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The Future of Conventional Aircraft Ground Propulsion Systems in Relation to Fuel Consumption and CO_2 Emission

Iniobong Edem[a], Owunna Ikechukwu[a], Ikpe Aniekan E. [a,*], Ememobong E. Ikpe[b]

[a] *Department of Mechanical Engineering, Coventry University, Priory Street, CV15FB, West Midlands UK*
[b] *Department of Instrumentation and Control, Exxon Mobil Producing Nigeria, Eket, Akwa Ibom State, Nigeria*

Abstract

Aircraft spends a minimum of 20 minutes using its main engine to taxi from the airport terminal gate to the runway, where the aircraft takes-off and similarly to the terminal gate after landing. During taxi operation, aircraft burns a lot of fuel, generates large quantity of emissions and the engine in the process of taxiing is exposed to damage due to Foreign Object Damage (FOD). This results in huge operational and maintenance cost as well as carbon emission tax which are all at the expense of the airline. EGTS is a recent technology designed to prevent aircraft from using its main engine for taxi operation and this in turn reduces the rate of fuel consumption, slashes carbon emissions and minimises operational and maintenance cost. This paper examines the viability of using EGTS in single engines for taxi operation rather than the aircraft engine. Block fuel savings was calculated for two engine, single engine and hybrid aircraft and it was observed that two engine aircraft using EGTS saved 110kg block fuel, single engine saved 74kg and for hybrid engine the block fuel savings was 50kg. Block fuel savings was calculated for aircraft such as airbus A320, airbus A380, Cessna 172 and A600ST and it was observed that EGTS is more compatible with airbus A320 but was not recommended for A600ST and A380 due to extra weight implication and for Cessna 172, EGTS was not necessary because the aircraft weight is low and consumes less fuel already. It was observed that the higher the aircraft weight including the extra weight of EGTS, the higher the fuel consumption emission as well as the torque required to overcome drag force when the aircraft operates in air. CO_2 emission was also calculated for aircraft with EGTS and aircraft without installation, the result for aircraft with EGTS showed 797.56kg reduction of CO_2 emission when compared to aircraft without EGTS. Comparably, EGTS was proven to be viable in terms of fuel savings, CO_2 emissions, operational and maintenance cost than its contemporary Ground Propulsion Systems (GPS) for single aircraft engines and therefore, was recommended for aircraft in airbus A320 category to help minimise global warming which results from CO_2 emission during taxing operations.

Keywords: *Aircraft, CO_2 Emission, Fuel Consumption, Weight, Ground Propulsion, Cost Savings*

1. Introduction

The concern for minimisation of operation cost, improvement of fuel efficiency and reduction in Green House Gas (GHG) emissions during taxi of aircraft has brought various technologies into existence, in attempt to maximise the overall efficiency of aircraft operations [23]. However, the idea of aircraft taxing has always been an essential procedure required for taking off and landing of an aircraft through the use of engine thrust. Taxiing in this context implies the movement of an aircraft using its own power from one location to another on the ground through taxiways. This is not quite different from taxi-out which often involves push-back, an action in which an aircraft moves backward from the airport gate using external vehicles such as tugs or pushback tractors and the process of connecting and disconnecting the tug potentially delay the flight from schedule [1]. As shown in Figure 1, the principles adopted by taxi-out is very similar to that of taxi-in, in a sense that both taxiing processes describes movement of the aircraft to and from the terminal gate (taxing-out prepares the aircraft for taking off whereas taxing in prepares the aircraft for landing) irrespective of the means used to enable the aircraft movement [10].

* Corresponding author.
E-mail: ikpeaniekan@gmail.com

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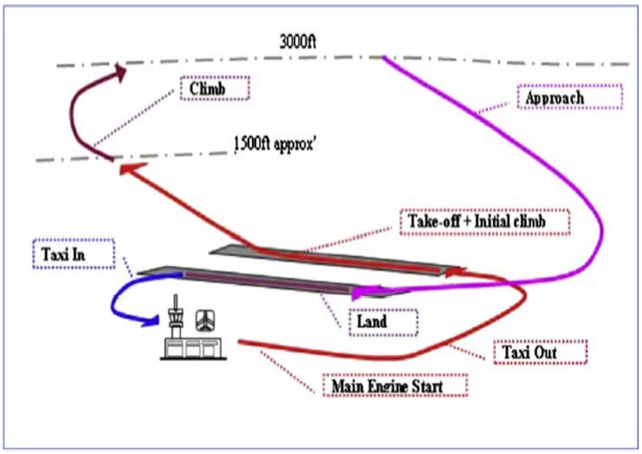

Figure 1: Procedures Required for Taking-off and Landing of an Aircraft [10]

Each of these taxiing processes which functions when the engine is engaged results in fuel consumption, thereby increasing operational cost required for the trip and Green House Gas (GHG) emissions. For example, Lufthansa Technik [17] reported that about 3% of kerosene is consumed during aircraft taxing. Moreover, Jordan [16] reported that fuel expenditure incurred by airline industry is about 32% of the industry's budget, the second highest expenditure after labour. From the statistics published by the International Aviation Transport Association (IATA) the airline industry incurred total expenses of about $209 billion on fuel in 2012 which was over $33 billion higher than the amount spent on fuel in 2011 [13]. In addition, environmentally friendly energy resource and reduction of Green House Gas (GHG) effect has gained much attention in the world today, and the idea of aircraft taxiing is likely not an environmentally compatible technology with cost effective ground operations. However, the development of innovative taxing system also referred to as Aircraft Ground Propulsion (AGP) system such as Electric Green Taxiing System (EGTS), TaxiBot, wheel tug etc can provides a more viable technology that is environmentally viable, cost effective in terms of fuel cost and also saves time, energy and resources required for taxi-out, pushback, taxi-in etc. Electric taxiing systems is a leading technology in the aircraft industry that can effectively shape the operations of aircraft taxiing with its innovative concept, as it uses electrical power supplied by electric motors and this in turn reduces the rate of fuel consumption by the aircraft as well as reduction of GHG emissions such as CO_2 (one of the major promoter of global warming) during taxi operations to and from the Airport terminal gate [2].

2. Overview of Aircraft Ground Propulsion Systems (AGPS)

With the rise of oil prices and environmental pollution, airline companies are looking for new ways to save fuel, reduce operational costs and also reduce emission of environmental pollutants. In 2005, the aviation sector was responsible for about 3.5% of total anthropogenic contributions which increased radiative forcing. It is even expected to rise more to 4.0-4.7% by 2050. These numbers exclude the large uncertain impact of Aviation Induced Cirrus (AIC). As at 2010, the cost of fuel constituted almost 30% of America's airline expenses and about 29% was consumed to passenger revenue [6]. Aircraft taxing operations represent a significant part of an airlines fuel cost. For short haul fleets operating a single aisle aircraft, up to 6% of the total fuel consumption is being used for taxiing only. All short haul aircrafts consumes about 5 million tons of fuel per year during taxing operations alone [22]. However, reducing fuel consumption is very important in the aviation industry because if fuel consumption is reduced, the benefits will include low environmental emissions, plus low operational cost on airline companies which in turn reduce the amount of fuel during various aircraft operations. Therefore, using electric taxi system is one of the ways of reducing fuel consumption and emissions during taxiing airline companies. For example, Johnson and Gunawan [15] in their findings estimated that with an electric taxi installed on an light passenger aircraft like a Boeing 737or Airbus A320, the fuel burn will reduce by 1.1% and 3.9%. Jerew [14] reported that the fuel burn that occur when using only one engine while taxiing out, and concluded that the fuel consumption and emissions used for ground operations can actually be cut to about 25% to 40% by using an electric taxiing system. This review will focus on the conventional electric taxi systems, particularly Electric Green Taxing System (EGTS), and how fuel consumption and GHG emissions by aircrafts can be minimized using EGTS. Reference will also be made on existing work/research, performance and evaluation analysis, system requirement, cost and benefits as well as operational issues of EGTS. As mentioned earlier, the aircraft moves in the backward direction away from the airport gate during pushback, and this is achieved by means of external power such as pushback tractors or tugs. This is one of the actions that take place during conventional taxiing where the aircraft engine operates at minimal speed, resulting at extremely low efficiency and high emissions. Consequently in the case of EGTS, landing gear brakes are engaged in this stage, resulting in high energy consumption and intense heating effect. To minimize the negative effects on operational cost and the immediate environment as a result of these operations, Aircraft Ground Propulsion systems (AGPS) such as TaxiBot, EGTS, WheelTug etc have been necessitated in recent times as alternative technology to salvage the increasing effect particularly in the aspect of minimizing global warming which aircraft operations is likely one of the potential agents contributing to such effect. Other suggested solutions that can minimize excessive aircraft fuel consumption and emissions during taxing at the airport runway includes the development of procedures that are eco-friendly such as single-aisle engine [9, 11], effective control in the rate of Pushback [24], implementation of Spot and Runway Departure Advisor (SARDA) [12] etc. while the other approach may include implementation of technologies such as engineless taxiing, design of fuel-efficient engines as well as alternative jet fuels [21]. Existing technologies with respect to taxi operation of an aircraft in relation to AGPS as well as operations, effects, usefulness, pros and cons of propulsion systems relative to aircraft will be considered in this paper. Each aircraft taxi system comes with its own unique design which either serves as advantage or disadvantage to the performance of the aircraft during taxi operation. For example, the difference in the design and operation of wheeltug and EGTS is that wheeltug applies the principles of pulling the aircraft using the nosewheel while EGTS uses the principles of pushing during taxi operation and the effect results in differences in speed, turning radius, efficiency etc. The advantages and disadvantages of conventional AGPS can be summarised as shown in Table 1.

Table 1: Advantages and Disadvantages of Conventional eTaxi Systems

TaxiBot-Advantages	TaxiBot-Disadvantages
i. Can operates at a high speed of about 23kt. ii. Reduction of GHG emissions in-flight. iii. Adds no weight to the aircraft. iv. Saves fuel during aircraft taxi operation. v. Protect aircraft engine from FOD. vi. Reduce operational and maintenance cost.	i. Connection/disconnection of the aircraft nosewheel to the TaxiBot takes time. ii. Not fully autonomous as driver is required in some phases.
EGTS-Advantages	**EGTS-Disadvantages**
i. Can operates at a high speed of about 20kt ii. Reduction of GHG emissions during taxi operation. iii. Saves fuel during aircraft taxi operation. iv. Protect aircraft engine from FOD. v. Reduce operational and maintenance cost.	i. The additional weight slightly increases fuel consumption and GHG emissions in-flight. ii. Installation of electric motor on the main landing gearwheel affects surrounding components but improves traction. iii. Breaks generate a lot of heat and therefore require time to cool down.
WheelTug-Advantages	**WheelTug-Disadvantages**
i. Reduction of GHG emissions during taxi operation. ii. Saves fuel during aircraft taxi operation. iii. Protect aircraft engine from FOD. iv. Reduce operational and maintenance cost. v. The electric motor on the nosewheel adds about 140kg to the gross weight of the aircraft. vi. Can operate at a high speed of about 10kt. vii. Maneuverable, speed-up boarding and time saving.	i. The additional weight slightly increases fuel consumption and GHG emissions in-flight. ii. Installation of electric power unit on the nosewheel results in poor traction performance. iii. Relatively low speed (about 10kt).

3. Methodology

The methodology adopted for this paper involves the use of basic formulas to determine some parameters that are of great importance to aviation industry. For example, it has been discussed earlier that airline operators incur a lot of expenses during taxi operations between the terminal gate and the runway. Looking at the statement from a more critical aspect, it can be observed that a number of factors such as traffic, distance travelled by the aircraft, weight of the aircraft, engine size etc all contribute to the fuel consumption rate of the aircraft during taxi operation. Although a few alternative taxi systems has emerged in this area, it is important to validate any data relating to the taxi systems in order to determine their viability and suggest recommendations that can save the increasing cost incurred by airline operators. Hence, the fuel consumption rate by different aircraft using EGTS and the same aircraft without EGTS as well as the cost involvement was examined. Estimations from existed work will be used to backup the examinations which will cut across different aspects of aircraft taxi systems. Finally, CO_2 emission for single aisle aircraft engine such as airbus A320 (which is the reference aircraft in this paper) with and without EGTS will also be considered.

3.1. The A320 is the reference aircraft,

The eTaxi system adds additional weight of over 400kg to the gross weight of the aircraft; but the effect on block fuel is minimal. Therefore, on a 500 NM (Nautical Mile) flight range, the 400kg extra weight is included and this amounts to additional 16kg of fuel degradation for a trip in this range.

3.2. Taxi Fuel

Double engines Taxi = 12.5kg/min
Single engine taxi + APU = 9.5kg/min
Hybrid electric taxi (one engine at idle + APU) = 7kg/min
Full electric taxiing (EGTS) = 2kg/min
Total taxi time (taxi-out + taxi-in) = 20 minutes
Time considered for engine warm up = 5 minutes
Time considered for engine cooling = 3 minutes
Tractor connection and disconnection time is not included in the above estimations [19].From the above parameters, the block fuel saving for a flight of 500 nautical miles for double engines with full etaxi, Single engine with full etaxi, Hybrid etaxi with double engines and Hybrid etaxi with 2 engines can be calculated using equation 1;

Trip fuel degradation on 500nm - (engine taxi trip fuel-fuel used by APU) x (total taxi time) - (engine warm up + cooling time) [19] (1)

Substituting taxi trip fuel for the following engines we have;

3.2.1 Block fuel saving for Double engines with Full eTaxi (EGTS)

Taxi trip fuel for full etaxi with double engines Taxi = 12.5kg/min
Substituting 12.5kg/min into equation 1 we have

$$\text{Fuel saving} = 16\text{kg} - (12.5\ \text{kg/min} - 2\ \text{kg/min}) \times (20\ \text{min} - (5\ \text{min} + 3\ \text{min}))$$

$$16\text{kg} - (10.5\text{kg/min} \times 12\text{min}) = -110\text{kg}$$

3.2. 2 Block fuel saving for Single engine with Full eTaxi (EGTS)

Taxi trip fuel for full etaxi with single engine Taxi = 9.5kg/min
Substituting 9.5kg/min into equation 1 we have

$$\text{Fuel saving} = 16\text{kg} - (9.5\ \text{kg/min} - 2\ \text{kg/min})\ \text{x}\ (20\ \text{min} - (5\ \text{min} + 3\ \text{min}))$$

$$16\text{kg} - (7.5\text{kg/min x } 12\text{min}) = -74\text{kg}$$

3.2.3 Block fuel saving for Hybrid eTaxi using 2 engines (Taxi bolt)

Hybrid eTaxi in principle uses only one of its engine plus APU while the other engine is at idle mode. Therefore;
Taxi trip fuel for full etaxi with 2 engines Taxi = 7kg/min
Since one engine is in idle mode, we divide 7kg/min by 2 to obtain 3.5kg/min
3.5kg/min + APU (2kg/min) = 5.5kg/min
Equation 1 can be written as;

Trip fuel degradation on 500nm - (engine taxi trip fuel + fuel used by APU) x (total taxi time) - (engine warm up + cooling time) (2)

Substituting 3.5kg/min into equation 1 we have

$$\text{Fuel saving} = 16\text{kg} - (3.5\ \text{kg/min} + 2\ \text{kg/min})\ \text{x}\ (20\ \text{min} - (5\ \text{min} + 3\ \text{min}))$$

$$16\text{kg} - (5.5\text{kg/min x } 12\text{min}) = -50\text{kg}$$

Since only one engine is active in the case of hybrid etaxi with 2 engines, then only one engine will still be active in the case of single engine.

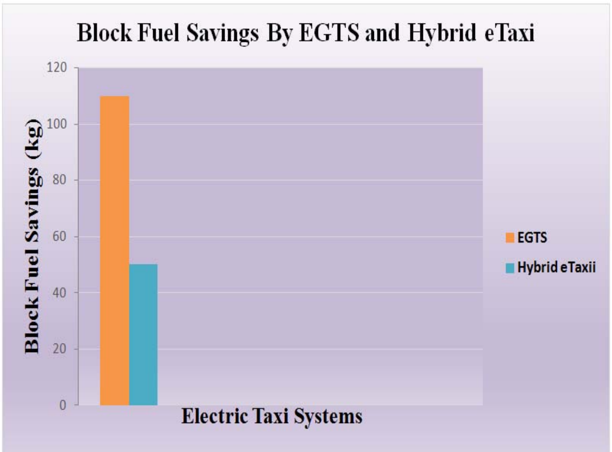

Figure 2: Block Fuel Savings by EGTS and Hybrid eTaxi

Table 2: Block fuel saving by EGTS and Hybrid eTaxi with Double engines

EGTS	-110kg
Hybrid eTaxi	-50kg

3.3 Cost Saved Per Flight by EGTS and Hybrid eTaxi

1kg of fuel = £0.5
To determine the cost saved by EGTS and Hybrid eTaxi per flight, the block fuel saving is multiplied by £0.5 to obtain the values represented in the Table 3

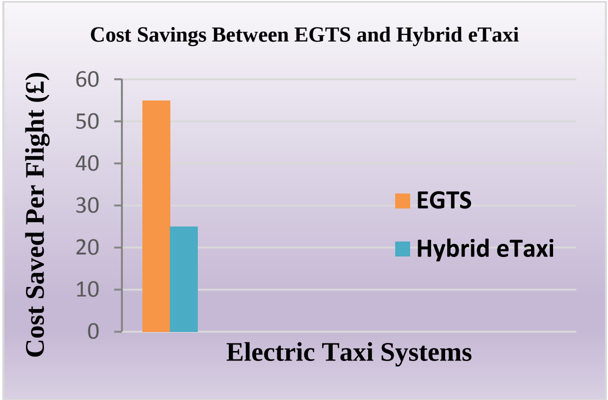

Figure 3: Cost Saved per Flight (£) using EGTS and Hybrid eTaxi

Table 3: Cost Saved per Flight (£) using EGTS and Hybrid eTaxi

Electric taxiing comparison	Cost saved per flight (£)
EGTS	55
Hybrid eTaxi	25

3. 3. 1 Performance of EGTS on other aircrafts in terms of block fuel savings in other Aircraft

As mentioned earlier, the nautical miles (Nm) which is the distance travelled by the aircraft has an influence on the fuel consumption rate which in this case is the trip fuel degradation. However, trip fuel degradation involved in the nautical miles of some aircraft operating with EGTS will be used as reference to calculate the block fuel savings for 2 engines. Therefore, using the following formula shown in equation 3, the block fuel savings for different aircraft in the A320 family can be calculated as follows;

Trip fuel degradation on 500nm - (2 engine taxi trip fuel – fuel used by APU) x (total taxi time) – (engine warm up + cooling time) [19] (3)

3.3.2. Block fuel saving for A320 using EGTS over Nautical miles 700nm

Taxi trip fuel for full etaxi with 2 engines Taxi = 12.5kg/min
Trip fuel degradation = 22.4kg
Substituting 22.4kg into equation 3 we have

$$\text{Fuel saving} = 22.4\text{kg} - (12.5\ \text{kg/min} - 2\ \text{kg/min})\ \text{x}\ (20\ \text{min} - (5\ \text{min} + 3\ \text{min}))$$

$$22.4\text{kg} - (10.5\text{kg/min x } 12\text{min}) = -103.6\text{kg}$$

3.3.3. Block fuel saving for A380 using EGTS over Nautical miles 5000nm

Taxi trip fuel for full etaxi with 2 engines Taxi = 12.5kg/min
Trip fuel degradation = 160kg
Substituting 160kg into equation 3 we have

$$\text{Fuel saving} = 160\text{kg} - (12.5\ \text{kg/min} - 2\ \text{kg/min})\ \text{x}\ (20\ \text{min} - (5\ \text{min} + 3\ \text{min}))$$

$$160\text{kg} - (10.5\text{kg/min x } 12\text{min}) = -34\text{kg}$$

3.3.4. Block fuel saving for A600 ST using EGTS over Nautical miles 5510nm

Taxi trip fuel for full etaxi with 2 engines Taxi = 12.5kg/min
Trip fuel degradation = 176.32kg
Substituting 176.32 into equation 3 we have

$$\text{Fuel saving} = 176.32\text{kg} - (12.5\ \text{kg/min} - 2\ \text{kg/min})\ \text{x}\ (20\ \text{min} - (5\ \text{min} + 3\ \text{min}))$$

$$176.32\text{kg} - (10.5\text{kg/min x } 12\text{min}) = 50\text{kg}$$

3.3.5. Block fuel saving for Cessna 172 using EGTS over Nautical miles 475 nm

Taxi trip fuel for full etaxi with double engines Taxi = 12.5kg/min
Trip fuel degradation = 15.2kg
Substituting 15.2kg into equation 3 we have

$$\text{Fuel saving} = 15.2\text{kg} - (12.5\ \text{kg/min} - 2\ \text{kg/min})\ \text{x}\ (20\ \text{min} - (5\ \text{min} + 3\ \text{min}))$$

$$15.2\text{kg} - (10.5\text{kg/min x } 12\text{min}) = -110.8\text{kg}$$

From the following calculations, the block fuel savings by different aircraft using EGTS can be summarized as shown in Table 4.

Table 4: Block Fuel Savings by Different Aircraft Using EGTS

Aircraft type	Nautical miles(nm)	Trip degradation (kg)	Block Fuel saving(kg)
A320	700	22.4	-103.6
A380	5000	160	-34
A600 ST	5510	176.32	50
Cessna 172	475	15.2	-110.8

As represented in Figure 4, it can be observed that there is correlation between the literature in this study and the result obtained for EGTS in terms of the block fuel saving which is over -103kg for 700 NM flight. Similarly, the block fuel saving for Cessna 172 exceeds that of every other aircraft in this category and this could be due to the low trip degradation fuel (this implies that the weight of the aircraft is very low compared to other aircraft in this comparison) and the flight distance which in this case is over 475NM. The block fuel saving for A380 shows the least value of -34kg in this category which may be due to its weight compared to A600ST which the block fuel saving is 50kg, about 16kg higher than A380. In terms of efficiency, A320 and Cessna shows best efficiency in aircraft of this category and this is likely possible as a result of the EGTS installed on it. As mentioned earlier, EGTS adds additional weight to the gross weight of the aircraft which in turn affects efficiency of the aircraft and increases operational cost as well as carbon tax depending on the distance travelled. It is however observed that installation of EGTS on the main landing gear has its own disadvantage despite the fact that its improves traction performance, especially when the aircraft taxi's in undulating plane.

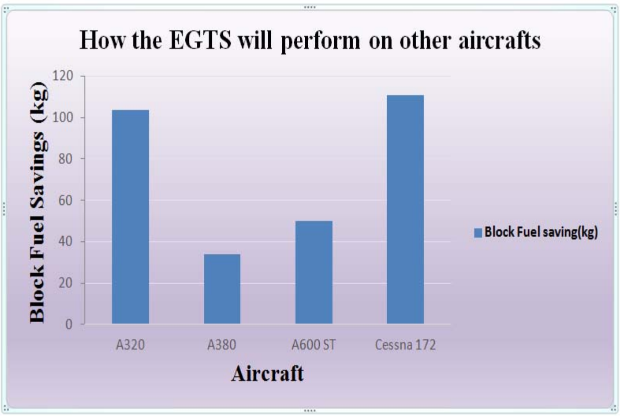

Figure 4: Block fuel savings by different aircraft using EGTS

3.4 EGTS Vs Normal Engine Taxing

Fuel burn per min for normal taxiing is 12.5kg/min but when EGTS is used, its 2kg/min and total taxing = 20mins [19].
Fuel burn during taxing = 12.5kg/min /20min= 0.625kg
For EGTS 2kg/min /20min= 0.1kg
The fuel consumption by aircraft using EGTS and normal engine during taxi operation can be summarized as shown in Table 5

Table 5: Fuel consumption by aircraft using EGTS and normal engine during taxi operation

Taxing	Fuel burnt (kg)
Normal taxiing	0.625
EGTS	0.1

As shown in Figure 5 above, it can be observed that the EGTS saves 0.625kg of fuel during taxing operation against 0.1kg of fuel saved during normal aircraft taxi where the engine is required to generate power needed for the operation. Hence, the result obtained in this case correlates with the information constituting the literature review concerning the efficiency of EGTS compared to taxi operation achieved through the use of the aircraft's main engine.

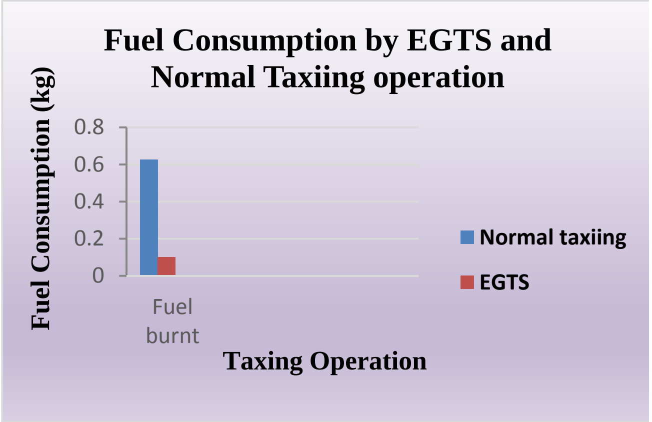

Figure 5: Fuel consumption by aircraft using EGTS and normal engine during taxi operation

3.5 The power required to drive the green-taxiing system prior to take-off and after landing reference aircraft A320

As mentioned earlier, EGTS requires power from the APU to enable movement. However, this section is meant to determine how much power that will be required by the APU to drive the aircraft using EGTS. This relates to the idea of evaluating the performance of EGTS on different weight aircrafts. To calculate the drag force acting on the aircraft (during taxiing or rolling prior to take-off) to oppose its motion, the following formula will be considered.

$$F = \text{Mass}_{\text{aircraft}} * g * C_{rr} \text{ [7]} \qquad (4)$$

Where
F is the rolling resistance force or rolling frictional force or rolling drag force. This is the force resisting the motion of the aircraft while rolling on the ground prior to take-off.
$\text{Mass}_{\text{aircraft}} = \text{Mass of Aircraft}$
g is the acceleration due to gravity
C_{rr} = Rolling resistance coefficient or coefficient of rolling friction of the aircraft.
C_{rr} is given as 0.008 [7]
Similarly, to find the driving Torque (T) required to overcome the Rolling resistance (R_r) of an aircraft tire for steady speed to be maintain on level ground surface (with no air resistance), equation 5 can be considered;

$$T = \frac{V_s}{\Omega} R_r \qquad (5)$$

Where
V_s is the linear speed of the aircraft
Ω is the rotational speed of the tire

These are the forces required to push the aircraft with zero air resistance per unit force of weight.

i. Maximum take-off weight for A320 = 73,500kg [3]
ii. Maximum take-off weight for A600ST = 155,000 kg [5]
iii. Maximum take-off weight for A380 = 590,000 kg [20]
iv. Maximum take-off weight for Cessna 172 = 1111kg [4]

3.5.1. Estimating the Power Required by A320, A600ST, A380 and CESSNA 172 Aircraft Using EGTS for Taxiing Operation

Mass of aircraft = 73,500kg (A320)
Acceleration due to gravity =9.8m/s^2
Maximum taxiing velocity (takeoff) = 10m/s
To determine the rolling resistance force in A320, the maximum takeoff weight for A320 is substituted into equation 4
Therefore,

$$F = 73500 * 9.81 * 0.008 = 5768.28\text{N}$$
$$\text{Power} = \text{Force} * \text{Velocity} \qquad (6)$$

Substituting the force that resists the aircraft while rolling, and the maximum taxiing velocity into equation 6,
Power = (5,768.28 X 10 = 57,682.8 which is approximately 58Kw.
From the above evaluations, the power required by EGTS prior to taking off in an A320 is 58Kw. Applying equation 6, power requirement for taxi operations for other categories of aircraft in this section can be calculated as shown in Table 6

Table 6: Power required by APU on different aircrafts for taxiing Operation

Aircraft type	Cost ($)	Maximum take off (kg)	Power required by APU (W)
A320	500,000	73,500	58,000
A600 ST	500,000	155,000	122,000
A380	500,000	590,000	463,000
Cessna 172	500,000	1,111	8,710

From Fig. 6 we can see that the power required by the APU system is highest in the A380 this is because of its take weight, then lowest in the Cessna 172, cause of its low weight. But the EGTS system is not best to use on such small aircrafts because the benefits are low, because the installation cost is very high and then the fuel burn of such aircrafts is very low so no need for using an electric taxiing system on it. Then for the A320 the power required is minimal when compared to the A380. Since this is a passenger airline, it is advisable to install the EGTS system on this aircraft, it will be highly beneficial because it would reduce fuel burn thereby reducing emissions. From the following evaluations, it can be observed that using EGTS system for A600ST is very less beneficial since it's a cargo plane, the weight is high and its range too, so any reduction in fuel burn during taxiing is negligible.

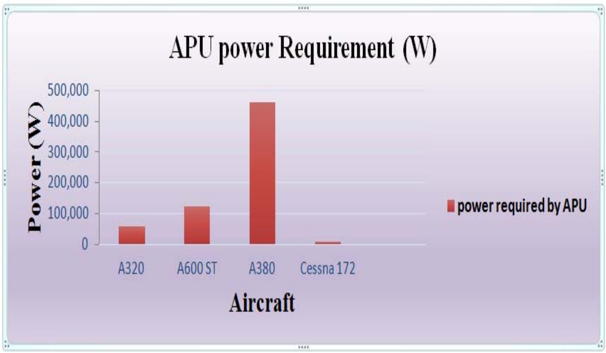

Figure 6: Power required by APU on different aircrafts for taxiing Operation aircrafts

3.6 Effect of EGTS Extra Weight on Aircraft

Cook [6] noted that major concerns have been raised by aviation industry experts concerning the fuel efficiency of aircraft using EGTS which is currently known to add about 320kg to the aircraft original weight (160kg per gear). Although the manufacturers of EGTS (Safran and Honeywell) believes that airline can still save upwards of $200,000 for each aircraft in a year, it is important to evaluate the extra weight implication, especially for different aircraft in order meet the aim of this paper which is to determine the viability of EGTS. Based on the extra weight estimated by Cook [6], the impact of extra weight of EGTS on other aircraft will be evaluated using the following formula, and the result obtained will be considered as the new aircraft weight

Maximum aircraft take-off weight + EGTS weight = new aircraft weight (7)

Amount of weight is equivalent to fuel burn i.e. the heavier the aircraft weight the higher the fuel burn. Also, Maximum aircraft take-off weight in this case is the initial aircraft weight

3.6.1 Extra Weight of EGTS on Cessna 172 Aircraft

Starting with aircraft with the lowest weight (which in this case is Cessna 172), the new aircraft weight can be determined as follows;
Substituting the initial aircraft weight of about 1,111kg and the extra weight of EGTS estimated as 320kg into equation 7;

$1111 + 320 = 1431$ kg

3.6.2. Extra Weight of EGTS on A320 Aircraft

Considering the initial weight of Airbus A320 with no EGTS installation, the new aircraft weight with EGTS installation can be determined as follows;
Substituting the initial aircraft weight of about 73,500kg and the extra weight of EGTS estimated as 320kg into equation 7;
$73500 + 320 = 73820$ kg

3.6.3. Extra Weight of EGTS on A600ST Aircraft

Considering the initial weight of A600ST aircraft with no EGTS installation, the new aircraft weight with EGTS installation can be determined as follows;
Substituting the initial aircraft weight of about 155,000kg and the extra weight of EGTS estimated as 320kg into equation 7;

$155000 + 320 = 155{,}320$kg

3.6.4. Extra Weight of EGTS on A380 Aircraft

Considering the initial weight of A380 aircraft with no EGTS installation, the following steps can be used to determine the new aircraft weight with EGTS installation;
Substituting the initial aircraft weight of about 590,000 kg and the extra weight of EGTS estimated as 320kg into equation 7;

$590{,}000 + 320 = 590{,}320$kg

The initial aircraft weight of the respective aircraft models (Cessna 172, A320, A600ST and A380) which does not include EGTS installation and the new weight which includes EGTS installation can be presented graphically as shown in Figure 7

As shown in Figure 7, it can be observed that the additional weight of 320kg being the weight of EGTS has increased the gross weight of Cessna 172, to 1431kg from the initial aircraft weight of 1111kg which included no EGTS installation. However, considering the original weight and duty cycle of the Cessna 172 aircraft, installation of EGTS may have a negligible significant in terms of block fuel savings, as the extra 320kg weight may require more fuel to balance with the torque needed for each operational cycle. Therefore, the additional weight constituted by EGTS installation may not be necessary for such a small weight aircraft because the aircraft itself burns less fuel and the more the weight of the aircraft, the more fuel consumed by the aircraft. The A320 is a short haul aircraft mostly used by aircraft companies for short/medium flight distances. Considering the 73,500kg initial weight of the airbus A320, the additional EGTS weight of 320 is negligible. This is because airbus A320 consumes much fuel during ground operations compared to Cessna 172, due to the initial gross weight of the aircraft and incorporating EGTS of about 320kg to significantly reduce the fuel consumption rate beyond the level that the same A320 aircraft does using its own engine is fair enough. Hence, installing EGTS on this Airbus A320 aircraft is proven to be beneficial in terms of block fuel savings during ground operations despite the new weight of about 73820kg when EGTS is installed as represented in Figure 7. The A600ST is a long haul cargo aircraft. Considering the original weight A600ST (155,000 kg) aircraft when EGTS is not installed, it can be observed that the weight is more than twice the weight of airbus A320 with or without the installation of EGTS. However, it is obvious that installation of EGTS on A600ST will amount to increasing the initial weight of the aircraft to 155320kg and this may likely affect the fuel saving efficiency. Furthermore, since the A600ST is a long haul aircraft, EGTS will be part of the long trip covered by the aircraft and this may imply saving fuel during ground operations and burning part of the same fuel in-flight. The case of airbus A380 is quite similar to that of A600ST, apart from the fact that the more the weight of the aircraft, the more fuel consumed in-flight. Airbus A380 is a long haul cargo aircraft. Considering the original weight A380 (590,000kg) aircraft when EGTS is not installed, it can be observed that the weight is about 531 times that of Cessna 172, 8 times that of A320 and 3 times that of A600ST without the installation of EGTS. However, it is obvious that installation of EGTS on A380 will amount to increase in the initial weight of the aircraft to 590,320kg as shown in Figure 7, and this may likely affect the fuel saving efficiency. Furthermore, since the A380 is a long haul aircraft, EGTS will be part of the long trip covered by the aircraft and this may imply saving fuel during ground operations and burning so much of the same fuel in-flight. From the following analysis, installing EGTS on Airbus A380 may not be necessary but the choice of installing the EGTS depends on what the airline is trying to achieve.

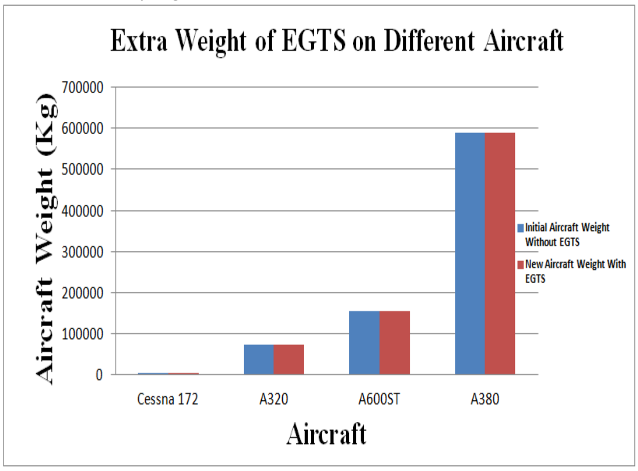

Figure 7: Different Aircraft Weights with EGTS and without EGTS Installation

3.7 Emission Generated by Aircraft without EGTS and Aircraft with EGTS Installation

Aircraft emissions is one of the major concern raised by Intergovernmental Panel on Climate Change (IPPC) as emissions from aircraft operations is believed to contribute immensely to climate change. However, airline operators suffer the consequence by pay carbon tax when the limit of emissions through aircraft operations is exceeded. Although aircraft emissions are quantified using specialised monitoring tools, it can also be calculated provided certain parameters such as the emission coefficient of GHG for certain type of fuel associated with aviation is known. This section will focus mainly on CO_2 emission airbus A320 (with EGTS and without installation) being the reference aircraft in this project. Energy Information Administration of U.S determined the emission coefficient of CO_2 generated by some aviation fuel as presented in Table 7

Most jet or commercial aircraft operation uses Kerosene because kerosene-based fuel has a much higher flash point than gasoline based-fuel. This implies that kerosene-based (has a flash point of about 120ºF) fuel requires significantly higher temperature to ignite than gasoline-based (has a flash point of about 30ºF) and the flash point in this context is the temperature at which the aviation fuel produces fumes that can be ignited by open flame [8]. Therefore, CO_2 emission value of 2.580 kg/L will be used for calculating the CO_2 emission generated by airbus A320. Using the following formula, the block fuel consumption during taxi operation without EGTS can be calculated from equation 8 and 9.

Trip fuel degradation on 500nm + (engine taxi trip fuel + fuel used by APU) x (total taxi time) + (engine warm up + cooling time) (8)

Trip fuel degradation on 500NM represents additional 16kg fuel burn.
Single engine taxi + APU = 9.5kg/min
APU = 2kg/min
Total taxi time (taxi-out + taxi-in) = 20 minutes
Time considered for engine warm up = 5 minutes
Time considered for engine cooling = 3 minutes [19]
Substituting the above parameters into equation 8 we have;

$$\text{Fuel consumption} = 16\text{kg} + (9.5\ \text{kg/min} + 2\ \text{kg/min}) \times (20\ \text{min} + (5\ \text{min} + 3\ \text{min}))$$

$$16\text{kg} + (11.5\text{kg/min} \times 28\text{min}) = 322\text{kg}$$

Therefore, CO_2 emission rate can be calculated using the following formula

$$\text{Fuel consumption} * \text{ emission Coefficient of } CO_2\ [18]\quad (9)$$

$$CO_2 \text{ emission rate for 500NM flight without EGTS} = 322 * 2.580 = 830.76\ \text{kg}$$

For CO_2 emission rate for the same 500NM flight without EGTS in airbus A320, it can be observed that several authors including Johnson and Gunawan [15]; and Norris (2013) reported that EGTS can save about 4% of block fuel consumption.
Therefore, 4% of 322 = 12.88kg
Substituting 12.88kg (block fuel consumption by aircraft with EGTS) into equation 9 we have;

$$CO_2 \text{ emission rate for aircraft with EGTS} = 12.88 * 2.580 = 33.2\text{kg}$$

The CO_2 emission when EGTS is installed and when it is not installed on airbus A320 (which is the reference aircraft in this paper) for taxi operation can be presented graphically as shown in Figure 8

As shown in Figure 8, taxi operation for 500NM trip using airbus A320 main engine generated CO_2 emission of about 830.76kg while for the same 500NM trip, using the aircraft with EGTS installed generated CO_2 of about 33.2kg. This shows CO_2 savings value of about 797.56kg in terms of emission generated by A320 compared to CO_2 emission generated by the same aircraft without EGTS installation.

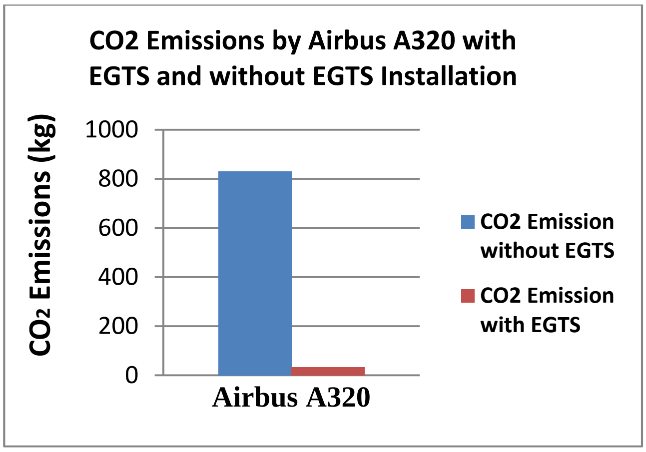

Figure 8: CO_2 Emission by A320 with EGTS and without EGTS Installation during Taxi Operation

4. Summary

Fuel economy is a measure of the quantity of fuel required by an aircraft to travel over a specified distance and can be expressed in kilogram or barrel. This is quite different from the power requirement or speed needed to attain a particular altitude or perform a certain task but as long as the aircraft is in operation, some energy will be loss as fuel. For example, aerodynamic drag which exerts a force that tends to oppose the motion of the aircraft in the opposite direction from the velocity plays a vital role in determining the torque and speed range needed to overcome the drag force and energy is loss in form of fuel in the process of achieving the task. However, each aircraft model is designed with its own maximum speed range for a specific gross weight (Fuel + payload) which is the speed required to achieve optimum fuel efficiency by the aircraft and travelling faster or slower than the required speed range per mile may consume more fuel than required. Moreover, the weight of the aircraft is one of the factors to be considered for fuel economy as more lift generating drag (induced drag occurs with increasing aircraft weight. From the above analysis shown in this section, it is obvious that the higher the weight of an aircraft, the higher the torque required to move the aircraft to the desired location, the higher the rate at which fuel is consumed. For example, it can be observed in Figure 4, from the block fuel savings by different aircraft with EGTS installation that airbus A380 saved the least amount of fuel over a distance of 500NM flight compared to the block fuel savings by Cessna 172 which happens to be the lightest aircraft in this category. Similarly, it can be observed that airbus A320 saves more block fuel than A600ST due to the weight differences in both aircraft. As mentioned earlier that the torque required to oppose drag force depends on how light or heavy the aircraft is and this goes a long way in determining the amount of fuel needed for the process, the extra weight by EGTS is more advantageous to some aircraft and also offer minimal benefit to some. For example, the weight of Cessna 172 seems too light for EGTS to be installed, while the weight of airbus A320 seems to be more compatible with the installation of EGTS and the weight of A600ST and A380 seems heavier already for any additional weight to be incorporated to it.

5. Conclusion

Electric Green Taxiing System (EGTS) alongside other eTaxi systems is very auspicious in terms of enabling aircraft autonomy and minimising the rate at which aircraft engines are used during taxi operations. These traits offers substantial benefits such as fuel saving and reduction of emissions which are the areas that airline operators incur a lot of expense. As illustrated in the methodology of the paper, installation of EGTS on the main landing gear wheel adds extra weight to the aircraft which tends to burn some amount of the fuel saved during ground operations when the aircraft is operating in air. Although the fuel consumed as a result of the extra weight, it should be noted that the rate of consumption depends on the gross weight of the aircraft as the extra weight is only 320kg. Therefore, if the gross weight of the aircraft (without EGTS installation) is high, installation of EGTS can only add to further increase which will amount to more fuel burn, but if the aircraft weight is low, fuel consumption by EGTS installation will always be negligible. However, the EGTS can still save a reasonable amount of fuel irrespective of the aircraft's gross weight due to the fact that the use of aircraft engine for taxi operation which is one area that airline operators incur huge costs is eliminated. Hence, EGTS offers more benefits than using the aircraft main engine for taxi operation which at the end of each operation saves the airline a lot of operation and maintenance cost. Since light weight materials are of the essence in aircraft manufacturing, there may be need for replacing the electric motor with light weight devices that can serve the same purpose in future.

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