ICAS 2020 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

Assessing the environmental impact of aircraft taxiing technologies

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Abstract

This paper assesses the environmental impact of various technologies and/or strategies for aircraft taxiing. The paper considers a standard taxiing route with four stops and general taxiway characteristics and breaks down the taxiing process into a mathematical model throughout which the distance, energy requirements, fuel consumption and emissions are computed. Several aircraft taxiing methods including full-engine, single-engine, tow trucks and onboard electrical propulsion techniques are investigated thus highlighting a technology route towards clean aircraft taxiing. The results obtained in the paper shows that tow trucks and onboard techniques consume less fuel compared to the full-engine and single-taxiing and produce lower fuel emissions. These should therefore be considered as alternative candidates for improving the environmental impact of aircraft taxiing.

Keywords: aircraft taxiing techniques; fuel consumption; emissions; energy required during taxiing; comparison

1. Introduction

Aviation is vital to Europe's economic competitiveness and cohesion. It supports 87.7M jobs around the world and contributes over 991 billion Euros to the economy. Aviation brings Europe's citizens closer together, enabling commercial and cultural exchanges. In the past two decades, air transportation experienced a yearly growth of 4.8%. While this was beneficial from a socio-economic perspective, it had a significant environmental impact. Aviation accounts to 2% of the global emissions and 14% of the EU's greenhouse gas (GHG) emissions from transport. The discourse on the urgent need for environmental action has been somewhat eclipsed by the COVID-19 pandemic. Despite that the pandemic has left devastating effects on the aviation industry, this has time and again demonstrated to be a resilient one. The aviation industry is forecasted to bounce back and experience significant growth by 2050. It is therefore important now to revisit the opportunities for a better balance between social, economic and environmental impact of the sector.

Flightpath 2050 [1] presents a strategy to achieve air travel in a sustainable manner while continuing to serve society's demands. The strategy set aggressive targets to reduce in flight CO_2 emissions by 70% and NOx emissions by 90% and a reduction of noise when compared to the year 2000. While historically, most of the R&D effort has been focused on the airborne phase, all aircraft movements on the ground are now set to be emission-free by 2050. Aircraft ground taxiing is a major source of emissions for large airports. Airport carbon footprint accreditation demonstrates that aircraft ground movement typically accounts between 5-20% of all emissions. Figure 1 shows an example of the emissions due to aircraft ground movement in Heathrow airport. Similar trends are found in major airports around the world.

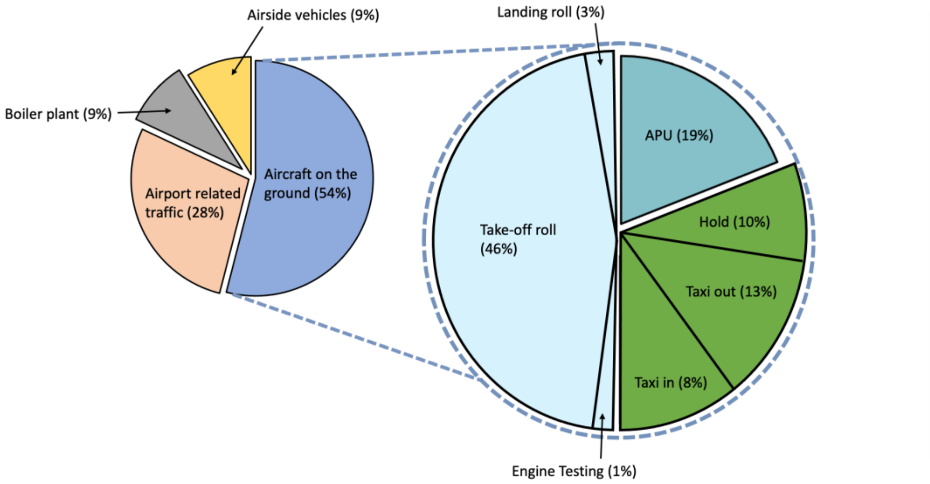

Figure 1 - Schematic showing the impact of aircraft ground movement on the carbon footprint of Heathrow airport [2].

This paper discusses a number of novel taxiing techniques and develops a tool to analyse their environmental impact with reference to the baseline standard taxiing method. The taxiing options investigated include:

- Standard taxiing method (used as a baseline)
- A single engine taxiing technique
- An external ground propulsion solutions system using either diesel, gasoline or electrically powered tow trucks.
- An advanced onboard electric taxiing technique powered by Auxiliary Power Unit. Such techniques include the suggested Electric Green Taxiing System (EGTS) project [2-4] and WheelTug [5].

Despite the development of the technologies, the effectiveness and environmental impact of each technological route is still unclear. The paper aims to fill this gap and is therefore structured as follows: Section 2 provides a review of the various taxiing techniques and associated technologies. Section 3 describes the mathematical modelling of the taxiing process, including the computation of energy required during taxiing, the fuel consumption and resulting emissions. The results are demonstrated in Section 4 where the emissions emanating from the various taxiing techniques are compared. A discussion and conclusion section is provided in Section 5.

2. Literature Review

Conventionally, aircraft engines have been used for taxiing purpose. Thrust engines are typically set at 7% idle thrust [3]. The leads to high fuel burn and a considerable amount of CO2 is released in air at ground level. Taxiing using engines can be segregated into full-engine and single-engine taxiing [4] [5]. In the former, all aircraft engines are used for taxiing while in the latter only a single engine is used [6] [7].

Engineless concepts for aircraft taxiing techniques are broadly divided into onboard and external systems. Onboard systems typically consist of electrical motors installed in either the main landing gear or the nose wheel, a power converter, a control system and an electrical energy source [3]. WheelTug [8] is such a system which was installed and tested in a Boeing 767. The system consists of two induction motors manufactured by Chorus Motors and installed at the nose wheel. The APU is used to power the motors during taxiing operation. This system is advantageous as it reduces the taxiing time. In a collaboration between DLR and Lufthansa Technik [3] [9] an onboard taxiing system was developed using brushless DC motors which were also installed in the NLG. The power was derived from fuel cells. The system was tested onboard an Airbus A320 at the Hamburg airport in 2011. Conversely, the Electric Green Taxiing System (EGTS) [3] was developed by Safran and Honeywell. The system consists of a rectifier, a control unit and a traction motor installed on the main landing gear. EGTS was successfully tested at the Paris Air Show 2013. The system achieved a speed of 20 knots at the Toulouse Airport.

On the other hand, external engineless taxiing makes use of tow trucks which pulls the aircraft along the entire taxi route. The tow trucks can be powered by diesel/gasoline ICE engines or may be fully electric. The advantage of external taxiing is that they are noninvasive to the aircraft design [3] [5] and no additional weight is added to the aircraft. One such example of external taxiing systems is Taxibot [10] [11] [12]; a semi-autonomous hybrid tractor design for pushback, taxi-in and taxi-out procedures. The truck is run on diesel engines with electric motors installed in the four wheels. The aircraft direction is controlled by the pilot through the tiller as in normal taxiing. Sensors installed in the vehicle detect the steering of the NLG and other wheels are steered accordingly while the braking is carried out using the main landing gear. Taxibot has been certified for use on Boeing 737 and Airbus A320 aircraft models. Maximum power achieved by Taxibot is around 500 kW and it has reached the speed of 45 knots towing a B737 aircraft at MTOW [3]. It is being operated by Lufthansa at the Frankfurt International Airport since Nov 2014.

3. Mathematical models

To establish the environmental impact for each technology route, the paper develops a method by which the taxiing route is analyzed and broken down into a mathematical model. This is then used to calculate the energy requirement for the taxiing process. By establishing the source of energy powering the technology, the equivalent emissions index is used to determine the overall emissions throughout the taxiing process. Figure 2 provides a schematic of this process. The following sections provide more detail into each of these steps.

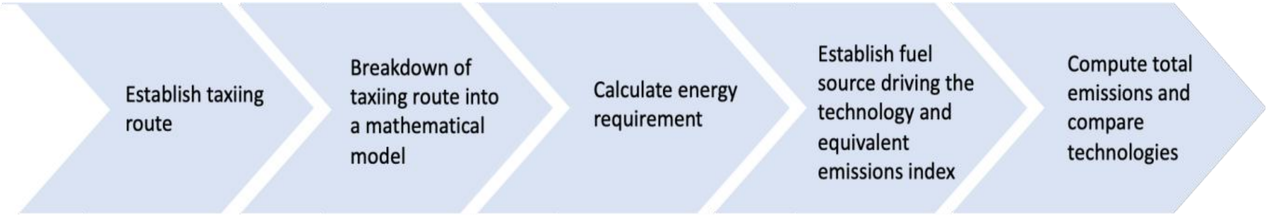

Figure 2 - Schematic showing the process for comparing the environmental impact of different taxiing technologies.

3.1 Establishing the taxiing route and developing a mathematical model

Throughout this paper, a taxiing route which consists of four segments and four stops is considered. The segments are divided into accelerating, constant velocity and braking components. The Figure 3 given below shows a transformation from a taxiing route on an aerodrome to segments and velocity components. The force required to propel the aircraft has been discussed in [13] which proposes a model for computing energy needed for taxiing. The computation incorporates components signifying the aerodynamic drag, tractive forces and the taxiway and runway slopes. It also takes into account headwind, coasting speeds, acceleration and deceleration during taxiing. The model evaluates tractive force, energy and power requirements. This model was tested on six different category aircrafts and a comparison was drawn.

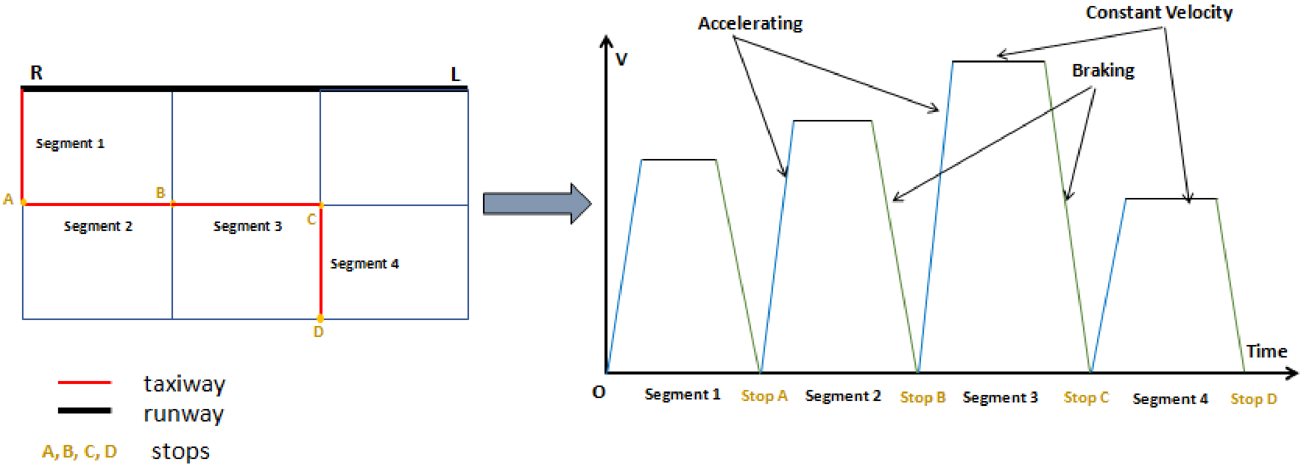

Figure 3 - Transformation from a taxiing route on an Aerodrome to a mathematical model using segments.

3.2 Calculation of the energy requirement for taxiing

Having established the route and the forces required to move the aircraft, the energy required for taxiing along a particular route is computed with designated values of velocity, acceleration and deceleration and standard airport taxiway characteristics. The total work or energy used during taxiing segments can be computed using the following equation:

$$A_{tot} = \sum_{i=1}^{4} A_i = \sum_{i=1}^{4}\left(\int_{s_{i-1}}^{s_i} F_i * ds\right) = \sum_{i=1}^{4}\left(\int_{t_{i-1}}^{t_i} F_i * v_i(t) * dt\right) \qquad (1)$$

Where:A_{tot} is the total energy, F_i is the force, *ds* is a small distance, v_i is the velocity and *dt* is a finite time.

Using Newton's second law of classical mechanics, the total force (in horizontal direction) acting on an aircraft during taxiing operation can be written as:

$$\text{Force} = M_{eff}a = M_A.K.\frac{dv}{dt} = F_{tract} - D_a(v) - \mu_{CRR}(v).W_A.\cos\varphi - W_A.\sin\varphi \qquad (2)$$

Where: *v* is the instantaneous groundspeed and *a* is the instantaneous translational acceleration. W_A is the aircraft weight, M_{eff} is the aircraft mass and *g* is acceleration due to gravity. F_{tract} is the traction force, D_a is the aerodynamic drag, μ_{CRR} is the rolling coefficient and φ is the taxiway slope in radians. For small angles φ, $\cos\varphi = 1$, $\sin\varphi = \varphi$

Equation (2) can be rearranged as follows:

$$F_{tract} = M_A.K.\frac{dv}{dt} + D_a(v) + \mu_{CRR}(v).W_A + W_A.\varphi \qquad (3)$$

By substituting the traction force (3) into (1) gives:

$$A_{tot} = \sum_{i=1}^{4}\left(\int_{t_{i-1}}^{t}\left(M_A.K.\frac{dv}{dt} + D_a(v) + \mu_{CRR}(v).W_A + W_A.\varphi\right) * v_i(t) * dt\right) \qquad (4)$$

The rolling resistance μ_{CRR} was defined as:

$$\mu_{CRR} = \mu_0\left[1 + \frac{v}{v_0}\right] \qquad (5)$$

Where: μ_0 is the rolling resistance constant (assumed to be 0.01), *v* is the aircraft velocity and v_0 is a reference point of 80 knots.

The aerodynamic drag was computed using:

$$\mathrm{D_a = G.(v + v_w)^2, \;\; where\; G = \frac{1}{2}\rho_{SL} S C_{D_{taxi}}} \tag{6}$$

Where: ρ_{SL} is the density at sea level, S is the wing area. $C_{D_{taxi}}$ is the coefficient of drag during taxi, computed as:

$$\mathrm{C_{D_{taxi}} = C_{D_0} + \beta.K.C_L^2} \tag{7}$$

Where: C_{D_0} is the coefficient of drag at zero angle of attack, β is the ground effect influence factor, K is the coefficient of drag due to lift, C_L is the coefficient of lift.

The total tractive work or energy needed for taxiing for each taxiing route segment with constant headwind can be derived using the above mentioned equations:

$$\begin{aligned}\mathrm{Energy\;(A_{tot})} = {} & \mathrm{\frac{M_A.\kappa.v_i^2}{2} + M_A.g.\phi_i.s_i + M_A.g.\mu_0.s_i + M_A.g.\mu_0.\frac{v_i}{v_0}\left[s_i - \frac{1}{3}\frac{v_i^2}{2a_i}\right] +} \\ & \mathrm{G.\frac{v_i^2}{2a_i}\left[\frac{v_i^2}{2} + \frac{4}{3}v_i v_w + v_w^2\right] + G.(v_i + v_w)^2\left[s_i - \frac{v_i^2}{2a_i}\right]}\end{aligned} \tag{8}$$

Where: M_A is the aircraft mass, v_i is the taxiing speed, s_i is the taxiing distance, κ is the rotational inertia factor, a_i is the taxiing acceleration and ϕ_i is the taxiing slope.

Having established the taxi route and energy requirement to get the aircraft from point A to point B the following section computes the fuel consumption and emissions level for each technology.

3.3 Establishing the fuel consumption and emissions level

The fuel consumption and emissions level for aircraft taxiing is dependent on the technology being adopted. Therefore, this section will discuss each technology and compute its fuel consumption and emission level individually.

3.3.1. Full-engine taxiing:

Zhang et al. [4] suggest fuel consumption models for full and single engine taxiing. The model also considers the low visibility and taxiing conflict information. This model was further developed to compute the emissions from the engines. In the single-engine taxiing scenario, one engine is reserved during taxiing. It also considers the preheating of the other engine which is necessary before entering into the runway. The calculation model was constructed on the basis of ICAO database. This model utilises fuel flow, taxiing time, number of engines and low visibility factor to compute fuel consumption needed for taxiing. The model can also incorporate states (such as acceleration, deceleration and waiting) during conflict situation during taxiing. The full engine taxiing method involves usage of all aircraft engines for taxiing operation. The aircraft engines are typically run at 7% thrust with brakes on. The fuel consumption using full engine taxiing can be was defined in [3] as:

$$\mathrm{Fuel\;Consumption} = \sum \mathrm{t * n * f * \alpha} \tag{9}$$

Where: *t* is the taxiing time, *n* are the number of engines, *f* is the fuel flow and α is the coefficient of low visibility weather. The fuel flow *f* is defined as:

$$\mathrm{f = Thrust\;needed\;for\;taxiing * TSFC} \tag{10}$$

where $TSFC$ is the thrust specific fuel consumption.

Conversely the coefficient for low visibility (α) is defined as:

$$\alpha = \frac{\bar{\mathrm{V}}_{\mathrm{normal}}}{\bar{\mathrm{V}}_{\mathrm{low\ visibility}}} \tag{11}$$

Where: $\bar{V}_{normal}$ is the average taxiing velocity and $\bar{V}_{low\ visibility}$ is the average taxiing velocity in low visibility conditions.

The results obtained from the equation 9 for the fuel consumption using full engine taxiing were verified from the fuel consumption models as following (equations 12 and 13) [14]:

$$\text{Fuel Consumption (kg)} = (a_1 + b_1 * t + c_1 * n_s + d_1 * n_t) * \sqrt{T_{amb}} \tag{12}$$

Where: $\mathrm{T_{amb}}$ is the ambient temperature at the airport, $\mathrm{a_1}$, $\mathrm{b_1}$, $\mathrm{c_1}$ & $\mathrm{d_1}$ are the empirical parameters estimated by regression, t is the taxiing time, $\mathrm{n_s}$ is the number of stops during taxiing and $\mathrm{n_t}$ is the number of turns during taxiing.

$$\text{Fuel Consumption (kg)} = (a_2 + b_2 * t + c_2 * n_a) * \sqrt{T_{amb}} \tag{13}$$

Where: $\mathrm{a_2}$, $\mathrm{b_2}$ & $\mathrm{c_2}$ are the empirical parameters and $\mathrm{n_a}$ are the acceleration events during taxiing. An acceleration event occurs when an acceleration of 0.15 m/sec^2 is observed for 10 sec.

The table 1 given below enlists the empirical parameters for narrow-body aircrafts such as A320 and B737 used in equations 12 and 13.

Table 1 - Empirical parameters showing the fuel consumption for a narrow-body aircraft

Empirical parameters	$\mathbf{a_1}$ kg/k^0.5	$\mathbf{b_1}$ kg/sec-k^0.5	$\mathbf{c_1}$ kg/k^0.5	$\mathbf{d_1}$ kg/k^0.5	$\mathbf{a_2}$ kg/k^0.5	$\mathbf{b_2}$ kg/sec-k^0.5	$\mathbf{c_2}$ kg/k^0.5
Values	-0.26	0.0125	0.1	-0.02	-0.0896	0.0124	0.1174

3.3.2 Single-engine taxiing:

In the single engine taxiing method, the aircraft reserves one engine during the taxiing operation. Therefore, only one engine is responsible for providing thrust and the resulting emissions during the taxiing process. However, the reserved engine has to be preheated before entering the runway. The preheating time is 2-5 minutes. The engines are also needed to cool down after landing operation before entering taxiing. Studies have shown that this strategy reduce fuel burn and associated costs and emissions by approximately 32% [5]. However. operating with a single engine also requires additional system checks to be carried out which necessitates crew attention. The fuel consumption during single-engine taxiing operation can be computed using the equations developed in [3] and replicated here:

$$\text{Fuel Consumption} = \sum \mathrm{t} * \frac{\mathrm{n}}{2} * \mathrm{f} * \alpha + \mathrm{t} * \frac{\mathrm{n}}{2} * \mathrm{f} * \min(\mathrm{t_i} * \alpha, 0.5) \tag{14}$$

Where: $min\ (t_i * \alpha, 0.5)$ indicates that if the taxiing time is longer than 5 min, then this preheating time is set to 5 min and if the taxiing time is less than 5 min, then this preheating time is taken as taxiing time.

3.3.3 Engineless taxiing using external systems:

Engineless taxiing using external systems makes use of a specialized tow truck which delivers the aircraft from the gate to the runway (and vice versa). Examples of such technologies include

Taxibot, developed by Israel Aerospace Industries (IAI). The tow truck could be fuelled with diesel or gasoline, or could be fully electric. The fuel consumption for a tow truck using an internal combustion engine was defined in [5] as:

$$\text{Fuel Consumption } = 2.5 * \text{t} * \text{bhp} * \text{f} \tag{15}$$

Where: t is the taxiing time, bhp is the break horsepower of the engine and f is the fuel flow.

Usually, taxiing using a tow truck is much slower than taxiing using aircraft engines. This model incorporates a factor of 2.5, which takes into account the actual taxiing time. The calculation for an electric tow truck was also carried out. The power needed by an electric tow truck for taxiing can be found using the following equation:

$$\text{Power (in kWh) } = \frac{\text{A}_{\text{tot}} * \text{t (in hr)}}{\text{t (in sec)} * 1000} \tag{16}$$

Where:A_{tot} is the total energy (from equation 1) and t is the taxiing time.

3.3.4 Engineless Taxiing using onboard systems:

Engineless taxiing using onboard operations makes use of technology that is inbuilt onto the aircraft. Such examples include WheelTug [8] and EGTS [9]. While WheelTug installs electrical motors on the nosewheel of the aircraft, EGTS installed electrical motors on the main landing gear. However, both systems require the APU to power the machines.

Thus, the fuel consumption required by the APU for taxiing can be computed using the equation:

$$\text{Fuel Consumption} = \text{ t} * \text{f} \tag{17}$$

Where: t is the taxiing time and f is the fuel flow (APU jet fuel)

3.4 Emissions

3.4.1 Emissions for fuel-driven taxiing

Table 2 shows the emissions indices of different pollutants (Hydrcarbons - HC, Nitrous oxides – Nox, Carbon monoxide – CO and Carbon dioxide – CO2) according to various fuels (Diesel, Gasoline and Jet fuel). The emissions indices belong to the common pollutants emitted from fuels. Emission indices are thoroughly explained in [3]. These indices were used to compute emissions of various pollutants from the fuel consumption found in the previous section.

Table 2 - Emission indices of pollutants from various types of fuel

	Pollutants	Diesel fuel	Gasoline fuel	Jet fuel
1	HC	1.2 (gm/bhp-hr)	4 (gm/bhp-hr)	3.8 (gm/kg)
2	NOx	11 (gm/bhp-hr)	4 (gm/bhp-hr)	9.4 (gm/kg)
3	CO	4 (gm/bhp-hr)	240 (gm/bhp-hr)	37.6 (gm/kg)
4	CO2	3169 (gm/kg)	3169 (gm/kg)	3155 (gm/kg)

3.4.1 Emissions for electrically driven external taxiing

Electric powered tow trucks produce less pollutant emissions on the ground. However, they still produce emissions from the electricity production at the power plants, which needs to be accounted for. In this research paper, the power requirement for an all-electric tow truck to follow the taxiing route was established as 41.02 kWh. This energy is supplied through batteries which will need to be charged from the grid. Various countries have different emissions factors accounting for their electricity production. This paper considers the examples of China and Europe as shown in Table 3.

Table 3 - CO2 emissions factors and emissions for China & Europe in case of a full-electric taxiing tow truck

	CO2 emissions factor (kgCO2/kWh)	CO2 emissions (kgCO2)
China	0.555	22.7661
Europe	0.275	11.2805

Having reviewed the mathematical model which governs the energy requirement along a specific taxiing route, and the resulting fuel consumption and emissions for the various technologies, the following section will compare the results.

4. Results

Table 4 shows the results of energy needed for taxiing for 1st, 2nd, 3rd & 4th segments, with reference to Figure 3.

Table 4 - Energy needed for taxiing for different segments

Energy needed for taxiing	Segment 1 MJ	Segment 2 MJ	Segment 3 MJ	Segment 4 MJ
Values	19.6	35.6	41.5	49.2

Depending on the taxiing technique and technology being utilized, the energy required in each segment is satisfied at an associated cost of fuel consumption and emissions produced. Figure 4 shows a comparison of the fuel consumption for the different taxiing technologies. It can be shown that full engine taxiing consumes the most fuel, followed by a single engine taxiing strategy. The results are in line with the literature which show around 30% reduction in fuel and associated emissions [5]. These are followed by towtruck taxiing methods and onboard system such as WheelTug or EGTS powered through the APU. Totally electric systems are not considered to consume any fuel on the ground. However, an emissions level was associated for the charging of their battery through the emissions indices.

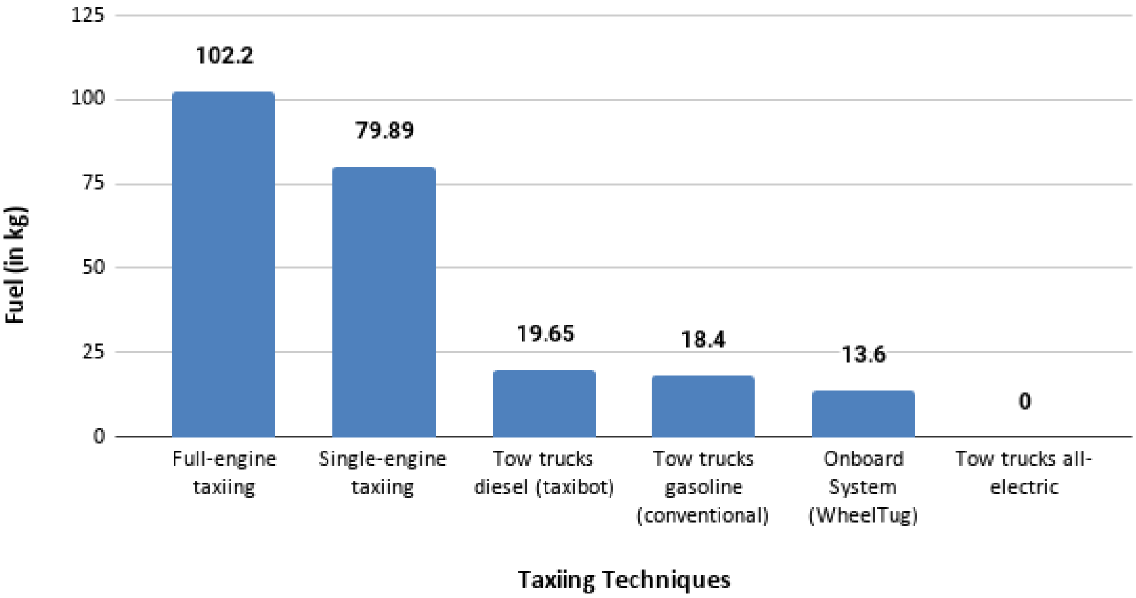

Figure 4 - Comparison of fuel consumption by different taxiing techniques

Due to their chemical composition, the combustion of different fuels result in different emissions. Table 5 details the computed results of HC, NOx, CO and CO2 emissions from the fuel for the different taxiing strategies and associated fuels. The results follow similar trends found in the literature [18], [19]. The comparison of the emissions for the various taxiing strategies are depicted in Figure 5 and Figure 6. It can be shown that full engine taxiing offers collectively the most emissions. This is followed by single engine taxiing. Conversely, diesel powered tow trucks would lower HC, CO and CO2 but increase has NOx emissions that are comparable to full engine taxiing and higher to single engine taxiing. Likewise, gasoline powered tow trucks would offer a reduction in HC, NOx and CO2 but has CO emissions comparable to full engine taxiing and higher than single engine taxiing. Onboard systems powered by the APU offers the greatest overall reduction in overall emissions for fuel powered systems. Unfortunately, the indices for generation of HC, NOx and CO in power generation systems were not readily available in the literature and therefore the effect of charging electric tow trucks could not be established and compared to other strategies. However, this technique offered the biggest reduction in CO2 emissions.

Table 5 - HC, NOx, CO and CO2 emissions for different taxiing methods

	Taxiing methods	**HC (gm)**	**NOx (gm)**	**CO (gm)**	**CO2 (kg)**
1	Full-engine taxiing	388.36	960.68	3842.72	322.441
2	Single-engine taxiing	303.582	750.966	3003.864	252.05295
3	Tow trucks diesel (taxibot)	102	935	340	62.27085
4	Tow trucks gasoline (conventional)	65	65	3900	58.3096
5	Onboard System (WheelTug)	51.68	127.84	511.36	42.908

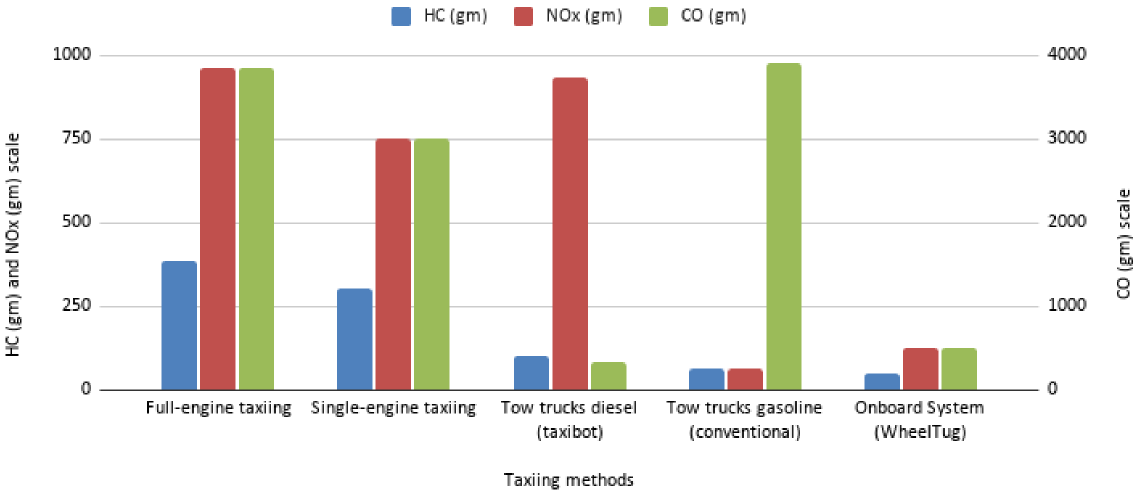

Figure 5 - Pollutant emissions from various taxiing techniques

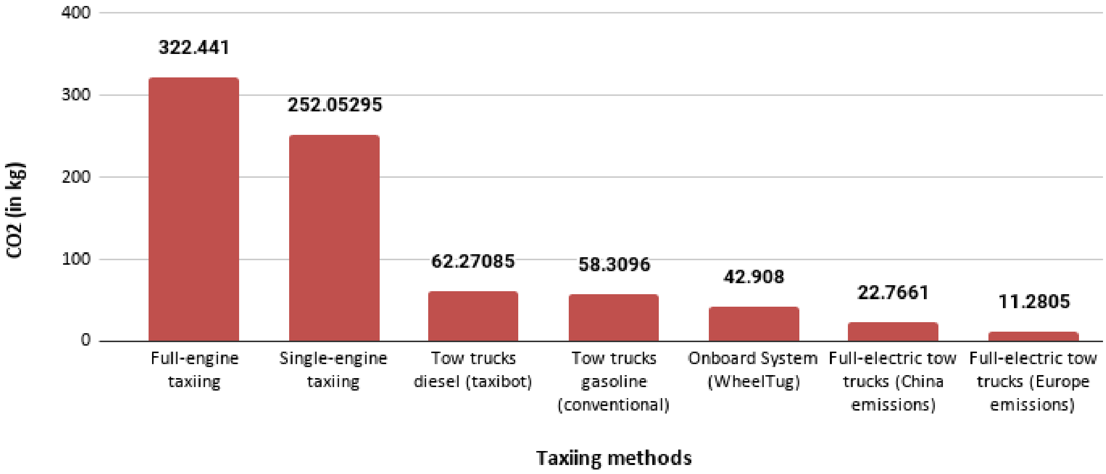

Figure 6 - CO2 emissions from various taxiing techniques

6. Discussion and Conclusion

Despite that various strategies have been proposed in the literature, their effectiveness to reduce the environmental impact of aircraft movement on the ground remains unclear. Indeed, the technological route to achieve zero emissions from aircraft movement on the ground is still uncertain. The paper fills this gap by developing a tool for estimating the environmental impact of various aircraft taxiing solutions. The tool translates the taxiing route into an energy demand and then assess the fuel consumption required by the various taxiing strategies and outputs their resulting emissions.

It was shown that as we move from away from using main thrust engines for taxiing and adopt engineless taxiing methods, there is a clear impact and a reduction in emissions. However, engineless taxiing still present significant challenges.

Diesel-powered tow trucks suffer from high NOx emissions while gasoline-powered tow trucks suffer from high CO emissions. Fully electric tow trucks offer the highest benefit in CO2 reduction. However, their contribution to HC, NOx and CO remains unsolved due to missing emissions indices in the literature. It is safe to assume that the collective emissions for electric tow trucks would decrease as more renewable energies are adopted and integrated into the power generation system of various countries. While an external engineless taxiing solution can be retrofitted to the current aircraft fleet, achieving this still requires to address a number of challenges primarily:

- A significant investment by the airport and/or service provider to upgrade or introduce a fleet of tow trucks;
- Setting up adequate taxiing infrastructure within airports,
- Management of tow trucks and taxiing to ensure no delays are created due to added system complexity, and
- Ensure that no conflicts and compromises to safety due to added complexity.

Conversely, despite that onboard taxiing solutions have demonstrated an overall reduction in emissions on the ground, it is still unclear if this is offset to the flight portion due to the heavier systems. The APU is now required to deliver larger amounts of power to drive the electric motors and therefore a larger generator is required. This technology is also challenging to retrofit and therefore make an impact the existing fleet. The authors are aware of advances in fuel cell and battery technologies which could be used to provide power during taxiing. However, their effect is still to be considered in a separate work.

Acknowledgement
This work is a result of project KERS-air. Project KERS-air is financed by the Malta Council for Science & Technology, for and on behalf of the Foundation for Science and Technology through the FUSION: R&I Technology Development Programme.

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