Aircraft Taxiing Strategy Optimization

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Developments in aviation technology have led to the emergence of new aircraft taxiing strategies such as electric driven aircraft nose gear. Selecting appropriate aircraft taxiing strategies is crucial in view of increasing concerns surrounding airport ground emission and fuel consumption. This paper reports on the performance of strategies regarding aircraft taxiing processes at airports. The research aims to optimize emission reductions hence simultaneously minimizing fuel consumption. The performance measurements of taxiing operations were based on total emissions and fuel consumption. Daily data on aircraft arrivals and departures, runways and gates were analyzed, and the preferred aircraft taxiing strategy was presented. Amsterdam Schiphol Airport and Kuala Lumpur International Airport were selected as the case studies. The International Civil Aviation Organization, (ICAO) emissions database was used to determine the emission index and fuel-burning index for each type of aircraft. In order to model the taxiing strategies, discrete event modeling tools of DELPHI 7 with THOMAS compiler were used. The performances linked to each strategy were compared between airports. The estimated effectiveness of each strategy was evaluated. On the basis of this analysis, recommendations are made for future research so that aircraft taxiing performance at both airports can be improved.

Nomenclature

APU = auxiliary power unit
ATC = air traffic control
CNG = compressed natural gas
CO_2 = carbon dioxide
CO = carbon monoxide
FAA = federal aviation administration
FOD = foreign object damage
H_2O = water compound
LTO = landing and take-off
NO_2 = nitrogen dioxide
NO_x = oxides of nitrogen
SO_x = oxides of sulphur

I.Introduction

Aircraft taxiing operation takes place during the turn-around process. After landing, the pilot taxies the aircraft from the end of the runway to the gate, and from the gate to the beginning of the departing runway. During taxiing operations, hydrocarbons and CO are found to be the highest emitted pollutants [1] due to the low engine thrust of 7% [2][3][4][5][6][7]. Furthermore, researchers have shown that the growth rate of the total taxiing time has been larger than the airborne time growth rate, the total mission time growth rate and the total number of operation growth rate[8]. The trend directly results in an increase in fuel consumption and ground emissions. It is therefore becoming increasingly difficult to ignore the importance of optimizing aircraft taxiing operations.

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Rapid technological development in aircraft electrical nose gear and electric powered towing trucks provide an opportunity to improve the flexibility of aircraft taxiing operations. In most cases, the pilot taxies the aircraft with all engines in operation. Alternatively, there are three more taxiing strategies available for aircraft taxiing i.e. single-engine taxiing, operational towing, and the implementation of electrical nose gear. So far, there has been little discussion on performance comparisons between all the available taxiing strategies. For example, only several previous studies have been conducted to compare the performance between single engine taxiing and operational towing[8][9][10][11].

In addition, it is hard to find previous research that surveyed the performance of electrical nose gear taxiing and operational towing using electrical powered towing trucks as both technologies are still very much in the development phase. Performance predictions concerning every available taxiing strategy are important for future research into optimizing taxiing operations and decision making. The literature section will discuss in detail previous research on each taxiing strategy.

The aim of this study is to evaluate the performance of four aircraft taxiing strategies i.e. ; 1) full engine taxiing, 2)single engine taxiing, 3)operational towing, and 4)electrical nose gear implementation. The performances of each strategy were analyzed together with the effect of the aircraft's engine warm-up and cool-down process. To that end, a mathematical model designed at the Embarcadero RAD studio 2010 and written in Delphi 7 development environment is used to predict the performance of each taxiing strategy. To determine the percentage reduction in fuel consumption and emissions achieved by each taxiing strategy, the performance of full engine taxiing is used for comparison. Amsterdam Schiphol Airport and Kuala Lumpur International Airport were chosen to justify the consistency of all strategy performances.

The results of the model are encouraging and serve as a feasibility study to consider different taxiing strategies during the aircraft turn-around process in future. The model shows positive results for each taxiing strategy when compared to the conventional full engine taxiing. This will help the researcher to evaluate the best taxiing strategy to be performed simply in the inbound or outbound direction, or with a combination of available strategies. The results help to encourage future research on the effect of aircraft taxiing strategies in connection with gate assignment determination, gate design, departing aircraft queuing patterns and the improvement needed concerning airside configuration.

A. Statement of problem

The emissions produced and the fuel burnt during LTO operations at airports relates directly to the taxi time. More emissions will be produced and fuel will be consumed if the taxiing time is longer. At present, there are several strategies available for the aircraft taxiing process. The performance linked to these strategies needs to be evaluated to optimize the taxiing process. However, the effect of the warm-up and cool-down process of the aircraft engines on the strategy performance evaluation needs to be considered. The performance comparison concerning the taxiing strategies selected for types of emissions and total fuel consumptions needs to be justified.

B. Literature

This section will examine the present available strategies for the aircraft taxiing process. The strategies are 1) Full-Engine Taxiing, 2) Single-Engine Taxiing, 3) Operational Towing, and 4) Implementing electrical Nose-Gear. The advantages and drawbacks of each strategy are discussed on the basis of previous research findings.

1. Full-Engine Taxiing (Strategy A)

The most basic strategy when taxiing an aircraft involves using full-engine taxiing. During taxiing, aircraft engines are in their idling condition and operated at low power settings of 7% thrust[2][3][4][5][6]. During idle mode, an engine's performance is less efficient due to the low combustor temperature. This induces higher fuel consumption, and emissions of hydrocarbon and CO[1]. However, recent research shows that 7% of applied thrust is not constant during the whole taxiing process and leads to a 16% fuel over-estimation[12].

There are several drawbacks to full-engine taxiing when compared to other strategies. In the outbound direction, pushback operation is required to pull the aircraft away from the gate. Airbus estimated that a pushback operation using an APU with 12 minutes taxiing time produces an additional APU fuel burn of 30 kg for an A320, and 60-70kg for an A340[13]. Operating all aircraft engines contributes directly to high noise levels as well to high engine maintenance costs. Apart from periodical maintenance, running an aircraft engine could suck items into it thus leading to (FOD). The danger zone produced behind the engine could also be hazardous to the nearby surroundings. So, extra headway between aircrafts is needed to avoid any incidents. Based on these drawbacks, the single-engine taxiing strategy has been introduced to improve the taxiing process.

2. Single-Engine Taxiing (Strategy B)

Compared to full-engine taxiing, this strategy is conducted by turning off an engine or operating with only one engine to taxi the aircraft. This depends on the total number of aircraft engines. Depending on the manufacturer, the aircraft engine still needs to be warmed-up after being turned-on, or cool-down before switching-off which takes around 2-5 minutes[8][11]. So, this strategy will only be effective if the taxiing time is longer than the engine's warm-up or cool-down time. Previous studies have proven that this strategy could significantly reduce between 32% to half of the emissions of HC, CO and fuel consumptions through well-planned single-engine taxiing[3][8][14][15]. Furthermore, single-engine taxiing requires no extra physical investments on the aircraft and airport airside. This strategy could be quickly implemented and made applicable to all aircraft. However, previous studies have reported several drawbacks identified on single-engine taxiing strategy[8][9][11][16]. In some cases, taxiing using one engine could create jet blast especially with wide-body aircraft. This could lead to safety issues such as hazardous situations for nearby work in progress in the area. Airbus does not recommend this procedure for uphill slopes or slippery surfaces, when deicing operations are required, and when there are sharp and tight taxiway turns. This could result in reduced redundancy, and increases the risk of loss of braking capability and nose wheel steering. Push back operations still needing to be conducted while leaving the gate.

3. Operational Towing (Strategy C)

This strategy takes advantage of the aircraft push back process from the gate in the outbound direction. Despite towing the aircraft during pushback, the tow truck extends the towing process until starting on the runway. During this process, the aircraft engine is turned off until the warm-up time. The aircraft's electrical and air-conditioned system is powered by the APU. So, this strategy is practical only if the taxi time is longer than the engine's warm-up time.

Based on previous studies, this strategy has its pros and cons. From the operational perspective, aircraft taxiing using electrical towing truck reduces fuel burn, emissions and field noise and has no trade-offs[16]. Taxiing the aircraft with no operating engines reduces the noise level, the FOD cost, and eliminates the danger area behind the engine. There is a trade-off concerning the ground pollutant emissions produced. Emissions produced by aircraft engines are reduced, and tow truck emissions are introduced at the same time. The strategy performance on emissions and fuel consumption mainly depends on the tow truck's engine performance as reported in the previous study [8] [11] [17].The strategy of operational towing could be highly beneficial if the tow truck produces less/ zero emissions. To achieve that objective, on-going research is being done to achieve zero emissions produced by the tow-truck. The technology developed by TugBot consists of electric-powered engine towing. This semi-robotic towing truck can be operated by pilots on board. This will minimize the manpower and efficient taxiing process.

Previous research has also pointed out several disadvantages of this strategy. No aircraft nose gear has yet been designed that is suitable for extended towing. There is therefore potential damage to the nose-gear due to the stressed imposed over time[11]. Operational issues such as communication protocols between the ATC, the cockpit and the tow truck operator and further logistic considerations such as increased traffic congestion on the airside need to be considered. This strategy might also increase the taxi time due to the lower towing truck speed, the large staging area for engine warm-up and the un-coupling area, the increased controller workload, additional equipment and manpower etc. Virgin Atlantic at Heathrow found that the A340-500 taxiing time was tripled when compared to the normal dispatch procedure [3].

4. Electrical Nose Gear (Strategy D)

Invented by Steven Sullivan from Delos Aerospace[18], this strategy is implemented by installing an electric motor in the aircraft nose gear. The electric motor is powered by the APU which allows the aircraft engines to be turn-off. This could lead to power efficiency and decrease the total emissions and fuel consumption during taxiing operations. This strategy could also replace the function of the tow truck during push back operations hence also reducing delay. Furthermore, it could also reduce tow truck operation costs and aircraft engine maintenance costs, risk of FOD, and minimize the danger zone. This could increase airside flexibility and improve the safety aspect.

WheelTug is one of the electrical nose gear solutions available for aircraft taxiing. It has successfully been tested for Boeing 737-700 narrow body aircraft taxiing at Prague Ruzyne Airport. It is able to perform on all pavement types as well as wet and oil-slicked tarmac surfaces. It is reported that the product could save over $200 per flight and could be dismantled in less than two hours, as tested on the Germania 737-700 aircraft[19][20][21].Several carriers have decided to install this system into their aircraft such as El Al, Jet Airways, Onur Air and the latest is KLM [21][19].

The German Aerospace Centre (DLR) supported by Airbus and Lufthansa Technik has also developed an electrical nose gear system. The system operates by installing two electric motors in the rims of the nose wheel and power generating that is from a low-temperature polymer electrolyte fuel cell [20]. The system boasts an efficiency of 40-50%, as opposed to the 33-35% achieved by conventional (combustion engine and generator) methodology [22]. It has been tested while taxiing around Hamburg Finkenwerder Airport on an Airbus A-320 narrow-body aircraft. Based on the test, the system known as DLR Airbus A320 ATRA could significantly reduce 95% of the noise hindrance, decrease up to 17% of all ground emissions and save about 44 tons of daily kerosene consumption hence reducing the engine operation up to 2 hours daily and the engine maintenance interval [23].

However, one drawback has also been identified to this strategy. The electrical motor installed in the nose gear will increase the dead weight of the aircraft. This means that the aircraft needs to carry the extra weight all the time. This would contribute directly to extra fuel consumption. However, this strategy could reduce the amount of reserve jet fuel required for unexpected delay at the airport during taxiing. It is expected that the trade-off produces more advantages than drawbacks.

C. Research Question

In view of the limitations of the related works and the records available to support our investigation, the following research question can be formulated: “What is the contribution that the available taxiing strategies make to total emissions and fuel consumption”. Consequently, the comparisons between each strategy performance could be analysed, and recommendations for future research could be outlined.

II.Model Development

To analyze the effect of each taxiing strategy on fuel consumption and emission, a model was developed in the Embarcadero RAD studio 2010 that was written in the Delphi development environment. Based on the daily schedule of Amsterdam Schiphol Airport and Kuala Lumpur International Airport, calculations were made for aircraft taxiing during arrival and departure. The number of engines and engine characteristics such as the fuel flow and emission index were determined according to aircraft type. The detailed specifications of aircraft engines were obtained from the ICAO database. The average taxiing distance is calculated on the basis of the existing arrival and departure runways and gates. The percentage of routes utilized for aircraft taxiing is based on the daily schedule of aircraft arrival and departure times. The inbound aircraft were assumed to be similar to the outbound aircraft. During the entire taxiing process, the aircraft engine power setting was assumed to be constant at 7% of thrust. Consequently, the effects of the warm-up and cool-down process on each strategy were evaluated.

For single engine taxiing, the speed was assumed to be similar in full-engine taxiing. For operational towing, two types of tug were used depending on aircraft type. For narrow-body aircraft, two diesel engines of 294 kW were used and two diesel engines of 540 kW for wide-body aircraft. The return trip of tugs was excluded from the analysis due to the very low impact compared during towing. The APU of aircrafts were also assumed to be in normal operation, and all aircraft engines were shut down during towing. The APU specifications were determined from the Airport Air Quality Manual. When taxiing using electrical nose gear, it was assumed that all aircraft engines were turned-off and the aircraft carried extra weight from the electric motor load. Reserve taxiing fuel for the electric nose gear strategy is also assumed to be of a similar volume to other strategies. For full engine taxiing, single engine taxiing, and electrical-gear taxiing, the taxi-in speed was assumed to be 10 m/s and 6.5 m/s during taxi-out. For operational towing, the taxi-in speed was assumed to be 5 m/s and 4 m/s for taxi-out. The taxi-out speed was lower than the taxi-in speed due to the airside congestion consideration.

The main mathematical formula used is:

$$Q_E = n_{max} \text{ x } Q_{A,idling} \text{x } t_{wucd} \text{ x } EI_{idling} + Q_{E,strategy} \text{x } (t_{total} - t_{wucd}) \qquad (1)$$

In which,

Q_E	Total emissions during taxiing operation (gram)
n_{max}	Total number of aircraft engines
$Q_{A,idling}$	Specific fuel consumption of an aircraft engine when idle (kg/s)
t_{wucd}	Total time required for the warm-up or cool-down process of the aircraft engine (s)
EI_{idling}	Emissions Index of an aircraft engine when idle (gram emissions/kg fuel)
$Q_{E,strategy}$	Emission rate during taxiing (gram/s)
t_{total}	Total taxi time (s)

III.Case Study

Two case studies were selected for the model, i.e. Amsterdam Airport Schiphol and Kuala Lumpur International Airport. The descriptions of the airports are given below:

1. Amsterdam Airport Schiphol

Amsterdam Airport Schiphol has seven piers and six runways. Due to the wind that comes from many directions, the airport has a large number of runways to optimize its capacity for landing and take-off. The airport has a wide range of aircraft taxiing distances. The longest distance being around eight kilometers and the shortest around one kilometer. Runway usage mainly depends on the wind direction. There are two identified main inbound and outbound modes for runway utilization at this airport. This is based on approximately 90 % of the annual daytime operations [24]. Oostbaan Runway is only suitable for small aircraft. A week schedule of arrival and departure aircraft was obtained from the airport website [25] whereas runway usage distribution was gathered from online sources of data [26]. Both sources were used to create a fleet mix and airport data type of input. Only daytime runway usage was analyzed (6.45 a.m. to 9.45 p.m.).

2. Kuala Lumpur International Airport

Kuala Lumpur International Airport has two runways for arrival and departure. Both runways are parallel to each other. This is because the wind in Malaysia mostly comes from a similar direction. Both runways can be operated in both directions. The airport has three main piers. Pier A and Pier B are for domestic flights whereas Pier C is for international traffic. The input data of aircraft arrival and departure schedules and aircraft types were obtained from the airport authority (MAHB, 2013).

IV.Results and Analysis

As mention in the Introduction part, the initial aim of this paper is to determine the performance of each taxiing strategy with the warm-up and cool-down effect of the aircraft engine process. To evaluate the significance of each strategy performance, the conventional method (full-engine taxiing) is used as the comparison. The analysis begins with the results of each taxiing strategy performance and the percentage change compared to strategy A at Amsterdam Schiphol Airport. Overall, each taxiing strategy indicates a significantly large reduction in fuel consumption and total emissions (Table 1). For strategy A, the reduction in fuel consumption and total emissions is almost equal. The percentage values of the difference between strategy A and strategy B is less than 50 % reduction due to the effects of the engine's warm-up and cool-down process. For strategy C, the reductions are significantly larger than the performance of strategy A except for the emission of NO_x.

There are two possible reasons why strategy C produced a better result than strategy B. Firstly, the towing truck used during operational towing has a higher NO_x emission index when compared to the aircraft engines. Secondly, aircraft taxiing produces operational towing results at slower speeds when compared to full-engine taxiing. Slower speed increases the taxiing times thus producing higher NO_x emissions. Taxiing with electrical nose gear (strategy D) produces the largest reduction in fuel consumption and emissions. However, aircraft need to carry the extra weight of APU for electrical nose gear operations for the whole journey. This results in additional fuel consumption when cruising. The manufacturer of electrical nose gear systems mentioned that the operation will not increase the aircraft weight [19]. This is because the aircraft can reduce the amount of reserve fuel for taxiing and replace it with the extra weight of the electrical nose gear system that has to be carried throughout the entire journey.

Based on Table 1, the amount of fuel saved for strategy D is 440 ton (1073-633). This is around 110 kg per LTO cycle. The reduction weight is less than the electrical motor system (the assumed weight is 150 kg). Based on the value calculated by the model according to several assumptions, the statement of the manufacturer to the effect that the operation will not increase aircraft weight is falsified. Strategy D increased the total emissions and fuel consumption during cruising due to the extra weight. Strategy B and C could reduce the amount of fuel consumption and total emissions during cruising due to no additional weight impacting the aircraft.

Table 1: Results of the taxiing strategy performance and percentage change compared to strategy A at Amsterdam Schiphol Airport

Strategy	**A**	**B**	**(A-B)%**	**C**	**(A-C)%**	**D**	**(A-D)%**
Fuel consumption aircraft (ton)	1073	793	-26,1 %	682	-36,5 %	633	-41,0 %
Fuel consumption tug/ mass (ton)	N/A	N/A	-	115	-	140	-
CO_2 emission (ton x 1000)	3,39	2,51	-26,1 %	2,51	-26,0 %	2,00	-41,0 %
HC emission (ton)	2,59	1,91	-26,2 %	1,49	-42,6 %	1,34	-48,4 %
CO emission (ton)	23,25	17,15	-26.2 %	13,97	-39,9 %	11,91	-48,8 %
NO_x emission (ton)	4,69	3,47	-26,0 %	4,80	2,5 %	3,28	-29,9 %

Note:
A : Full-engine taxiing
B : Single-engine taxiing
C : Operational towing
D : Electrical nose gear

Table 2 shows the performance of each strategy and the percentage reduction of fuel consumption and emissions when compared to strategy A at Kuala Lumpur International Airport. The results show a similar trend to the performance at Schiphol Airport. However, the percentages of reductions are slightly lower than in Table 1. This is because Kuala Lumpur International Airport has a shorter taxiing distance compared to Schiphol Airport. The maximum taxi distance at Amsterdam Schiphol Airport is around 8 km. The distance is almost double the maximum taxi distance at Kuala Lumpur International Airport. The aircraft type's composition is also different between the two airports. Based on the weekly arrival and departure at Amsterdam Schiphol Airport, there are more than 20 types of aircraft boarded at the airport. Meanwhile, most of the aircraft type composition at Kuala Lumpur International Airport mainly consists of Airbus and Boeing. The impact of engine's warm-up and cool-down process reduces the performance of the strategies because of the shorter strategy time that is implemented.

Table 2: Results of the taxiing strategy performance and percentage change compared to strategy A at Kuala Lumpur International Airport

Strategy	A	B	(A-B)%	C	(A-C)%	D	(A-D)%
Fuel consumption aircraft (ton)	1157	873	-24,5 %	750	-35,2 %	705	-39,0 %
Fuel consumption tug/ mass (ton)	N/A	N/A	-	100	-	166	-
CO_2 emission (ton x 1000)	3,65	2,76	-24,5 %	2,68	-26,7 %	2,23	-39,0 %
HC emission (ton)	2,34	1,77	-24,0 %	1,38	-40,8 %	1,26	-46,1 %
CO emission (ton)	20,37	15,40	-24,4 %	12,65	-37,9 %	10,89	-46,6 %
NO_x emission (ton)	5,60	4,22	-24,6 %	5,34	4,6 %	3,99	-28,7 %

V. Conclusion

Aircraft taxiing optimization is crucial to reducing fuel consumption and total emissions during the aircraft turn-around process. The three suggested aircraft taxiing strategies could all lead to a large reduction in fuel consumption and total emissions. Single-engine taxiing is the easiest system to implement because the strategy needs no additional investments or aircraft modifications and it results in large emission reductions. However, issues such as the suitability of the airside (sharp turns and maximum gradients) seem to be the limiting factor. The effectiveness of aircraft maneuvering also needs to be considered for wide-body aircraft. Operational towing produces better performance than single-engine taxiing. The results could be considerably improved if electrical towing trucks were introduced. However, this strategy reflects high impacts on airport logistics operations and management. Aircraft taxiing with electric nose gear shows the best fuel consumptions and total emissions reduction performance. However, this technology is still being researched and developed. The limited data results in more assumptions and estimations concerning the model analysis.

V.Recommendation for Future Research

This analysis will be a stepping-stone for future project research in the team. The taxiing strategy performance based on taxi-in and taxi-out comparison, and narrow-body and wide-body aircraft comparison can be further analyzed. Based on estimated reduction of fuel consumption and total emissions, the available strategy has proven worth exploring. Aircraft turn-around processes could be simulated using Delphi and THOMAS modeling environment and the effectiveness and queuing trend could be predicted on the basis of different strategies. In order to reduce the process time hence improve airport airside logistics, flexible gate allocations could be added in the simulation.

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