to traditional generators. Proton exchange membrane fuel cell (polymer electrolyte)(PEM) is the most promising cell for vehicles²³. Fuel cells are not limited to hydrogen as fuel; using a fuel reformer, a wide range of fuels can be used to produce hydrogen; however, fuel reformers are expensive, and reduce energy efficiency²⁸. Hydrogen has a specific energy of 33.3 kWh/kg (higher than jetfuel), but a very low energy

density, and has to be stored in a certain way, as in liquid state at low temperatures or in a pressured vessel (storage options go from 0.5 to 1.2 kWh/l²⁷).

Auxiliary Power Units (APUs), which are a component of an aircraft, consist basically of a small turbine engine, which produces energy for aircraft systems, engine starts and everything that is required when main engines are off and there is no ground power sources available. Auxiliary power unit taken for aircraft as the A320 is the Honeywell 131-9. This turbine provides up to 300 kW when it is at full load (main engines start). In standard conditions the usage of the APU for the aircraft requirements is about 85 kW, through a generator up to 90/115 kVA, using the bleed air for pneumatic purposes. This means that there is energy available for the electric motors in the wheels. The power that could be available is about 200 kW²⁹. Maximum power is developed through bleed air for the start of the main engines (APU mode: main engine start, MES), not the electric generator. It is necessary to modify the APU so as to transform all the power developed by the APU into electrical energy, perhaps using a generator and probably a gearbox; however, in this issue just a weight for the extra modifications will be estimated along with the electric motor.

3. METHODOLOGY

Using the TAP fleet as reference, as most of its aircraft fleet are A319 and A320 types, these will be the aircraft used as reference when calculating the alternative taxiing methods and emissions and fuel consumption. In Europe, A320 and A319 are commonly used and occupy ranks #1 and #3 in movements³⁰. Data for the engines and the aircraft itself is obtained from TAP and manufacturers (CFM int., Michelin, Airbus). Engines considered to study the alternatives, due to its spread of usage, are the 5B5/P for the A319 and the 5B4/P for the A320. Newest engines show better performances in NOx emissions and fuel consumption, due to ICAO Annex 16 normative (CAEP regulations) and the interest on more efficient engines⁵, which can be a good complement to alternatives in taxi. Figure 2 shows alternatives considered in this study.

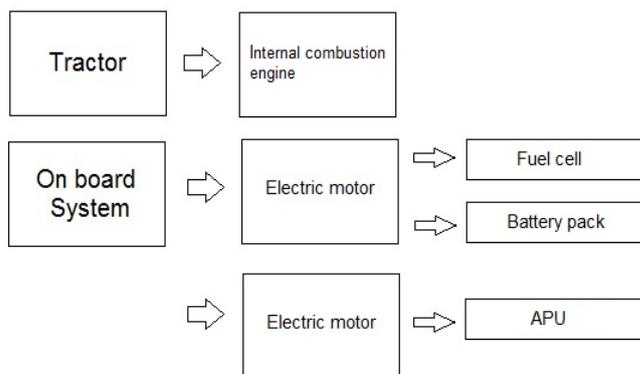


Figure 2-Alternatives studied in ground taxi movements

Taxiing speeds are limited to 46 km/h in taxiways¹⁷, however, this speed differs from actual speeds as during the taxi phase aircraft have to turn, stop and slowdown in several situations. As reference to estimate the energy and power required by the aircraft in the taxi phase, runway crossing rules are applied. ICAO prescribes a minimum of 90 m in a common approach procedure, between the holding position and the operation itself; another authorities are more cautious²⁹, considering this distance and a safety time to cover it twice. It is also assume that the taxiway has no slope (maximum permitted by ICAO is 1.5%) to calculate the average taxi needs, but it is considered in case of the maximum force required. The acceleration considered is 0.25 m/s²²⁹ taking into account the safety needs of acceleration. Usual taxi range from 6 m/s to 10 m/s, although depending on the airport they vary and in some long straight taxiways speeds are higher³¹. Total force required for driving a vehicle at a constant speed can be calculated as follows³²:

$$F_{friction} = C_{rr} \times m \times g \quad 1$$

$$F_d = \frac{1}{2} \rho \times v^2 \times C_d \times S \quad 2$$

$$F = m \times a + F_d + F_{friction} \quad 3$$

$$F_{slope} = m \times g \times \sin \phi \quad 4$$

$F_{friction}$ = force needed to overcome rolling resistance

F_{slope} = force needed to overcome a slope

F_d = force needed to overcome drag

C_{rr} = rolling resistance coefficient

m = mass of the vehicle (kg)

g = gravitational acceleration constant (9.81m/s²)

v = velocity of the vehicle (m/s)

ρ = density of air (1.22 kg/mm³)

S = reference wing area (m²)

C_d = coefficient of drag

ϕ = angle of the slope

For coefficients, it is assumed a rolling resistance coefficient of 0.01 (trucks) and a non-drag lift coefficient of 0.017, to be conservative³³. Motor's inertia is not considered. Torque needs and speeds (figures 3 and 4) are calculated through the

$$T_{axis} = F_{wheels} \times r \quad 5$$

$$T_{axis} = T_{motor} \times \frac{Gear\ ratio}{1} \times \eta_{transmission} \quad 6$$

$$V_{vehicle} = 2\pi r \times \frac{1}{Gear\ ratio} \times 1/60 \times n_{motor} \quad 7$$

$$P_{available} = P_{motor} \times \eta_{transmission} \quad 8$$

equations below:

Where:

T_{axis} = torque delivered in the axis

F_{wheels} = force available or required to move the aircraft

T_{motor} = torque delivered by the motor

n_{motor} = speed of the motor (rpm)

$V_{vehicle}$ = speed of the vehicle (tractor, aircraft)

P_{motor} = power at the output of the motor

η_{trans} = efficiency of the transmission (axles, gearbox, etc.)

Gear ratios considered are 1, 2, 4 and 12. These speeds give an accurate approximation of the maximum speed that the motors required for this purpose have to achieve with enough torque.

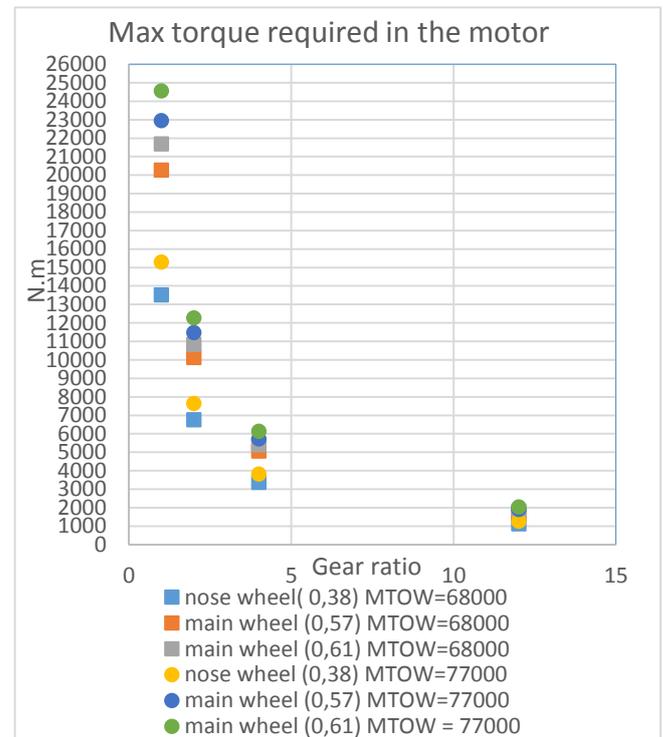


Figure 3 – Maximum torque required in the motor depending on gear ratio, MTOW and wheel radius.

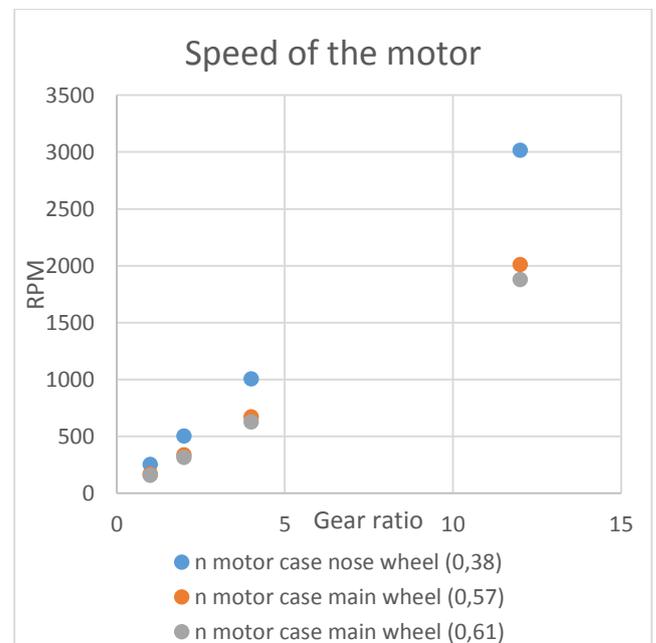


Figure 4- Motor speeds requirements with each gear ratio

To make an approach to the needs of energy:

$$P_{avg} = F_{avg} \times v_{avg}$$

9

77000 kg MTOW A320 will be used as a reference for the power source.

As for the on board electric actuators, in order to test the viability of a wheel hub motor for the A320 nose gear, the Institute of Vehicle Concepts has designed and built a prototype for the German Aerospace Centre. The results showed the possibility of a torque up to 10kN, with a maximum speed of the motor of 2000 rpm³¹. Considering the requirements in terms of motor torque for the considered aircraft and taxi requirements, the nose wheel motor option has to be rejected for a complete taxiing procedure. As for the main wheel system, it can be considered a direct drive wheel actuator that, given that there are four big wheels, it may be feasible to achieve the performance requirements for ground movement of the aircraft with direct drive, which will increase the reliability of the system, as they would not have a gear reduction. In this case, an study of the viability of the Green Taxi solution (EGTS), mentioned before, but without gearbox, shows a device between 65-75 kg³⁴, that is suitable for taxi procedures considering 4 direct drive devices. In on board actuators, controllers required to use the electrical motor are supposed to have an efficiency of 98%, and 95% for transmission.

Emissions calculation methodology and fuel burnt

Regarding emissions in conventional taxi procedures, thrust considered by ICAO as reference for taxi phases is 7%³⁰, Equations used to estimate emissions during taxi phases:

$$FB = t \times 60 \times FF_{idle} \times N \quad 10$$

$$E_i = t \times 60 \times FF_{idle} \times EI_i^{idle} \times N \quad 11$$

Where

FB = fuel burned

t = time (min)

FF_{idle} = fuel flow at idle conditions (kg/s)

E_i = emissions of pollutant i

N = number of active motors (2)

EI_i^{idle} = emission index for pollutant i at idle (g/kg of fuel)

Taxiing times are extracted from Eurocontrol³⁵, and engine emissions data from ICAO³⁵.

As for the APU, Data of fuel flow and emissions index for average APUs of each aircraft type are obtained from the report 64 of the Airport Cooperative Research Program sponsored by the FAA³⁶. Equations used to estimate the emissions and fuel consumption of the APU are similar to the ones used for the main engines in conventional taxiing:

$$FB_{APU} = t \times 60 \times FF_{MES} \quad 12$$

$$E_{pollutant_i}^{MES} = FF_{MES} \times EI_i^{MES} \times t \times 60 \quad 13$$

Where:

FB_{APU} = fuel consumed by the APU

FF_{MES} = fuel flow of the APU in the main engine start mode (kg/s)

$$E_{pollutant_i}^{MES}$$

= emissions of pollutant i in main engine start conditions

$$EI_i^{MES}$$

= emissions index of pollutant i in main engine start conditions (g/kg of fuel)

t = time (min)

Batteries considered to make the calculations are a lithium ion cell manufactured by EIG (Graphite/ Ni CoMnO₂), with 140 Wh/kg (at 300 W/kg) of specific energy and 895 W/kg of specific power and the Lithium Iron Phosphate LiFeO₄ (140 Wh/kg, 2000 W/kg). The efficiency of lithium ion batteries is high, sometimes over 95%, but a value of 0.9 is taken. Tank to wheel emissions related to this kind power system are considered 0 in the place of usage^{37,38}. Battery sizing is made based on the premise that it has to be multiplied by a factor (1.2). This is due to the state of charge required to be efficient²³ Equations used to estimate battery weight :

Battery pack weight

= factor

$$\times \max\left(\frac{\text{Energy required}}{\text{Specific energy}_{\text{Battery}}}, \frac{\text{Power required}}{\text{Specific power}_{\text{Battery}}}\right) \quad 14$$

$$\text{Energy required} = \text{Average power in taxi} \times \text{time} \times 60 \times \frac{1}{\eta_{tot}} \quad 15$$

$$\text{Power required} = \text{Maximum power required} / \eta_{tot} \quad 16$$

$$\eta_{tot} = \eta_{transmission} \times \eta_{motor} \times \eta_{battery} \times \eta_{controller} \quad 17$$

Fuel cells used for the study are PEM fuel cell selected from available transport fuel cells (modules) currently used for buses and trucks, extracted from the U.S. Department of Energy and manufacturers^{39, 40, 41, 42}.

A theoretical fuel cell of 230 kW (equation 24) is extracted from literature review, and so the calculations are based on performance reports of the cells systems instead of cell efficiencies. Calculations for hydrogen requirements are explained in following equations:

$$\text{Total weight required} = \text{fuel cell weight} + \quad 18$$

Hydrogen tank weight

$$\text{Hydrogen required} = \text{hydrogen consumption} \times \text{time} \quad 19$$

$$\text{Hydrogen tanks weight} = \text{mass}_{\text{hydrogen required}} / \left(\frac{\text{kg}_{\text{hydrogen}}}{\text{kg}_{\text{tank}}}\right) \quad 20$$

$$\text{Power required} = \text{Maximum power required} / (\eta_{transmission} \times \eta_{motor} \times \eta_{controller}) \quad 21$$

Conventional tractors emissions and fuel consumption

Performance characteristics in terms of consumption and emissions for narrow body and wide body type pushback tractors to move reference aircraft are obtained from literature⁴³⁹. The connection of the towing vehicle for the taxi in phase is a problem in terms of time and logistics, so in this case only taxi out is considered; even when with a good planning tractor used to tow a departing aircraft could be used to tow an arriving one, this solution seems too difficult to carry out. Taxi procedure performed by narrow body tractor type is considered slower than conventional taxi. The time of dispatch towing in these cases is assumed 2.5 times the current taxi time for narrow body type (round trip), to be conservative, and usual times for wide body, both working at its usual load factor of 0.8⁴³ to carry the aircraft, but 0.5 for the wide body type tractor when not towing.

Equations that define fuel consumption and emissions of conventional (diesel and gasoline) pushback tractors are shown below (where average rated horsepower is the power at the output shaft of the engine):

$$FB_{Tractor} = Load\ factor \times BHP \times FF_{BHP} \times t/60 \quad 22$$

$$\frac{E_{pollutant_i}}{EI_{pollutant_i}} = Load\ factor \times BHP \times t/60 \times \quad 23$$

$$E_{CO_2} = FB_{Tractor} \times EI_{CO_2} \quad 24$$

Where:

$FB_{Tractor}$ = fuel consumption of vehicle (l/BHP_h)

BHP = average rated horsepower

FF_{BHP} = fuel flow ($\frac{l}{BHP_h}$)

Extra fuel consumption and emissions due to added weight (on board systems)

Extra fuel burned due to the extra weight added by on board systems is estimated from seats available in each aircraft and average load factors per route, calculating fuel consumption per passenger and expressing the on board systems weight as a number of seats (and so the extra fuel consumption). Weight used to compare system with number of seats and fuel consumption is extracted from A320 maximum landing weight (maximum weight allowed in landing) and available seats (all economic). Fuel burned due to each passenger is estimated using ICAO's Carbon Calculation Methodology adapted for fuel consumption³, based on EMEP/EEA Emission Inventory Guidebook³⁰. In this case, average distances of the routes provided by TAP are used, and LTO cycles are modified for considered aircraft engines, using registered taxi times and standard times for the rest of the cycle.

$$\frac{Fuel\ consumption}{pax} = \frac{total\ fuel \times pax\ freight}{n_{y\ seats} \times pax\ load} \quad 25$$

Where:

$n_{y\ seats}$ = number of equivalent economy seats (aircraft)

Pax to freight factor is calculated given the number of passengers and the tonnage of another cargo, for a route group. Pax load factor is based on the passengers transported and the seats available. Data is obtained from TAP.

Reference scenario

Routes considered for the case studies are Lisbon-Porto, Lisbon-Geneva, Lisbon-Paris (Orly) and Lisbon-Milan (Malpensa). Firstly, a round trip in which the aircraft has to carry all the weight for both airport taxi phases in case it is used an on-board system, and any substation is made in Lisbon.

Secondly, the single trips between the airports are used, considering that all airports have infrastructure to change batteries or hydrogen tanks. Reference emissions for LTO cycles are extracted from ICAO engine emission databank⁵, and for en-route phases from EMEP/EEA inventory guidebook³⁰.

4. RESULTS

It is not feasible to avoid all emissions and fuel consumption during taxi phases because engines require some time to start up (2 min), warm up (3 min) and cool down (3 min). However, up to more than 70% of emissions and fuel consumption can be eliminated from taxi out and up to more than 65 % in taxi in for airports (ground movements).. Average taxi times will refer to average times for taxi in and taxi out in the airports considered for each route during a year, and peak taxi times will refer to 90th percentile of that taxi times. Fuel consumption is a key factor in the application of alternative systems; if fuel consumption for the overall operation is increased, there is no advantage in using the system in terms of fuel costs and carbon dioxide emissions.

Airport Name	Average taxi out time (min)	Peak taxi out time (min)	Average taxi in time (min)	Peak TXI taxi in time (min)
Geneva	11	16	4	5
Lisbon	13	19	5	7
Milan/Malpensa	13	18	5	8
Paris/Orly	11	16	6	9
Porto	11	17	5	7

Table 1- Taxi times for airports considered³⁵

Dispatch towing

As calculations are based on aircraft taxi times, dispatch towing solution shows the same reduction of emissions and fuel consumption for each airport in terms of percentage. This solution has no impact on the rest of the flight phases, as it does not require any extra weight in the aircraft. Results show very important reductions in carbon dioxide and in some pollutant emissions. Even so, results in diesel tractors show an increase of NO_x emissions (from 92.2% to 144%), and gasoline tractors produce a great amount of CO (up to 8 times more than those from conventional taxiing). The usage of these systems therefore

is charged with an increase of one pollutant while others are greatly reduced, and depends on aircraft as A319, for example, has less NO_x emissions related. In this case it is interesting to further study how hybridization could help to reduce pollutant emissions that can limit this alternative.

Figure 5 shows savings for A320 referred to time that tractor is working compared to the same time using engines (negative values mean an increase), in order to sum up all airports considered in one graphic. However, as mentioned before, smaller tractors are not likely to perform taxi phases in an accurate time, and this is an issue, especially in busy airports.

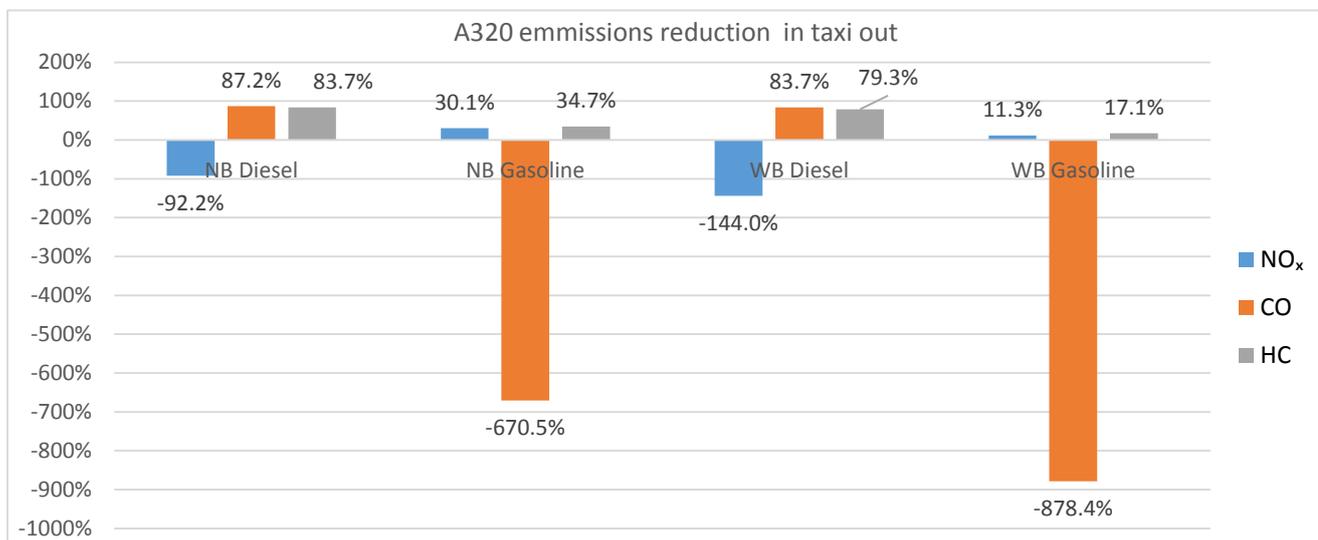


Figure 5 - NO_x, CO and HC savings from using dispatch towing (from maximum emissions savings)

Regarding fuel consumption and CO₂ emissions, dispatch towing shows jet fuel savings that depend on the airport. Those savings are higher for NB tractors, but in any case, both of them have CO₂ emissions reduction from 73% to 85% during the time that tractors are used (it does not include the warm up time of the engines) in both cases (higher for A320 and NB tractor).

On board systems

On board systems cause extra weight due to the electrical motors, the weight of extra components for transforming the energy stored into electricity and the weight of the storage. While battery weight depends on the time that is expected to be used, fuel cell system is heavier and hydrogen tanks' weight does not vary much compared to the system, and when considering APU as power source, fuel is assumed burnt during the taxi phase, so its weight is always fixed, with the disadvantage of its own emissions.

These systems have a cost in terms of pollutant emissions related to the extra weight of the on board systems, and is calculated for both aircraft and considering average times and peak times, for whole operations (LTO cycle plus en-route phase). These emissions are related to the complete flight but, in any case, the additional weight, regardless of the savings, will produce more emissions during the en-route phase.

NO_x emissions depend mostly on en-route phase and extra weight, as en-route conditions indices for NO_x emissions are higher. Regarding comparison with conventional operations, results show increases of

around 1-5% of NO_x emissions, except for some cases when extra emissions are lower or there are even savings. Best results appear in shortest routes with lightest systems; in direct route Porto Lisbon using APU for the A320 and peak taxi times, extra weight is not relevant enough to produce extra emissions that overcome the savings, even though en-route emission index is far higher than in taxi.

Results for complete operations show savings in CO and HC emissions in all cases considered, in quantities that depend on the route and taxi times considered; these emissions occur mostly in taxi phases (taxi in and taxi out), and so they are reduced the most with the usage of on board systems, showing similar reductions for all alternatives considered. Regarding the aircraft, the A320 shows less extra emissions, as well as more improvement in extra emissions when taxi times are higher (or less increasing). This is due to the fact that, apart from the A320 being bigger, as mentioned in section 3.2, systems characteristics are selected for A320 aircraft, and studied for A319 in order to check its viability in the smaller aircraft. Considering total NO_x emissions, APU seems to be the best option because it implies less extra weight and this means less related emissions during en-route phase. However, during taxi phases APU's NO_x emissions will be greater than for the other two alternatives regarding ground emissions.

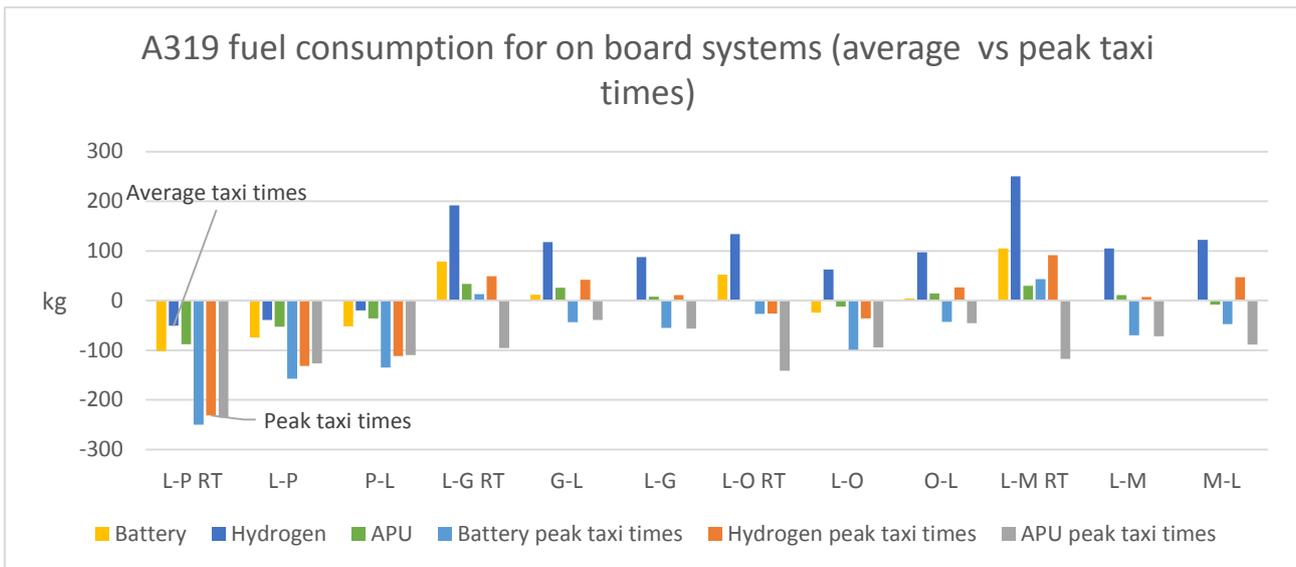


Figure 6 - A319 fuel consumption for on board systems (average vs peak taxi times). In each case considered, three columns in the left are for average taxi times, and three in the right for peak taxi times.

In average operations, the shorter route (Lisbon- Porto) shows greater fuel savings (figure 6), and for other routes depends on the weight of the system. Except for some routes and considering APU option, both aircraft in case of average taxi times have higher consumption or have almost no difference in the case of longer routes. Direct routes show less consumption per extra weight in the battery and fuel cell cases.. In this regard, it is important to notice that results have to be clearly positive to be considered, as taxi times vary depending on the day and the hour.

As mentioned before (section 1) LTO cycle is the reference in local air quality, and emissions in this part of the aircraft movement are those of more concern regarding pollutants. Savings in emissions during LTO for NO_x and CO₂ have lower values in percentage than those for HC and CO, and in LTO cycle weight of the system, load factor of the route and taxiing times influence clearly the results. Influence of HC and CO emissions savings from taxi phases (taxi in and taxi out) is, as seen before, greater as long as taxiing times increase. Savings for LTO cycles are up to around 50% in both A319 and A320 cases for average taxi times and show increasing up to 20% with peak taxi times. CO₂ results variation percentages are reduced compared to those of CO and HC. Considering average taxi times, highest reductions are between 15 and 20% difference for both aircraft. Regarding both aircraft and NO_x, reductions in emissions are positive, and this means that savings in taxi phase compensate the extra emissions related to system weight. However, not all systems show equal performances and in some cases, depending on taxiing

times of APU emissions, one is more suitable. Even so, increase of NO_x emissions is not avoidable in the whole operation, and even though values obtained for LTO (figures 7 and 8) cycle show savings, these savings are mostly under 5% in the best option for average taxiing times, so emissions could increase in cases of shorter taxi times for the LTO cycle. Due to assumption errors the extra weight or the consumption associated could be greater and these small percentages of savings would be easily turned into losses. On the other hand, improvements in system weights could mean a guarantee of success in the future.

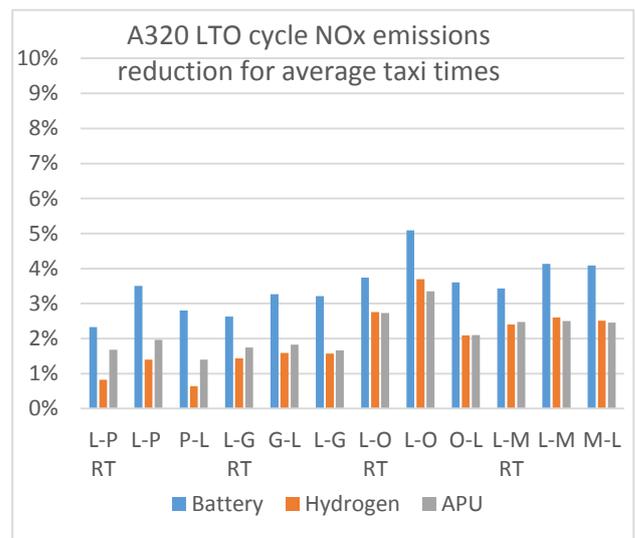


Figure 7 - A320 LTO cycle NOx emissions reduction for average taxi times

5. CONCLUSIONS

On board systems show good results for short routes, reduction in LTO emissions and overall fuel consumption. NO_x emissions for overall operations show small increases for shorter routes, and even reductions in some cases. Dispatch towing with conventional tractors shows savings in fuel and some emissions but worse results. Preferences for each system will depend on availability of resources and airport needs and possibilities.

Of all the alternatives studied, main difference between them is that towing vehicles do not add any extra weight to the aircraft, and so there are not extra fuel consumption and emissions related during en-route. Batteries and fuel cells have zero emissions related with its use, and APU option has less CO, HC and NO_x emissions than tractors, but slightly higher CO₂ emissions and fuel consumption on the ground. Regarding difficulties in infrastructure and investment, on board system powered by APU option seems to be the most suitable option since it has compatibility with airport infrastructures and procedures (as it is used currently for other purposes). Other options of on board systems show less emissions and fuel consumption related, but are likely to mean an additional cost due to lack of infrastructure and equipment. In particular, battery option shows best results for short direct routes (change of batteries at destination). Dispatch towing shows selective savings and present logistic and monetary constraints, but could be a suitable solution if one pollutant is a particular issue in the airport. In this regard, future development of hybrid or electric tractors and improvement of batteries and fuel cells for on board systems (as well as infrastructure development) are a key factor to help alternative taxiing procedures.

Further studies and field tests should be made to test the viability of these systems that appear to be feasible to check security issues, increasing of total costs and better adjustment of energy sources sizes.

Nomenclature

APU- Auxiliary power unit

LTO-Landing Take Off cycle

NB- Narrow Body

WB-Wide Body

ICAO-International Civil Aviation Organisation

MTOW-Maximum take-off weight

EGTS-Electric Green Taxiing System

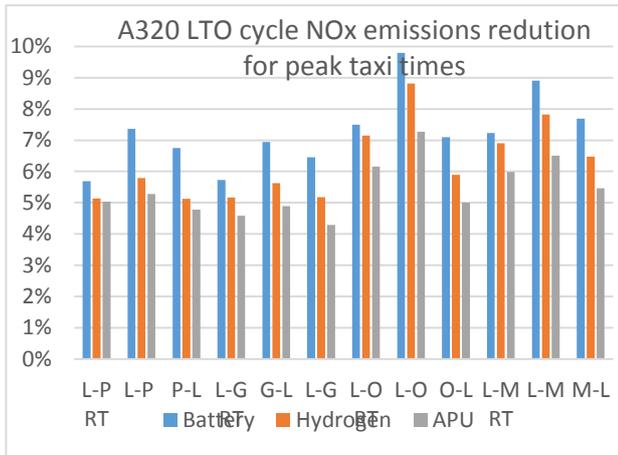


Figure 8 - A320 LTO cycle NOx emissions reduction for peak taxi times

Ground emissions

Regarding direct comparison between dispatch towing and on board systems, comparison is made for raw emissions during taxi out (when dispatch towing is considered). In this case, battery and fuel cell powered electric actuators have zero emissions on the ground (taxi). Comparison between APU and tractors show less emissions for APU but slightly higher CO₂ emissions compared to NB options. WB options show less savings than NB. Figure 9 shows an example of NO_x, CO₂ and HC emissions. CO emissions for gasoline are high and the result is an important increase (several times the reference value).

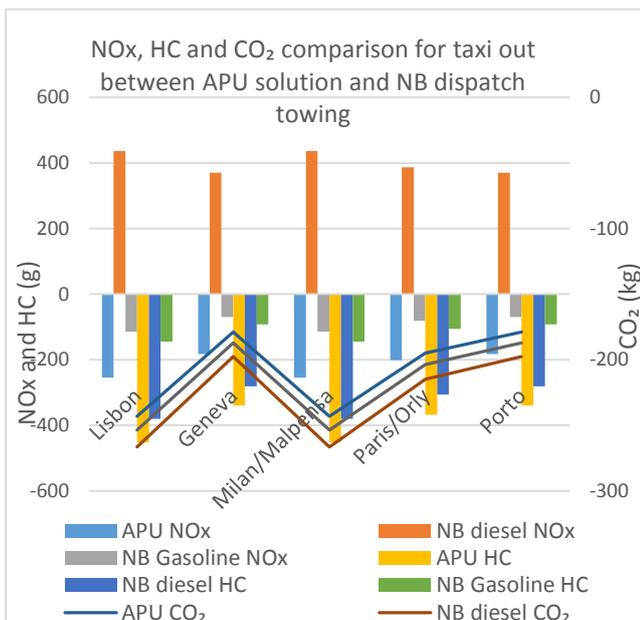


Figure 9-Ground emissions comparison between APU and NB tractors

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