IMPACT OF ON-GROUND TAXIING WITH ELECTRIC POWERED TOW-TRUCKS ON CONGESTION, COST, AND CARBON EMISSIONS AT MONTRÉAL–TRUDEAU INTERNATIONAL AIRPORT

Abdulrazaq Lemu Salihu

A Thesis

In

The Department

Of

Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of Master of Applied Science (Industrial Engineering) at

Concordia University

Montreal, Quebec, Canada

June 2020

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Abdulrazaq Lemu Salihu

Entitled: Impact of On-Ground Taxiing with Electric Powered Tow-Trucks on Congestion, Cost, and Carbon Emissions at Montreal-Trudeau International Airport.

And submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Industrial Engineering)

Complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final Examining Committee:

Dr. Waizuddin Ahmed ______________________________ Chair

Dr. Onur Kuzgunkaya ______________________________ Examiner

Dr. Fereshteh Mafakheri ______________________________ Examiner

Dr. Ali Akgunduz ______________________________ Co-Supervisor

Dr. Shannon Lloyd ______________________________ Co-Supervisor

Approved by ____

Dr. Waizuddin Ahmed, Ph.D
Chair of Department or Graduate Program Director

__________ 2020 ______________________________________

Dr. Amir Asif, Ph.D
Dean of Faculty

Abstract

Impact of On-Ground Taxiing with Electric Powered Tow-Trucks on Congestion, Cost, and Carbon Emissions at Montréal–Trudeau International Airport

Abdulrazaq Lemu Salihu
Concordia University, 2020

Everyday millions of litres of jet fuel are burnt during the aircraft's on-ground taxiing operations, releasing tons of greenhouse gas emissions in the atmosphere. Aircraft manufacturers and researchers believe that replacing the current aircraft taxiing operation with more efficient on-ground taxiing operations could meet future market requirements. Multiple factors such as safety, airport throughput, energy efficiency, air emissions, and total cost need to be considered when designing airport taxi operations. This research reports on the performance of utilizing electric tow-trucks during on-ground taxiing operations. It builds on previous studies to assess the impact of the initial investment of implementing these alternative taxi system on congestion, cost and carbon emission on the on-ground taxi operations. We developed a Discrete Event Simulation model to schedule electric powered tow-trucks to provide taxiing services to aircrafts. The simulation enables aircrafts to request an available tow-truck or use aircraft engines to perform taxiing operations. The performance measurements of the taxiing operations were based on total fuel consumption, emission, traffic delays and total cost of implementing the operational strategy. Montreal-Pierre Elliot Trudeau International Airport was selected as a case study. Based on the presented methodology, the result exhibits that utilizing electric-powered tow-trucks to perform all on-ground taxiing operations is the best practical solution to meet the future market requirements. The conducted investigation indicates that this approach provides both economic and environmental benefits to the aviation industry. Three extensive sets of numerical analysis have been conducted to provide better insights into the problem. In each part of these analysis, different determinant factors such as the total cost, fuel consumption, delay and emissions have been used to compare the obtained results of the proposed approach with the current situation at the airport. After analyzing the results, an environmentally friendly and economically efficient approach is offered.

Acknowledgement

First and foremost, all praise is due to God for giving me the ability to perform this task till the end. I wish to express my deepest appreciation to my supervisors, Dr. Ali Akgunduz and Dr. Shannon Lloyd for their patience, guidance, encouragement and steering me in the right direction through this research work.

Also, I must express my gratitude to my mother, siblings and friends for providing me with unfailing support and endless love throughout my years of study and researching.

Table of Contents

List of figures

List of Tables

1 Introduction

Over the past decades, the global aviation industry has been growing, playing a crucial role in connecting people and countries across the globe. As Airport Council International (ACI) reports, about 8.8 billion passengers were carried in 2018 by airlines worldwide, which means a growth of 6.4 percent compared to 2017(Airport Council International, 2019). As can be seen in figure 1, the increase in the number of passengers had a positive value over the last nine years, with the 2018 increase reported to be slightly above the 5.8 percent compounded average annual growth rate for passenger traffic from 2010 through 2018 (Airport Council International, 2019).

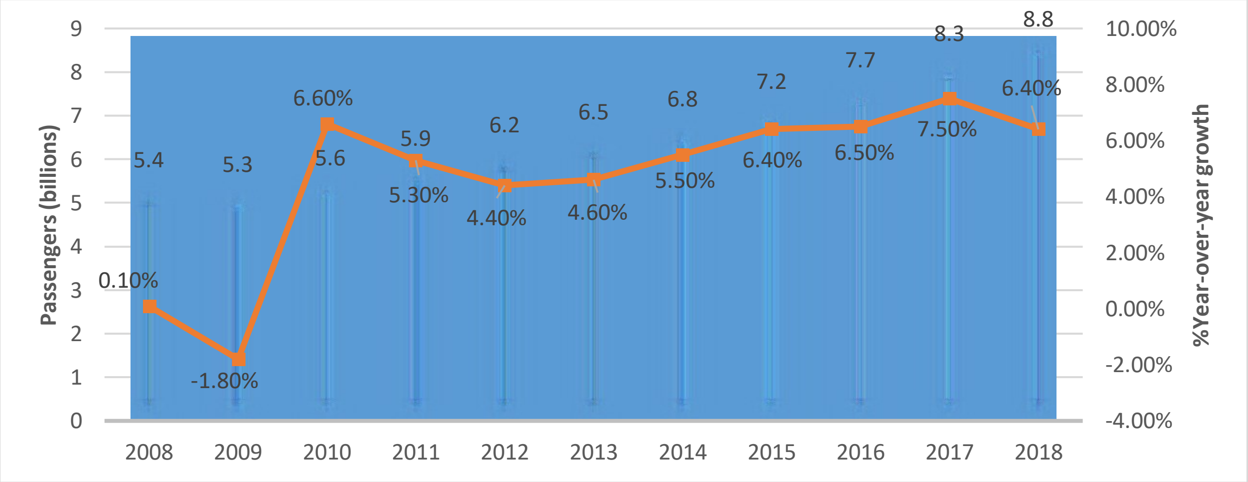


Figure 1.Annual growth in global air traffic passenger demand (Airport Council International, 2019)

Also, the number of global flights is expected to increase by up to 40.3 million in 2020 (See figure 2) (Statista, 2020). These conditions in the aviation industry have created many challenges as well as benefits.

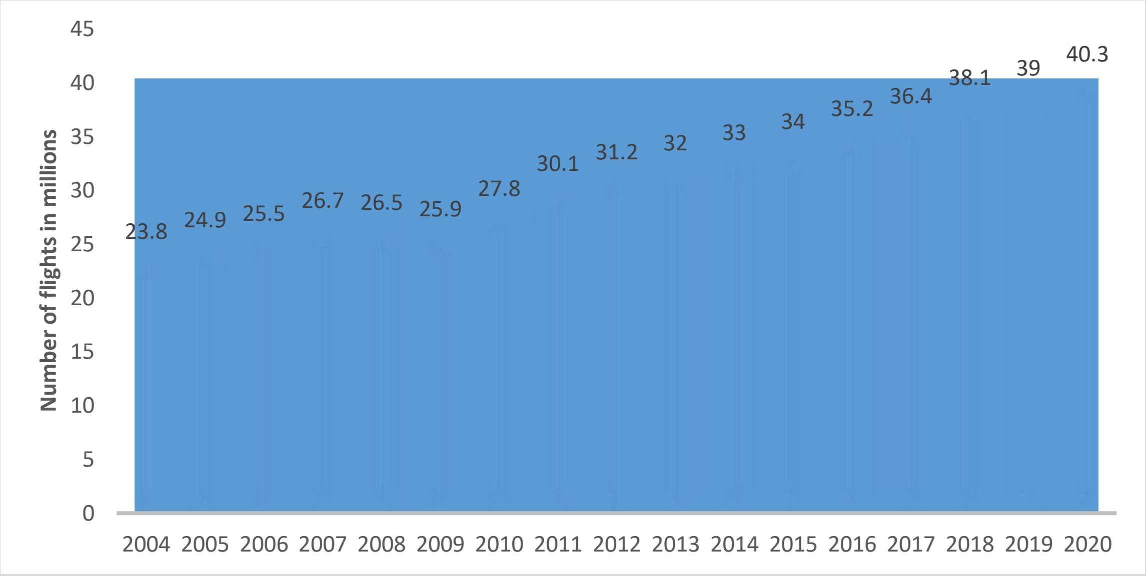


Figure 2.The number of yearly flights by the global airline industry (Statista, 2020)

Because of rapid growth in air transportation, the industry, government, and society at large are facing growing challenges regarding fuel consumption and emissions. In 2018,the transportation industry accounted for approximately 24 percent of global carbon dioxide (CO_2) emissions (International Energy Agency, 2019), with the aviation sector being responsible for about 2 percent of global CO_2 emissions (Air Transport Action Group, 2019) .However, these estimates are predicted to increase with the increase in global air traffic. These facts draw attention to the importance of the aviation industry's role in the global climate change.

Among several critical objectives of the air transportation system, minimizing fuel consumption has a profound impact on both the economic viability of airline companies and the environmental ramifications of air-transportation. Aircraft ground operations are one important source as global single aisle fleet in taxi operations accounts for over 13 million metric tonnes of CO_2 (Safran S.A and Honeywell Aerospace, 2013). On-ground operation (taxiing) is conventionally performed by exploiting the idle thrust of the main jet engines. Idling is a condition when no driving thrust is needed which results in fuel being wasted, as is the case when aircraft is decelerating or stopped (Ithnan et al., 2015).

According to Airbus, European flights spend up to 30% of the gate-to-gate travel time and consume 5% to 10% of the entire mission fuel on average for taxiing operations (Deonandan &

Balakrishnan, 2010).These issues are even more concerning considering that air traffic is expected to expand consistently with the International Air Transport Association (IATA) suggesting that passenger numbers could double in 2037 (International Air Transport Association, 2018). More traffic leads to an increased use of airports capacities, which results in a growing trend for taxi times too.

In 2016, the member states of the International Civil Aviation Organisation agreed to adopt a carbon offsetting and reduction scheme for international aviation emissions. This scheme, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is designed to stabilize the aviation's net CO_2 emissions by offsetting any growth in $C0_2$ emissions above 2020 levels (International Civil Aviation Organization, 2019). From 2021, airlines will be required to buy emissions reduction offsets from other sectors to compensate for the $C0_2$ emissions that exceed the average baseline emissions of 2019 and 2020. CORSIA will cover only international flights with domestic aviation emissions already covered by national policies related to meeting Paris Agreement goals (International Civil Aviation Organization, 2019). Some national policies include domestic aviation, some do not.

Although, many stakeholders have a role to play in the aviation industry's decarbonization, bold government action will help to define whether the aviation sector is able to achieve this goal (CAN & ICSA, 2018). In December 2017, the government of Canada committed to delivering a low carbon, clean growth economy by setting a target to reducing GHG emissions by 80 percent by 2050 (Government of Canada, 2017). The government of Canada also proposed a Carbon Tax Plan in an effort to reduce the amount of greenhouse gases emitted by big businesses and companies highly dependent on fossil fuel. They introduced a nation-wide carbon price, beginning at $20 per tonne of carbon dioxide equivalent emissions (tCO2e) in 2019 and rising to $50 per tonne (Government of B.C, 2019).

Also, while the current policy initiatives adopted by governments are a step forward in addressing emissions from aviation, they are not sufficient to achieve the requisite rates of deep decarbonization in the field (CAN & ICSA, 2018).

The issues mentioned above and the growing concern of climate change and the quest for cost efficiency alerted the aviation industry on minimizing the fuel burn during on-ground operations (taxiing).

As a first step, taxiing with only a subset of the main engines running was proposed in an attempt to optimize the ground procedures (Deonandan & Balakrishnan, 2010). This is referred to as single engine taxi for two-engine aircraft. In this case, one jet engine generates enough thrust to move the aircraft at constant speed. However, this taxiing method increases the risk of debris ingestion and foreign object damage due to additional thrust needed for acceleration and cornering (Guo et al., 2014). The responsibility of implementing such a taxi method is ultimately left to the pilots and airliners.

Using a different taxiing system than the main engines for ground operations is increasingly being considered as a promising solution. A number of Electric Taxi Systems (ETS) are currently being considered (Hospodka, 2014; Safran S.A and Honeywell Aerospace, 2013; WheelTug, 2020). These systems allow aircraft to perform on-ground (taxi) operation using either electric powered tow-trucks (Hospodka, 2014) or electrically powered motors attached to nose landing gear (Safran S.A and Honeywell Aerospace, 2013; WheelTug, 2020). With the growing concern of climate change, the traditional taxiing method whereby aircrafts perform on-ground operation using their engines is seen as not environmentally friendly nor fuel efficient. The proposed Electric Taxi System is predicted to limit fuel usage during the on-ground taxi process (Hospodka, 2014; Safran S.A and Honeywell Aerospace, 2013; WheelTug, 2020).

However, concerns regarding the additional weight of the on-board electric motor system have hindered the implementation of this ETS. The additional weight of the system increases fuel usage during the flight operations, thus, offsetting any potential fuel reduction benefits on ground (Soepnel et al., 2017). Currently, there are no certifications for this on-board electric motors (Gubisch, 2016; WheelTug plc, 2017). Hence, this study will focus on the ETS using electric powered tow-trucks as this is the only certified and operational alternative taxiing solution (Hospodka, 2014).

Although, aerospace professionals generally acknowledge that there is a potential for improvement in ground operation using the tow trucks for taxing (Quinn et al., 2012), the lack of detailed studies on its operational and procedural challenges makes it difficult to identify the conditions in which the benefits outweigh the drawbacks and ultimately puts the implementation of the taxiing method at risk. In order words, will the benefit on the fuel consumption and emission help the costs?

In this research, we provide a Discrete-Event simulation model to evaluate the implementation of electric-powered towing vehicles using different operational strategies. The proposed simulation model facilitates aircraft's request for a towing vehicle when available or performs traditional taxiing operations using aircraft jet engines. However, it should be noted that using electric powered towing trucks can be an efficient way of taxiing in airports if the source of the electricity is clean. Clean electricity is produced from renewable and non-emitting sources such as wind, sun, and water. Using burning fossil fuels like coal to produce the electricity might jeopardize the performance of the electric towing trucks in the taxi process. The government of Canada is determined to have 90% clean electricity nationwide by 2030 with a lot of provinces already producing clean electricity (Government of Canada., 2016).

In the next section of this chapter, the literature review is provided. In the second chapter, we present our simulation model in detail. The third chapter is dedicated to presenting our result and analysis. Finally, chapter four concludes this thesis by introducing conclusion and future work.

1.1 Electric Taxi Systems

The aerospace industry, as well as other transportation sectors, face the challenge to operate more efficiently to comply with future economic and environmental requirements. The transportation sector is the leading cause of carbon dioxide (CO_2) and other GHG emissions , accounting for 14% of the global emissions (Shaheen & Lipman, 2007) with aviation sector being responsible for about 2 percent of global CO_2 emissions (Air Transport Action Group, 2019). The demand to use less fuel and emit fewer emissions is on the increase with the growing traffic in the aerospace industry. According to the International Civil Aviation Organization (ICAO), passenger traffic has grown with an average of 5.2% between 1995 and 2012. ICAO estimates the demand for aviation will increase by an annual rate of 4.6% until 2032 and 4.5% until 2042(International Civil Aviation Organization, 2016). Although aviation is not currently the leading cause of global warming, industry development, and the increase in air transportation will make it a significant contributor to global warming in the coming decades.

In recent years, the automobile and rail industry introduced several alternative power sources with the potential to reducing their CO_2 emissions (Marin et al., 2010; Ugurlu & Oztuna, 2015). Unlike these industries, the aviation industry has seen little progress with regards to a breakthrough alternative power source. The increasing demand of air travel is projected to increase the aviation industry's CO_2 emissions (Soepnel et al., 2017). According to European aviation environmental report, one kilogram of burned modern Jet-A equals to 3.16 kg of CO_2 (EASA et al., 2019). Thus, a more efficient aircraft operation will directly impact the CO_2 emissions. In order to achieve the economic and operating improvements in the aviation industry, the transition to more electrified systems is currently being considered (Rosero et al., 2007). Indeed, to achieve such transition to a more efficient aerospace system, analyzing all aircraft operational processes is necessary, which also includes the on-ground operations with a special focus on the taxi operations.

The aircraft taxiing operation takes place during the turnaround phase of the flight mission. After landing, the pilot taxies the aircraft from the runway to the gate, and from the gate to the departure runway. Today's on-ground aircraft operations are mainly jet engine based. The aircraft's main engines are designed for flight operations at high power levels and not for idle operations at low power levels. As a result, utilizing the main engines for on-ground operations lead to increased fuel burn since the main engines are used in an inefficient manner (Safran S.A and Honeywell Aerospace, 2013). This in turn leads to an increase in fuel consumption and emission. Hence, more efficient alternative solutions need to be considered for the ground operations of aircrafts to ensure that future goals can be met.

In the last decade, Electric Taxi Systems (ETS) was presented as an alternative to improve the ground operations of modern aircrafts. The ETS is based off of electrified on-ground aircraft operations with the intent of achieving improved fuel economy and lower greenhouse gas emissions. The three main Electric Taxi Systems are, Wheeltug, Electric Green Taxi System (EGTS) and TaxiBot. These systems will be discussed in the next sections

1.1.1 Wheeltug

The concept of the Wheeltug aims at installing electric motors in the aircraft's nose landing gear. The motors are powered by the auxiliary power unit (APU) which allows the aircraft to be autonomously maneuvered to perform its on-ground taxi operation without its engines. This leads to power efficiency and decreased fuel consumption and emissions during taxi operation. Also, the system could replace the tow truck during pushback phase operations hence reducing delay (WheelTug, 2020).

Figure 3.Wheeltug (Howard, 2013)

In 2005, the Wheeltug system was presented as an ETS concept. Five years later, it was successfully tested for Boeing 737-700 narrow body aircraft taxiing at Prague Ruzyne Airport after the system was revised by the company (Ithnan et al., 2015). After the successful first ground test, the company received an approval by the US Federal Aviation Administration to proceed with the system's certification programme (Michael, 2017).

The system is estimated to weight about 140kg and currently only available for narrow-body aircrafts. The Wheeltug system is designed for short to medium haul flights (Thierry, 2014) .

However, there is uncertainty regarding the profit margin of the system. This is because of the additional weight the aircraft must carry during the flight which results in more fuel burned. This might jeopardize any benefits achieved on the ground (Soepnel et al., 2017).

1.1.2 Electric Green Taxi System

In 2011, Honeywell International Inc.'s Aerospace Division and Safran S.A both signed an agreement to launch a program to design an on-board Electric Taxiing System that is retrofittable to existing aircraft architectures. The system also knows as Electric Green Taxiing System (EGTS), is attached to the main landing gear and powered by a more powerful APU (Soepnel et al., 2017).

Figure 4. EGTS (Soepnel et al., 2017)

The first product was tested in the Paris Air Show in 2013, prompting Airbus S.A.S to sign a memorandum of understanding (MoU) to target the use of EGTS in its single aisle A320 aircraft family (Ewald Heinrich & Heinrich, 2015).

Like the Wheeltug system, the EGTS is designed for short to medium haul flights and it's currently available only for narrow-body aircrafts. The system is estimated to weight around 400kg (Soepnel et al., 2017).

Like Wheeltug, aircraft manufacturers have raised concerns regarding the safety and profit margin of the system. The additional weight of the system will be carried by the aircraft in the air, causing an increase in fuel consumption during the flight. Thus, offsetting any benefits on the ground (Soepnel et al., 2017). Also, there were concerns regarding the system not having enough traction in adverse conditions like icy and slopped surfaces. In 2016, the EGTS system was discontinued by Honeywell and Safran(Gubisch, 2016).

1.1.3 Taxibot

The TaxiBot is a pilot-controlled semi-robotic towbarless truck available for aircraft taxiing. Unlike the Wheeltug and EGTS, it is not integrated to the aircraft's landing gear. The towing truck possesses a diesel-electric hybrid powertrain to allow proper taxiing for "Narrow Body" or Single aisle as well as "Wide Body" commercial aircraft (Hospodka, 2014). The taxiing system has been designed by Isreal Aerospace Industries (IAI) together with TLD, Lufthansa LEOS as part of the Deutsche Lufthansa AG, Siemens AG, Airbus S.A.S., and the Boeing Company (Hospodka, 2014).

This TaxiBot system performs the push-back phase as well as the taxi phases of the flight mission. The TaxiBot driver loads the front wheel of the aircraft on a platform within the tractor before performing the pushback. After the pushback, the pilot gains control of the system and steers the aircraft to departure runway. Once the aircraft arrives the departure runway, the Taxibot will be detached and the driver either returns the truck to the gate or waits for an arriving aircraft to taxi back to the gate (Re, 2012)

Based on current studies, this ETS solution is the most accepted alternative solution in the aviation industry and is already available for today's aircraft on-ground operations after being certified by the European Aviation Safety Agency (EASA) for commercial use in fall 2014 (Surgenor, 2014).

Figure 5.Taxibot (EconomicTimes, 2019)

In 2019, Taxibot was used for the first time on a commercial flight by Air India(EconomicTimes, 2019).

However, concerns regarding the price and cost of operation have limited the use of the taxi truck in airports. The electric tow truck reportedly cost 20-30% higher than the price of a conventional tow truck. To avoid delays, especially in large airports, more than one tow truck will be needed for the on-ground taxi operations to be improved (Hospodka, 2014).

1.2 Literature Review

Initial studies on the impact of emerging alternative taxiing methods compare the environmental performance of traditional taxiing method with the emerging alternative taxiing methods in specific case studies, by replacing traditional taxiing procedures with alternative taxiing procedures (Guo et al., 2014; Ithnan et al., 2015). For example, (Guo et al., 2014) perform a comparative study of four alternative taxiing methods on the fuel consumption and local emissions produced during the on-ground taxi operation in ten airports. They conclude that adopting alternative taxiing methods can significantly reduce fuel consumption and emissions during the on-ground taxi operation compared with traditional methods. Thier findings suggest that on-board systems like Wheeltug, shows the best performance in emissions reduction while off-boards systems like taxibot burns the least fuel. While these studies are informative, they are incomplete in that they do not consider the cost of operating the alternative taxiing methods. Also, Ithnan et al. (2015) analyzed the environmental performance of three alternative taxiing methods. Without quatifying the economic implications, they conclude that aircraft taxiing with electric nose gear shows the best fuel burn and emissions performance.

The potential to benefit from alternative taxiing methods in the aerospace industry, and especially in ton-ground taxiing operations, has been identified and studied by different authors.(Hospodka, 2014) observes cost saving potential through using on-board taxiing systems for on-ground taxiing operation. His findings suggest a high potential for time savings during peak hours when there are inadequate number of pushback tractors. The on-board taxiing system will allow the aircraft to move backwards utilizing its own force, thereby reducing ground delays, handling cost and lower the risk of accidents when handling pushbacks. He suggests that the main engines can save some working time, slightly reduced by extended APU working time. This will have a direct impact on the maintenance cost of the engine.

Another study by (Khammash et al., 2017) compared the potential benefits of introducing different fleet of semi-robotic towbarless tractors to perform the taxi-out operations. Due to the aircraft fleet mix operating at the airport, they conclude that utilizing 4 Narrow-body TaxiBots can potentially lead to an annual direct cost savings of up to 1 million euros for airlines and more than 18% CO2 emissions reduction.

What most of the reviewed articles have in common is that they compare the potential environmental benefits and possible cost savings of using different taxiing methods without considering the impact of the initial investments for the taxiing system considered. This makes it difficult to quantify the actual operating cost of introducing the taxiing system. Therefore, the work aims to consider both the initial investment and benefits of operating the taxiing system considered.

Furthermore, the reviewed articles assess the impact of introducing the alternative taxiing method using existing operational procedures. This study aims to assess the impact of alternative operational procedures on the economic and environmental performance of implementing a taxiing method while ensuring a comfortable taxi operation with minimum delays and emissions. It is believed that changes of such magnitude would be difficult to justify otherwise.

1.3 Problem Statement

The potential impact of utilizing alternative taxiing methods seem promising and expected to be far reaching. However, new operational procedures need to be evaluated to ensure the viability and sustainability. The economic and environmental potentials seem high but difficult to quantify.

For a new technology to be implemented in the aviation industry, it must be safe, cost effective and provide functional benefits. The initial investments required to implement the alternative taxiing system need to be assessed to provide clarity on the overall operating cost. In addition, investors and other important stakeholders are increasingly demanding more economically sustainable solutions. As such, considering the impact of different operational procedure on both the environmental performance and cost of operation is a necessary step to speed up the implementation phase.

Therefore, the main objective of this thesis is to identify and quantify the influence of using off-board taxi system on the on-ground operations at Montreal-Trudeau International Airport.

The following sub-goals have been established for this thesis

- Identify different operational procedures that can be implemented with the use of the off-board taxiing system at Montreal-Trudeau International Airport.
- Develop a simulation model from which the effect of the off-board taxiing system on the overall on-ground taxi operation can be quantified
- Assess the impact of the off-board taxiing system on the airport throughput, cost and environmental performance.

- Analyze the results to determine to what extent the different operational procedures and number of off-board taxi systems can help alleviate delays if traffic increases and their impact on the overall cost of operation.

1.4 Summary

In this section, we reviewed different studies about the Electric Taxi Systems to improve the on-ground taxiing operations. It must be concluded that the (Taxibot) appears to be the only solution that has obtained certification and is currently available for commercial flights despite concerns regarding the operation cost and delays. Thus, this research study will focus on the TaxiBot concept as a solution to improve the on-ground taxi operations.

The fuel consumption and emission problems are mostly seen as technology issues where aircraft manufacturers and researchers focus on the design and development of a more fuel-efficient on-ground taxiing operation with little to no emphasis on its implementation to satisfy market requirements. Researchers have published papers regarding its potential fuel consumption and emissions reduction on the ground, but the objective of the stakeholders and airline companies is to ensure a safe and comfortable taxi operation with minimum delays and emissions, while sustaining a profitable business.

Hence, the proposed work provides airport taxiing operations planning with options to utilize electric powered towing truck while considering fuel consumptions, delay, emission and total cost.

2 Model and Simulation Description

This study utilized discrete event simulation (DES) and automation software to simulate the arrivals, departures, and taxiing of aircrafts at the Montreal-Pierre Elliot Trudeau International Airport (i.e., airport code YUL). The taxi simulation model was developed using Arena Simulation Software version 15 by Rockwell Automation Technologies.

2.1 Overview of Montreal-Trudeau Airport

The Montréal–Trudeau airport has one large terminal consisting of 64 gates which has been under extensive expansion in recent years. The terminal comprises four sectors, shown in figure 6 (Aeroports De Montreal, 2014), including the public area (shown in yellow), domestic area (shown in orange), international area (shown in green), and transborder area for the United States (US) and the European Union (EU) connecting flights (shown in blue) (Aeroports De Montreal, 2014). There are two parallel runways 24L-06R and 24R-06L which is intersected by runway 28-10 as illustrated in figure 7. According to the universal system of naming airports, the numbers correspond to the magnetic north pole (Federal Aviation Administration, 2018b). For example, runway 24 is at an angle of 240 degrees while runway 06 is at an angle of 60 degrees, with the difference between them always 180 degrees. Aircraft can land and takeoff in either direction on a given runway. Additionally, when you have 2 parallel runways, they are distinguished by letters R and L, based on whether they are to the left or right. To specify the direction of travel, the runways can be classified 06R, 24L,06L, 24R, 10, and 28. For example, an aircraft arriving or departing at 06R would be traveling in from 06R toward 24L, as illustrated by the arrow in figure 7 (Aeroports de Montreal, 2011).

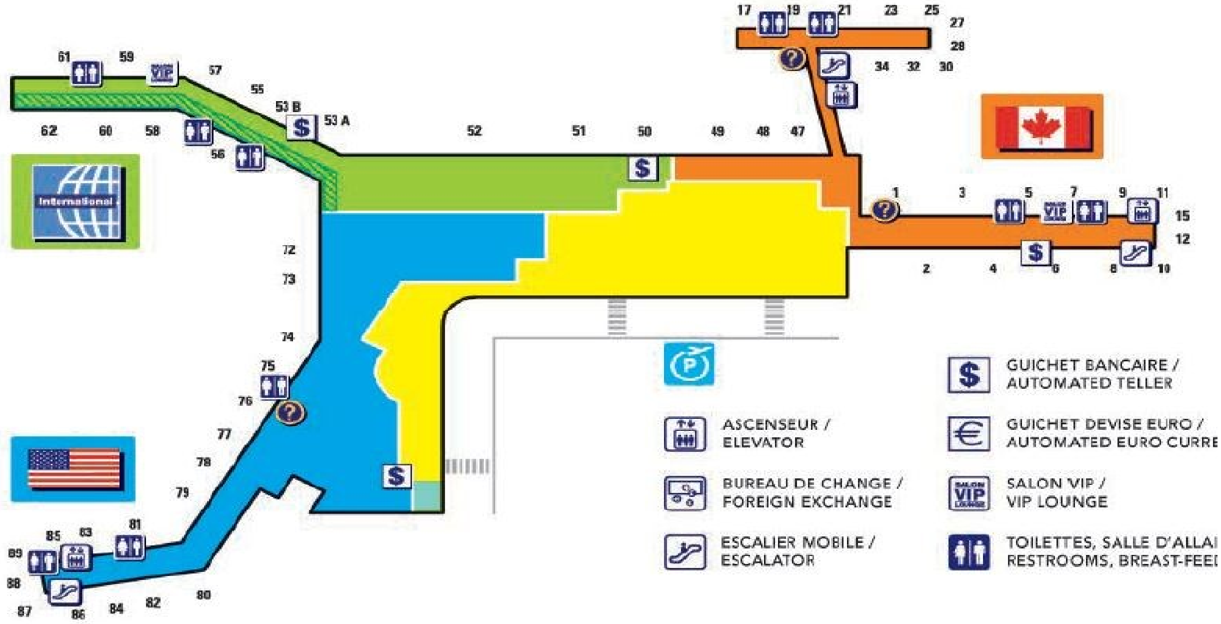


Figure 6.Montréal–Trudeau airport terminal (Aeroports De Montreal, 2014)

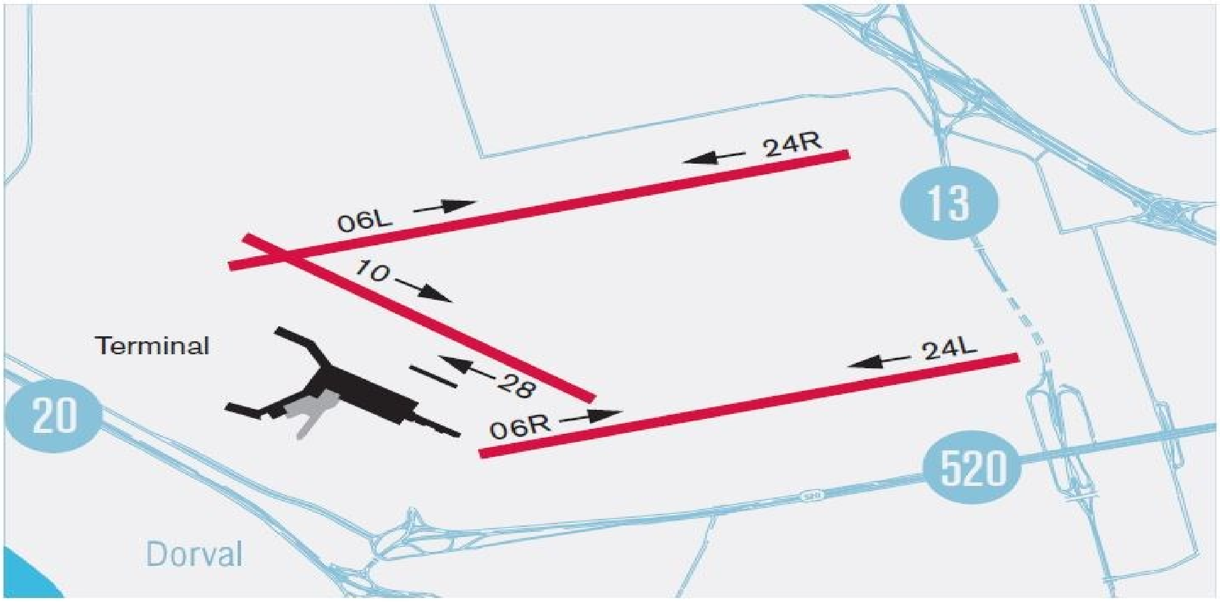


Figure 7.Runways at Montréal–Trudeau Airport (Aeroports de Montreal, 2011)

Aircraft traffic can be measured in several ways. As shown in Figures 8 and 9, both passenger traffic (the number of passengers enplaned and deplaned) and cargo traffic (the weight of cargo loaded and unloaded) at Montreal Trudeau have increased roughly 7% on average since 2013, with 18.4 million passengers and 230 tonnes of cargo in 2018. This one of the highest growth rates in North America. Despite the steady increase in passenger traffic, the number of aircraft movements has not experienced a similar growth rate. This is largely due to an increased proportion of international traffic which utilizes larger aircraft to move more passengers per movement. Figure 10 shows the number of aircraft movements in recent years with an average of over 242,000 flights per annum (Aeroports De Montreal, 2018). This ranges between 633 flights per day in 2014 to 723 flights per day in 2018. Figure 11 shows the distribution of flights movements for August 26, 2019 (Flightradar24, 2019). Approximately 93% of flights occur between 7 AM and midnight (Aeroports de Montreal, 2011). Less than 7% of flights occur between midnight and 7 A.M due to the noise abatement measures set by Transport Canada, which restricts aircrafts weighing more than 45,000kg from taking off between midnight and 7 A.M and landing between 1:00 AM and 7 A.M (Aeroports de Montreal, 2011).

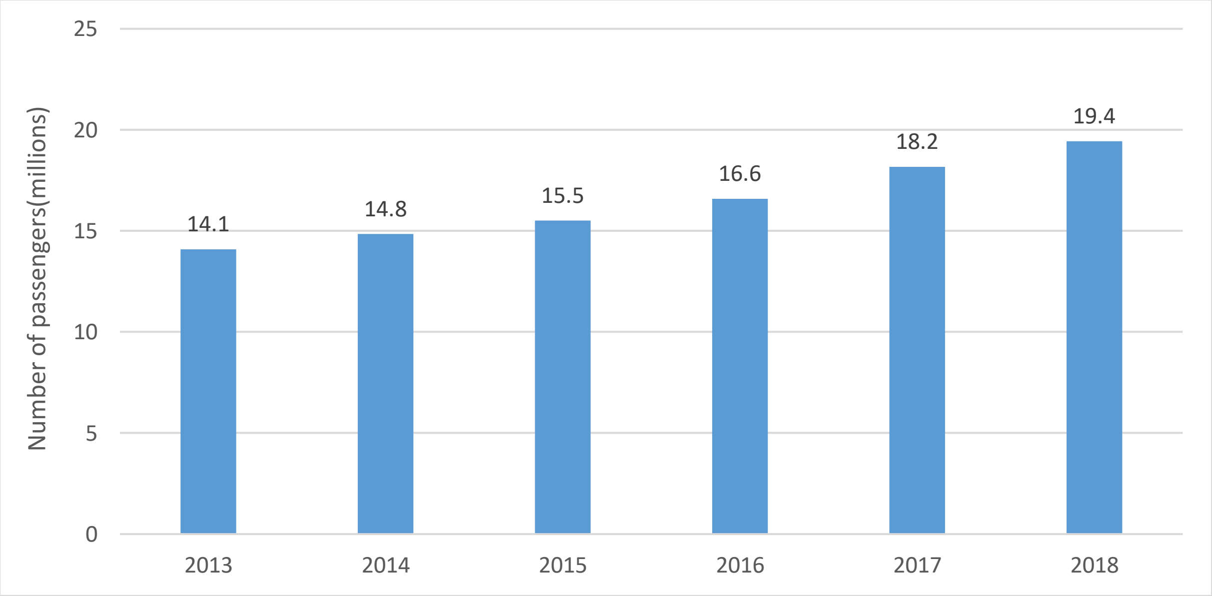


Figure 8.Annual Passenger Traffic at Montréal–Trudeau Airport (Aeroports De Montreal, 2018)

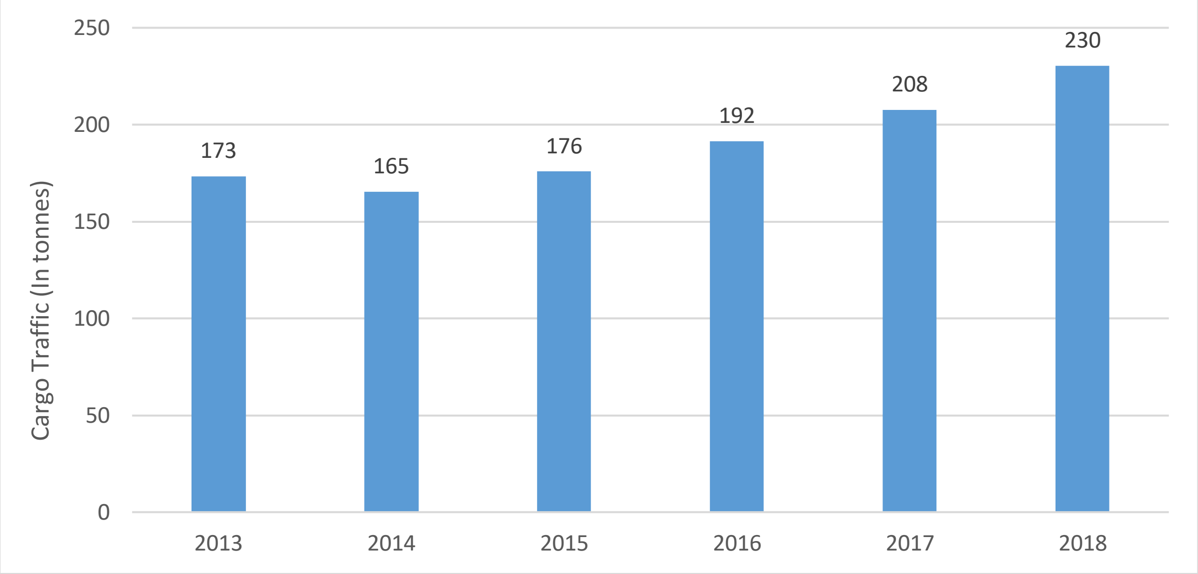


Figure 9.Annual Cargo Traffic at Montréal–Trudeau Airport (Aeroports De Montreal, 2018)

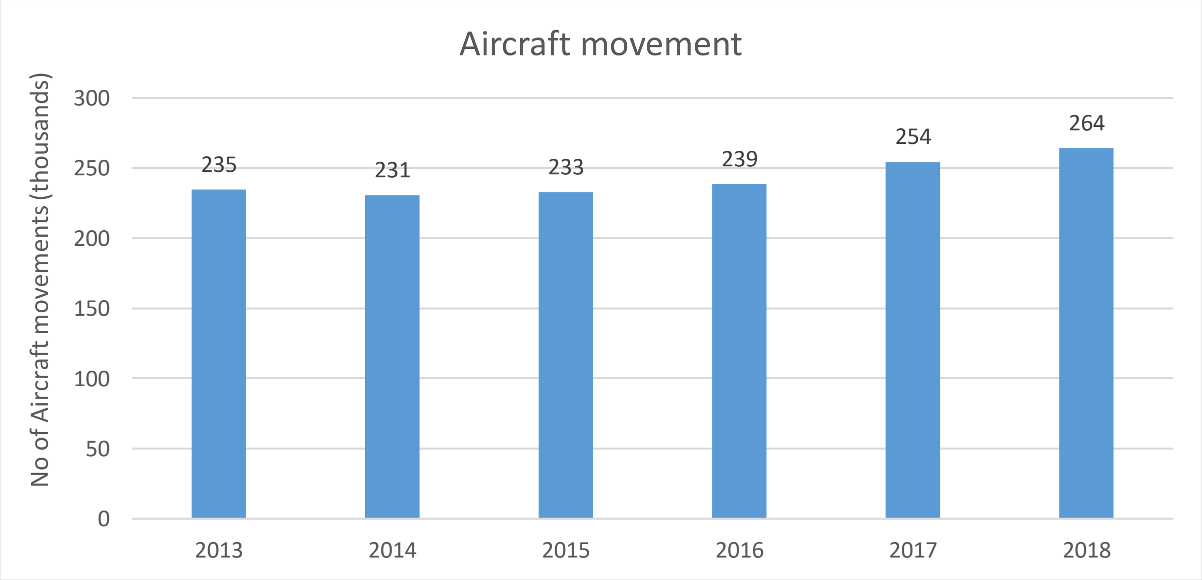


Figure 10.Annual Aircraft Movement at Montréal–Trudeau Airport (Aeroports De Montreal, 2018)

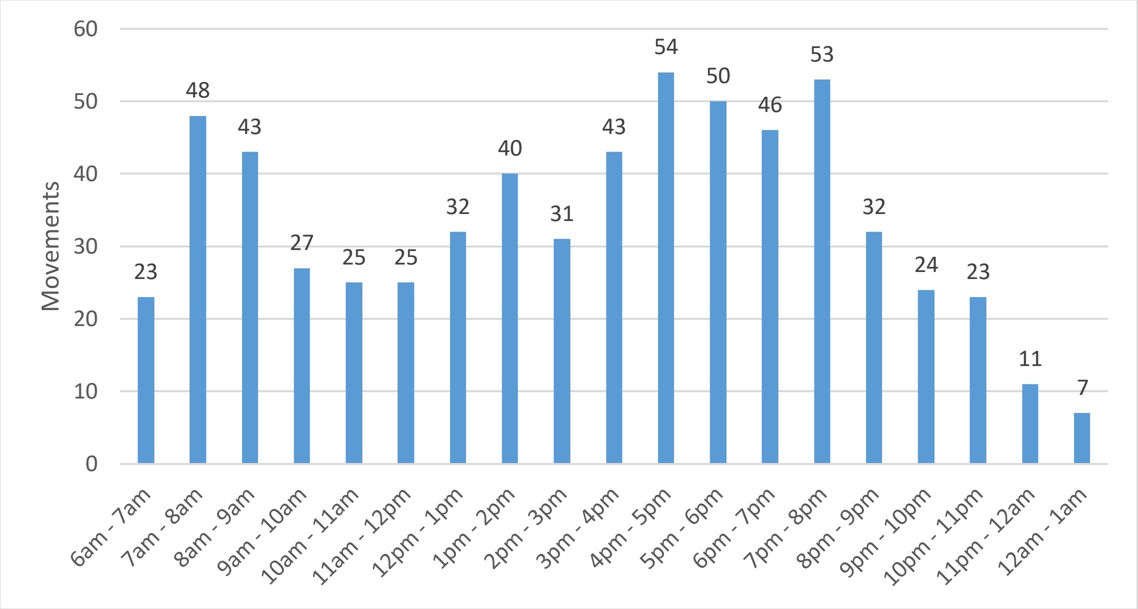


Figure 11. Movements per hour during non-restricted hours at Montreal-Trudeau on August 26,2019(Flightradar24, 2019)

Runway selection and the direction of landing and takeoff are dictated by NAV Canada, the organization that controls air traffic in Canada. Safety considerations and weather conditions are considered when selecting a runway. According to the rules of aerodynamics, aircrafts are required to land and takeoff into the wind. Table 1 shows Montreal-Trudeau's 2018 runway use statistics (Aeroports de Montreal, 2018). Runway 28-10 was rarely used, accounting for less than 1% of the arrivals and departures for that year. Runway 24L-06R was used for 85% of the departures while 24R-06L for 70% of the arrivals.

RUNWAY	DIRECTION	NO. OF ARRIVALS	% of arrivals	NO. OF DEPARTURES	% of departures
24R-06L	**24R**	62,155	52%	6,436	5%
	06L	21,358	18%	11,010	9%
24L-06R	**24L**	20,027	17%	75,019	63%
	06R	15,029	13%	26,353	22%
28-10	**28**	5	0%	423	0%
	10	0	0%	0	0%
	Total	118,574	100%	119,241	100%

Table 1.Runway use statistics for year 2018 (Aeroports de Montreal, 2018)

Table 2 provides an overview of the type of aircraft flying in and out of Montreal-Trudeau (Aeroports de Montreal, 2011). Boeing and Airbus families, regional jets such as bombardier CRJs, and Dash8 turboprops are the most widely used aircraft. Figure 12 shows the percentage of aircraft movements by aircraft weighing more than and less than 45,000 kg. Aircrafts weighing less than 45,000kg represents 68% of aircraft movements at Montreal-Trudeau. This is largely due to the noise levels of the smaller aircrafts which are generally quieter compared to the larger aircrafts (Aeroports de Montreal, 2011).

AIRCRAFT	**LESS THAN 45,000 KG**	**MORE THAN 45,000 KG**	**AIRCRAFT**	**LESS THAN 45,000 KG**	**MORE THAN 45,000 KG**
Airbus 320		●	**Challenger**	●	
Airbus 320		●	**Convair**	●	
Airbus 330		●	**CRJ 100-200**	●	
Airbus 340		●	**CRJ 700-900**	●	
Airbus 380		●	**Dash 8**	●	
ATR	●		**Embraer 135-145**	●	
Beech 1900	●		**Embraer 170**	●	
Beech 100 King Air	●		**Embraer 190**		●
Boeing 737		●	**Global Express**	●	
Boeing 747		●	**Gulfstream**	●	
Boeing 757		●	**Hawker HS125**	●	
Boeing 767		●	**Learjet**	●	
Boeing 777		●	**MD11**		●
Cessna	●		**Piper PA-31 Navajo**	●	

Table 2.Aircrafts flying in and out of Montreal-Trudeau Airport (Aeroports de Montreal, 2011)

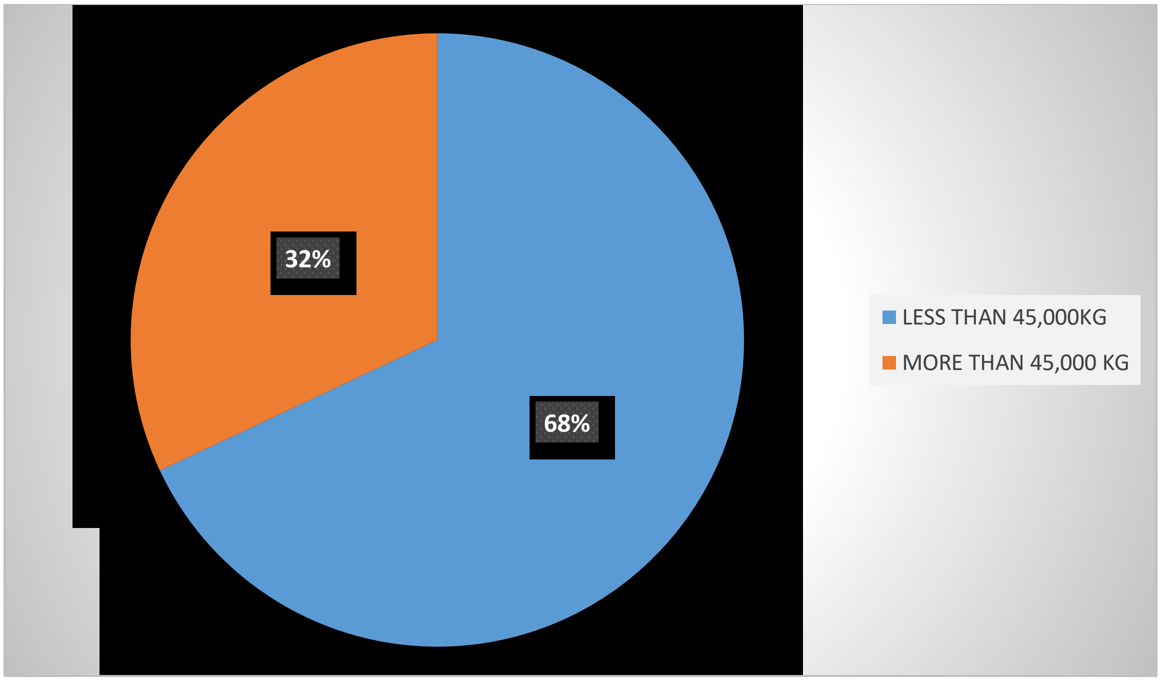


Figure 12.Breakdown of aircraft movements by aircraft weight(Aeroports de Montreal, 2011)

2.2 Modeled Airport Network

The airport was modeled as a network according to the layout of Montreal-Trudeau International Airport. Since a detailed airport diagram was not available for the airport, the Google maps measurement tool was used to measure the length of the runways and the distances between intersection points on the taxiways that connect the runways with the gates. The resulting network is shown in figure 13. Arriving flights are shown by green arrows and departing flights are shown by blue arrows. The taxiway, which provides a route for aircraft to move from a runway to a gate and vice versa, was constructed as a network of links and nodes. The nodes represent intersection points where aircraft queue to obtain clearance to move to the next link segment. The links represents the taxipath between each intersecting point. Upon landing, an aircraft gains access to the taxiway through a green node. Aircrafts landing on runway 24R-06L gain access to the taxiway through access node 2 while aircrafts landing on runway 24L-06R gain access to the taxiway through access node 3. After entering the taxiway, aircraft navigate via yellow nodes and taxiway links to a gate, represented by a red node A departing aircraft navigates to a blue node via the taxi links, where it exits the taxiway and enters the runway

Figure 14 shows the airport network on the Montreal Trudeau international airport map in ARENA Simulation software. This includes the layout of the runways, taxiways and gates with key intersections that aircraft traverse from the point of landing to the assigned gates and from the gates to the point of departure. We recognize points on the airport surface as nodes where aircrafts can be moved from gates to runways and vice versa. Appendix 01 provides the estimated distances between nodes and gates measured using the google map measuring tool.

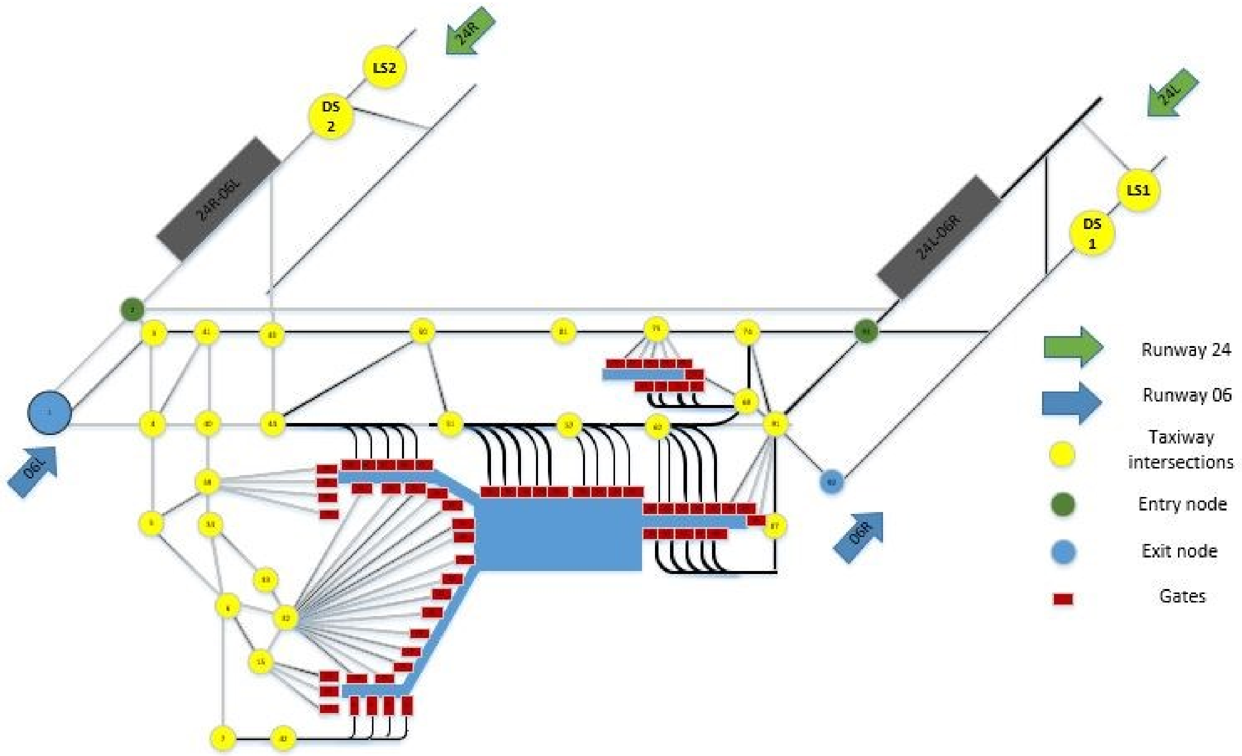


Figure 13.Airport Network for Montreal- Trudeau

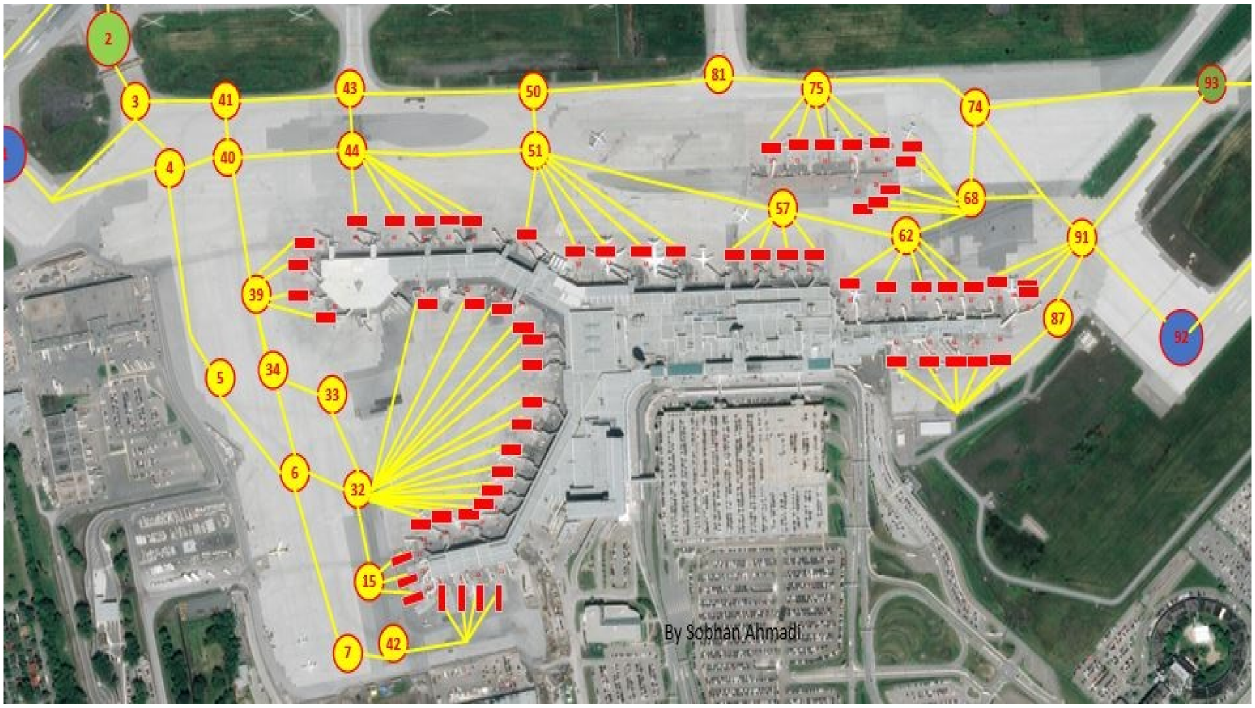


Figure 14.Airport network on YUL airport map

2.3 Simulated Aircraft Movements

For this model, flights are simulated for an 18-hour period between 6 A.M and 12 A.M. This captures the period when the greatest number of customers use the system and traffic delays and congestion are experienced on the taxiways. Prior to 6 A.M., aircraft would be expected to traverse the taxiway with no delays. Flight information for flights departing from Montreal Trudeau in the morning and arriving thereafter on August 26, 2019 was obtained from www.flightradar24.com , a popular website used to track flights. This day was taken as a representative day at Montreal Trudeau, and was used to develop an aircraft movement profile for the simulation. A total number of 325 flights were used to initialize the simulation model with 6 aircrafts departing at 6:00 A.M after an overnight stay at the airport; 319 inbound flights arriving at the airport throughout the day, disembarking passengers, embarking passengers, and departing from the airport. It was assumed that all 319 arriving aircraft subsequently departed Montreal Trudeau. This results in 644 aircraft movements. Appendix 02 shows the flight information obtained from www.flightradar24.com used to simulated flights. This information was only used to establish a profile of aircraft movements. It was not used to define the aircraft type.

2.3.1 Creation of Aircraft Entities

The first segment of the model includes the creation of the aircraft entities for the 6 initial departing flights and the 319 flights arriving throughout the day. . Each entity is then assigned the following:

- **Aircraft type**:: All aircraft are classified as wide-or narrow-body. Based on the aforementioned information about the mix of aircraft flying through Montreal Trudeau, as shown in figure 1-7, we assume that 68% of aircrafts are narrow- body while 32% are wide-body. Within the simulation, this assignment is made randomly .

- **Flight movement**: The initial six departing flights are classified as outbound and the 319 flights arriving flights are classified as inbound.

- **Departure gate**: The initial six departing flights are assigned to a gate randomly based on available gates

- **Departure time**: The departure time for the initial six departing flights is set to time 0 of the model, which is assumed to be 6:00 a.m. local time.

- **Departure runway**: Based on the aforementioned runway statistics (see Table 1), 85% of departing flights are assigned to runway 24L-06R in the direction 06R and 15% are assigned to runway 24R-06L in the direction 06L. Within the simulation, departure runways are randomly assigned …

- **Arrival runway**: Based on the aforementioned runway statistics (see Table 1), 70% of arriving flights are assigned to runway 24R-06L the direction 24R and 30% are assigned to runway 24L-06R in the direction 24L. Within the simulation, arrival r assignment is …

- **Assigned gate**: Arriving aircraft are assigned to an airport gate randomly based on the available gates

- **Arrival time**: The (scheduled/actual) arrival time is assigned based on the www.flightradar24.com data used for this simulation. Flights are assumed to have a delay in arrival with a distribution of TRIA(-15,0,30) minutes

When the flight information is assigned to each aircraft entity, the simulation entities for arrival flights are created at the runways while the simulation entities for departure flights are created at the gates. The simulation entities created at the runway represents the plane landing on the runway of its destination at the end of its airborne operation.

Since this study is primarily concerned with aircraft movement on the taxiway, the movement of aircraft on the runways was simplified. Table 3 provides the assumed runway assignment and direction of simulated arrivals and departures. Runway 24L-06R was assigned assumed for 30% of arriving flights in the direction 24L and 85% of departing flights in the direction 06R; runway 24R-06L was assigned for 70% of arriving flights in the direction 24R and 15% of departing flights in the direction 06L; runway 28-10 was considered to be inactive.

RUNWAY	DIRECTION	% OF ARRIVALS	% OF DEPARTURES
24L-06R	**24L**	30%	0%
	06R	0%	85%
24R-06L	**24R**	70%	0%
	06L	0%	15%
28-10	**28**	0%	0%
	10	0%	0%
TOTAL		100%	100%

Table 3. Runway use statistics for the model

2.3.2 Taxi Route

The algorithm described in Appendix 3 was developed to calculate the shortest path from the runway to its destination node (i.e., gate). For each arrival, the shortest path was calculated, and the aircraft followed this path without deviation to the gate.

Collision avoidance is an ongoing research problem in airport simulation. Three types of collision may occur during the process of taxiing:

1. Head collision. This occurs when two aircrafts moving towards each other on the same taxiway collide, as illustrated in Figure 15.
2. Tailgating collision. This occurs when an aircraft following another aircraft on the same taxipath collides with the aircraft in front of it, as illustrated if Figure 15.
3. Intersection point collision. This occurs when two aircraft meet at an intersection and collide, as illustrated if Figure 15.

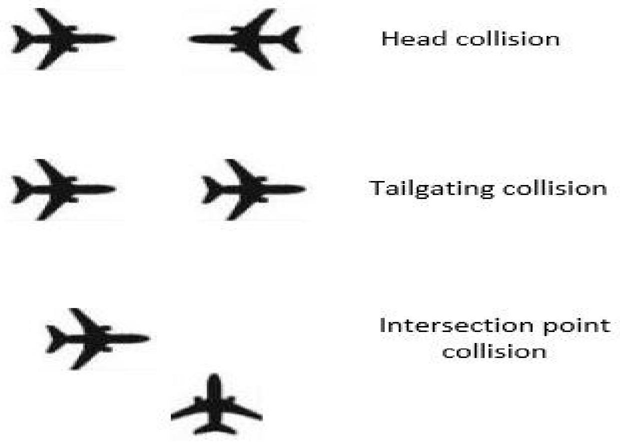


Figure 15.Illustration of the types of collision

There is ongoing research aimed at developing complex deadlock avoidance algorithms to solve this problem. For example, Zhou and Jiang (2015) developed an Algorithm to detect collision and reroute the aircrafts(Zhou & Jiang, 2015). The algorithm is a heuristic search algorithm used to solve dynamic programming problems, used for path planning. The algorithm calculates the estimated distances for all nodes connected to the beginning node. Then chooses the minimum as the successor node. The successor node becomes the beginning node,and repeats the procedure till the aircraft gets to its final destination. When a conflict is detected, the aircraft is rerouted to next shortest path. This technique is challenge to implement on discrete event simulation due to the inability to control the entities between each node and the distance between two aircrafts, therefore risking the chances of collision on the taxiway.

Collision avoidance is not the focus of this study. However, since the study is interested in delays that may occur from alternate taxiing systems, it is important to capture the movements that would be necessary to avoid collisions. In the simulation, the possibility of collision is eliminated by establishing aircraft right of way. When two aircraft meet head to head at an intersection (i.e., node) in the simulation model, right of way is determined on a first come, first serve (FIFO) basis. Each link has a maximum capacity of aircrafts it can accommodate at a time depending on distance between intersections (i.e., the length of the link), the length of the aircraft, and the required separation distance between aircraft. De Havilland Canada's DASH-8-400 is the most commonly used aircraft in the airport. Thus, the length of the aircraft (32.8 metres) will be considered to compute the maximum capacity of aircrafts on a link. Taxiway separation distances are not clearly defined by Transport Canada or the Federal Aviation Administration (FAA). The Australian Government's Civil Aviation Order 20.9), "Air service operations - precautions in refueling, engine and ground radar operations," specifies that a turbo-prop operating at or below normal taxiing power shall not be operated within 15 meters of another aircraft (Civil Aviation Safety Authority, 2011). Since nearly 67% of aircraft operated at Montreal-Trudeau weigh less than 45,000kg, a 15 m separation distance was used in the simulation. Therefore, 47.8 m of total space was required for an aircraft to enter a link.

2.3.3 Aircraft Turnaround

After arriving aircraft reach the gate, the turnaround process is simulated. The turnaround process is an important part of aircraft ground operations and describes all the phases for preparing an aircraft for its flight. This process starts when the aircraft arrives at its assigned gate and ends when the aircraft is ready to depart. The time spent in this process depends on the number of passengers, aircraft type, amount of loaded and unloaded cargo and the business model of the operators (Schmidt, 2017).Figure 16 shows the turnaround time correlation with the number of passengers for regional, single-aisle and twin-aisle aircraft based(based on manufacturer data) (Schmidt, 2017).Turnaround time for the aircraft types considered for this simulation was extracted from this chart. The turnaround time for wide-body aircrafts in our simulation is estimated based on the data provided for twin-aisle and is represented as a uniform distribution with a minimum value of 25 minutes and a maximum value of 130 minutes. The turnaround time for the narrow-body aircrafts is estimated based on the data provided for "single aisle narrowbody aircraft" and is represented as a uniform distribution with a minimum value of 26 minutes and a maximum value of 51 minutes. The simulation assumes no additional waiting time at the gate, for example, due to scheduled lags between arrival and departure or other unscheduled delays.

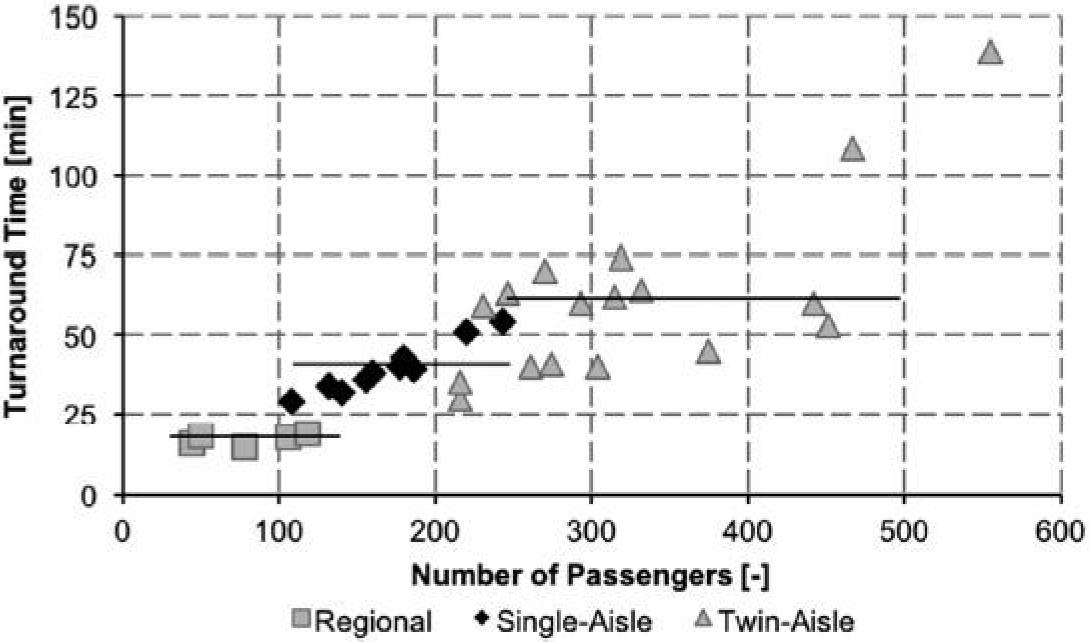


Figure 16.Turnaround time for regional, single aisle and twin aisle aircrafts (Schmidt, 2017)

Upon completion of the turnaround process, the aircraft is pushed back for departure. The aircraft is randomly assigned a runway according to distributions mentioned earlier in Table 3 and a sequence of taxi path to the runway for takeoff is assigned based on the generated taxi path using the same algorithm used above to determine the shortest path between runways and gates and provided in Appendix 3. Collision avoidance is achieved using the same FIFO basis described above.

2.4 Scenarios Simulated

Four scenarios were simulated, the baseline scenario, in which aircraft taxi using their own engine power, and three scenarios utilizing electric trucks. Each are described here. Each scenario is illustrated in Figure 17 and described below.

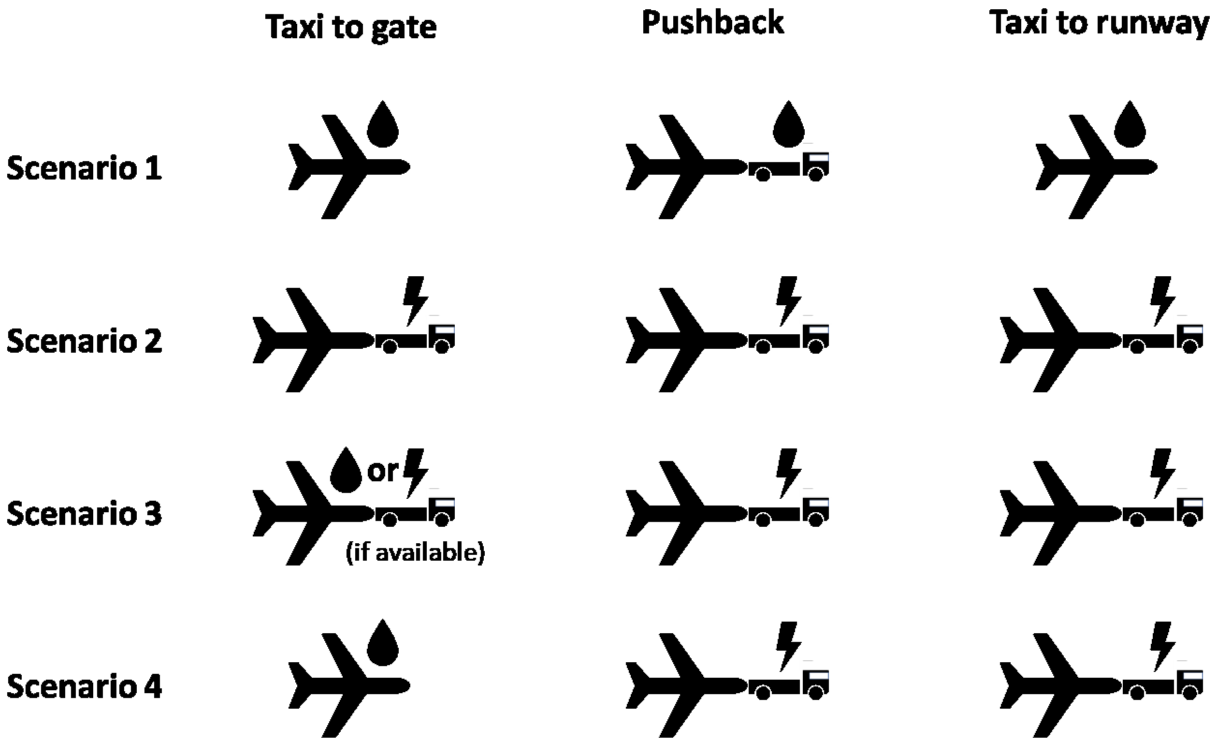


Figure 17. Scenarios simulated

2.4.1 Scenario 1 – Aircraft Taxi Using Their Own Engine Power (Baseline)

The On-Ground Operations (Taxiing) at Montreal-Trudeau airport follows the standard operating procedures for taxiing operations in most airports. Most modern aircraft ground operations start with the aircraft being prepared by the crew for its departure. Key actions in this preparation include fueling the aircraft, loading passengers, cargo, cleaning and other necessary action to prepare the aircraft for its departure. During this process, the auxiliary power unit (APU) is used to run the electrical systems of the aircraft (Altuntas et al., 2014). After the completion of the preparation phase, the pilot communicates with driver of the pushback truck to initiate pushback. The pushback truck connects a tow bar to the front wheels of the aircraft to push it away from the gate. There is very little publicly available market data about pushback trucks. For example, in the US, pushback trucks are generally powered by conventional energy sources such as diesel, gasoline, and liquefied petroleum gas (LPG) (Alliance to Save Energy, 2018) However, pressures to reduce GHG and other air emissions have led to the introduction of a number of alternative powered pushback trucks, with roughly 10% in the US being electric powered (Lindenfeld & Tran, 2015; Smith, 2013)While many aircrafts can use their thrust reversal along with the power of their engines to move backwards, restrictions on this practice have been imposed by many companies mainly due to the risk of foreign object damage from debris propelled into the air (Beinhaker, 2010). The pilot usually starts up the main engines using the auxiliary power unit (APU) as start power, for warm up before or while the aircraft is being pushed back to initialize the takeoff taxi phase. This warm period usually takes 3-5 minutes depending on the main engine type and its generation (Safran S.A and Honeywell Aerospace, 2014). It is desirable that the pilot spends the shortest idle time on the ground because this affects the timely operations of other arriving aircrafts due to congestion at the gate. For this model, we will assume the pushback and warm up as a single event that lasts an average 5 minutes for all pushbacks in the simulation. After the main engines are warmed up, the pushback truck will be disconnected from the aircraft and the aircraft gets confirmation to proceed to the taxi-out phase. The pilot in command gives a pre-taxi briefing that includes the expected taxi route and restrictions before advancing to the taxiway. The aircraft begins to move under its own power and moves on the taxiways to the assigned runway. Upon reaching the runway, the aircraft gets permission for takeoff from the Air Traffic Control (ATC) (Commercial Aviation Safety Team / Common Taxonomy Team, 2013). At the end of the airborne operation (flight), the plane lands on the runway of its destination. After touching the ground, the aircraft enters the braking phase to slow down the aircraft to appropriate taxispeeds before leaving the runway. At this point, the aircraft leaves the runway and moves independently, powered by its own engines, to its assigned gate. Finally, the aircraft reaches its desired parking position at the airport terminal and powers down, unloads passengers, cargo and its crew. At this point, the turnaround process begins with the preparation of the aircraft for its next flight.

Two series of events were simulated concurrently for arriving and departing aircrafts. Figure 18 shows the first series of events which represents aircrafts originating at Montreal-Trudeau (e.g., aircraft that landed late the previous day, parked overnight, and are scheduled to depart on the current day). The second series of events in Figure 19 represents the flights that arrive, taxi, deplane, load, taxi, and depart. Figure 20 represents the simulation diagram for these events. For this scenario, we will only calculate the fuel consumed by the aircraft during the taxi-phase (shown in the white boxes in Figures 18 and 19) as this is the focus of our study.

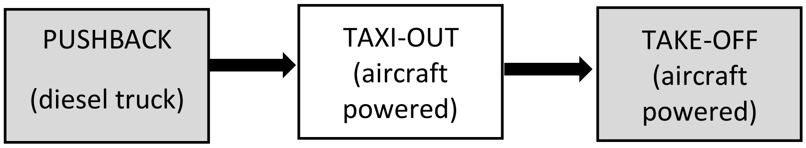


Figure 18.Series of simulated events for arriving aircraft

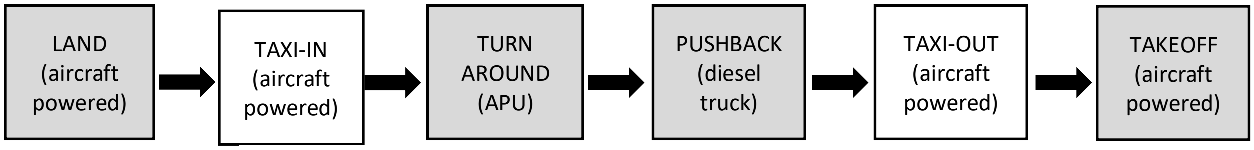


Figure 19.Series of simulated events for departing aircraft

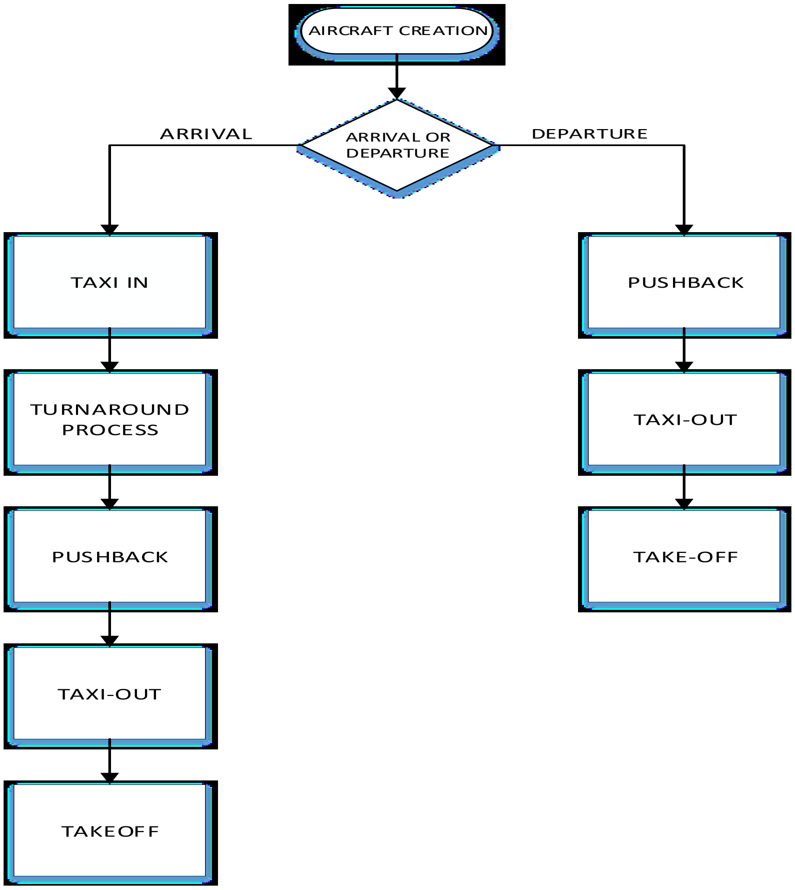


Figure 20.Baseline aircraft taxiing simulation

After touching the ground via the landing station on the runway, the aircraft entity is routed to the access node to gain access to the taxiway. This represents the braking phase of the flight when the aircraft slows down to the assumed taxispeeds before leaving the runway. At this point, the aircraft leaves the runway and moves independently, powered by its own engines to the access node of the taxiway. The aircraft entity is assigned a sequence of nodes to follow to arrive at its assigned gate. At every node, the aircraft entity checks the availability of the link before advancing to the destination node. Finally, the aircraft arrives its assigned gate at the airport terminal and begins the turnaround process. After the completion of the turnaround phase, the aircraft entities are assigned a runway and sequence of nodes to taxi to the runway. The aircraft are pushed back with a diesel-powered pushback truck to initialize the taxi-out phase. During the pushback, the pilot starts the main engines for warmup. The pushback and warm up are assumed to occur as a single event that lasts 5 minutes. The aircraft then utilizes its own engines to the taxi to the runway for takeoff. At this point, the aircraft exits the system. The process flowchart for the model can be found in Appendix 4

2.4.2 Scenario 2 – Aircraft only taxi with trucks

In this scenario, we assume that all flights (arriving and departing) perform their on-ground taxiing operation using electric tow-trucks. As with the baseline scenario, the aircraft entities are created at simulation time 0 and assigned their flight information. When the flight information is assigned, the arrival flights are created at the runways while the departure flights are created at the gates. When an arrival flight touches down its assigned runway, it is routed to the access node to gain access to the taxiway. On arriving at the access node, the aircraft powers down and a request module is used to request the nearest available truck to taxi the aircraft to its assigned gate assigned. Once the truck receives a signal, describing location and requesting node, it travels to the specified requesting node following the taxi path. As the truck reaches the requesting node where the aircraft is situated, it docks the aircraft and transports the aircraft to the gate. The truck uses the same process to select the route to the gate and determine right of way as the aircraft did in the baseline model. When the aircraft arrives its assigned gate, the truck detaches the aircraft and either returns to its previous location or waits to taxi another aircraft to the runway. This is an option ARENA provides in the truck settings. For this simulation, we assume the trucks wait to taxi another aircraft. After the turnaround process is completed and the aircraft is ready to depart, a request module is used to request for the nearest available truck. Once a truck receives the signal, it travels to the requesting gate. The truck then docks the aircraft and performs the pushback process and advances to the runway assigned to the aircraft through its taxi path. We assume that the engine warmup is performed during the taxi process. Upon reaching the designated node in the takeoff queue near the runway, the truck detaches from the aircraft and waits to taxi an arriving aircraft. The aircraft entity then waits to ensure the runway availability before taking off and exiting the system. Figure 23 represents the simulation diagram for this scenario. Figure 21 and figure 22 shows the type of energy used in the processes. Unlike the previous scenario, no fuel will be consumed during the taxi-phase because of the introduction of electric-powered tow trucks to perform the taxi process. According to (Eagle Tugs, 2019a) an electric-powered tow truck consumes between 27.75 and 33.5 Kilowatts when it is operated for 3.75 hours in a day. With Quebec having the cheapest electricity price in

Canada at 7.3 cents/KWh (Energyhub, 2020), the cost for operating an electric truck for 18 hours per day will be between \$9.7 and \$11.7. Based on the low cost of electricity, we will not be including it in our analysis.

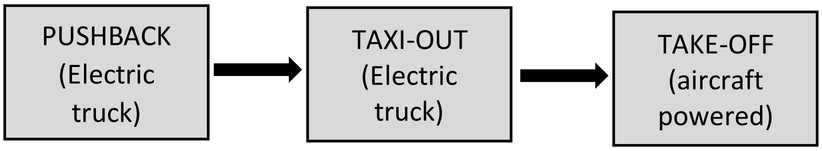


Figure 21. Series of simulated events for only departing aircraft

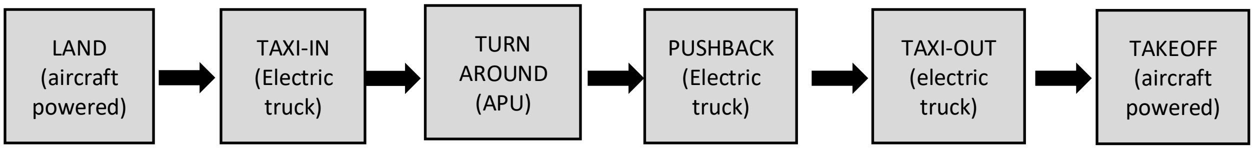


Figure 22. Series of simulated events for arriving-departing aircraft

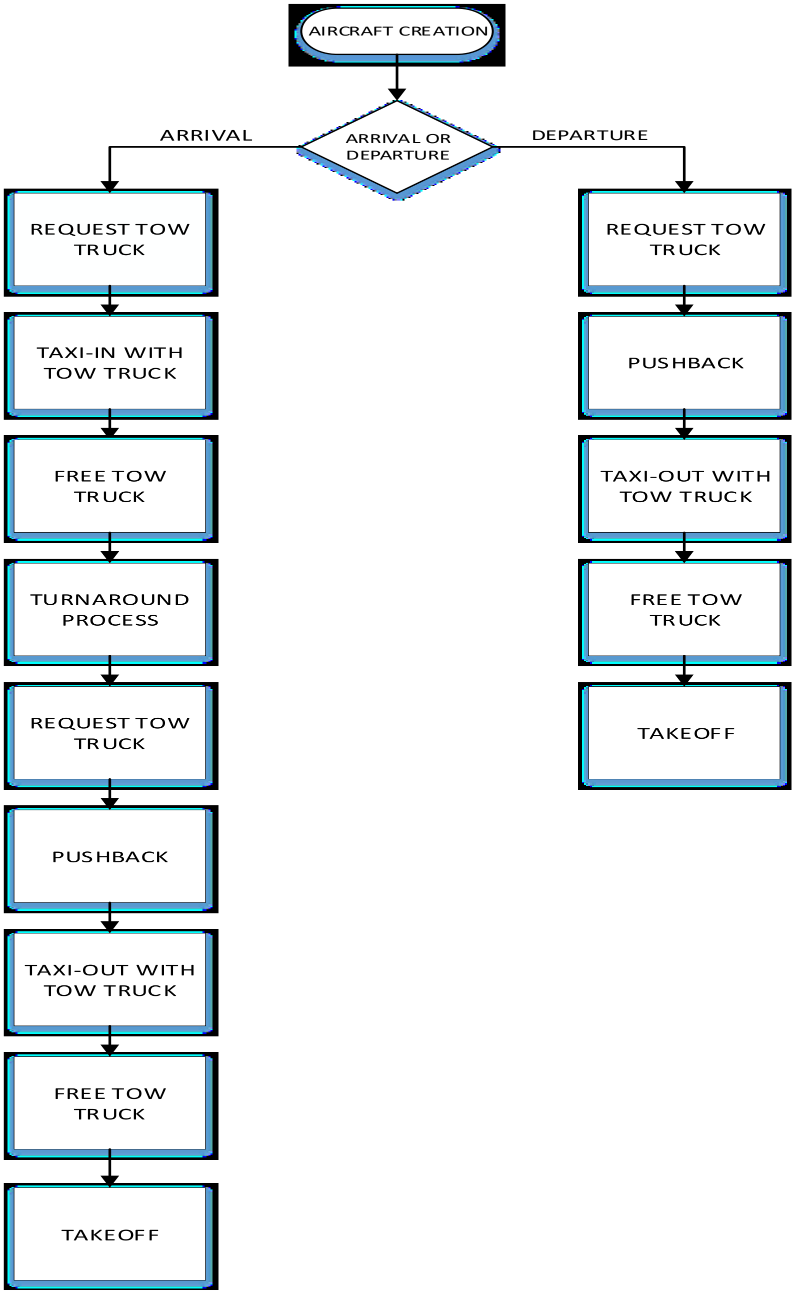


Figure 23.Aircraft taxiing only with trucks

2.4.3 Scenario 3- Aircraft taxi-in partially with trucks, Taxi-out with trucks

In this scenario, we assume that arriving flights perform their on-ground taxi operation using electric tow-trucks only when the trucks are available. While all departing flights perform their on-ground taxiing operation only with electric tow-trucks. When an arrival flight reaches the access node, a decision module is used to determine if an electric tow-truck is available for taxi. If an electric tow-truck is available for taxi, a request module is used to request the nearest available truck to taxi the aircraft to its assigned gate assigned and the aircraft powers down during this process. Otherwise, the aircraft performs its taxi-in operation with its engine. For departing aircrafts, the electric tow-trucks are utilized to perform the taxi-out operation. Figure 26 represents the simulation diagram for this scenario. Figure 24 and figure 25 shows the type of energy used in the processes. Unlike the previous scenario, fuel consumption will be calculated only for arriving flights that utilize their engines for the taxi-in operation.

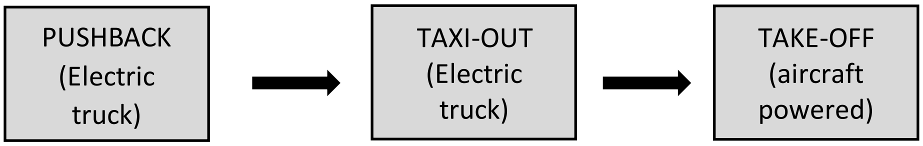


Figure 24.Series of simulated events for only departing aircraft

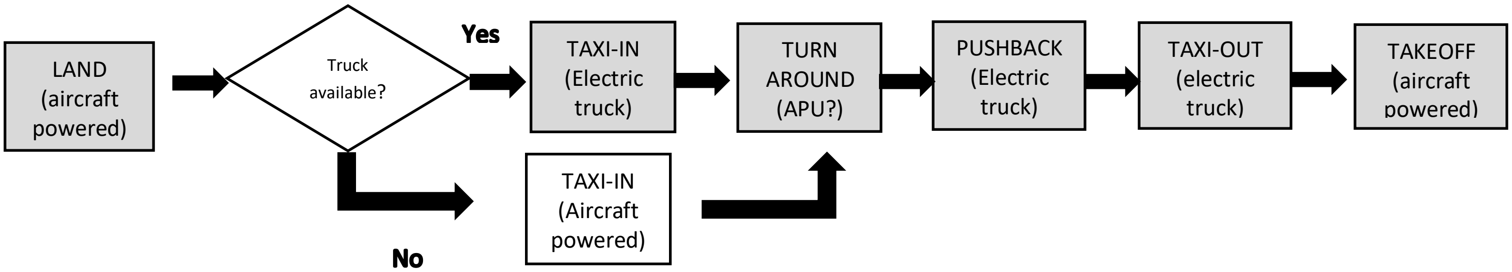


Figure 25.Series of simulated events for arriving-departing aircraft

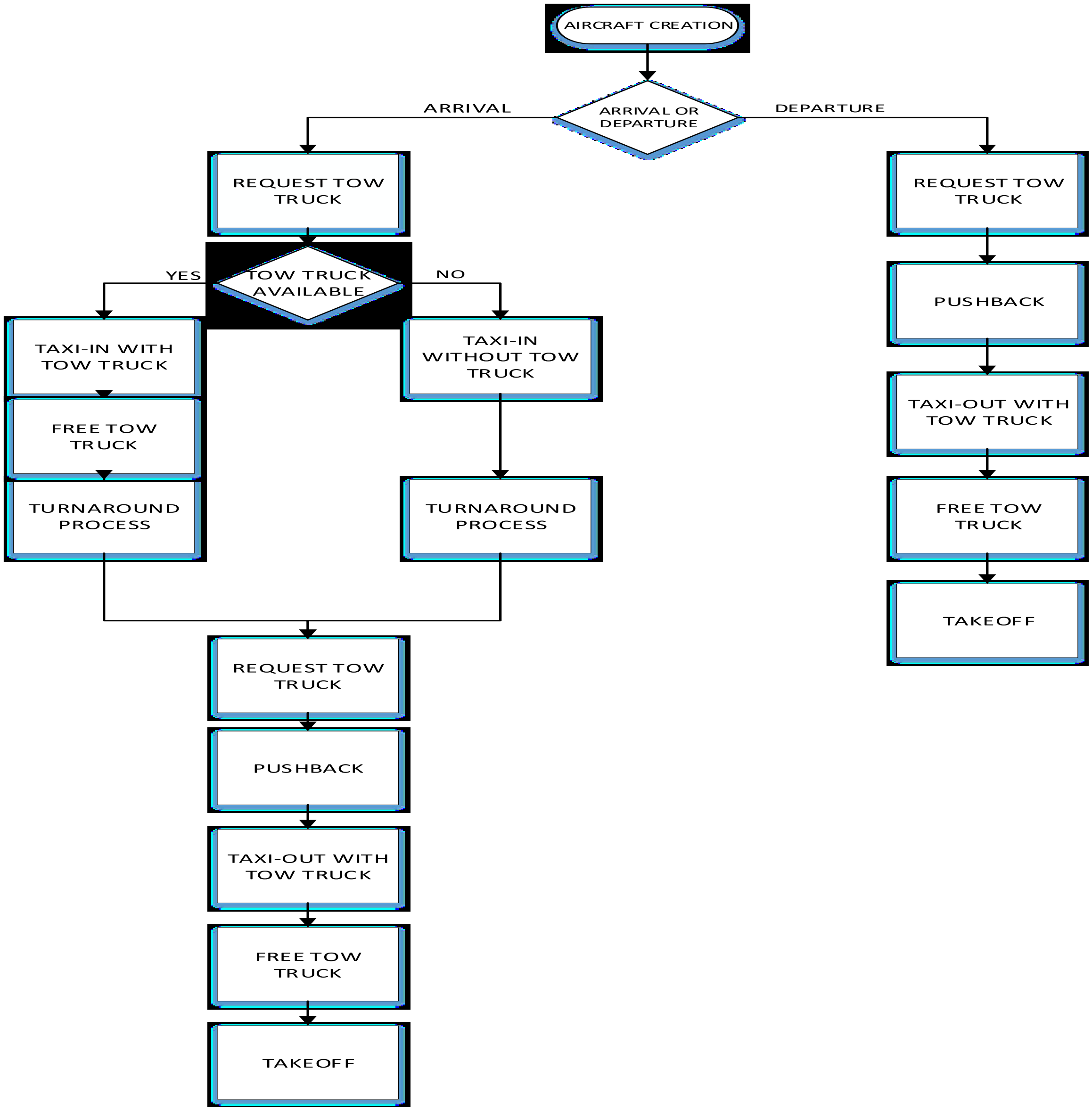


Figure 26.Aircraft taxi-in partially with trucks, Taxi-out with trucks

2.4.4 Scenario 4- Aircrafts only Taxi-out with trucks

In this scenario, we assume that all arriving flights perform their on-ground taxi operation with their engines while all departing flights utilize the electric tow-trucks for taxi. On arriving the access node, the aircraft taxis to its assigned gate using its engines. After the turnaround process is completed and the aircraft is ready to depart, a request module is used to request for the nearest available truck. Once a truck receives the signal, it travels to the requesting gate. The truck then docks the aircraft and performs the pushback process and advances to the runway assigned to the aircraft through its taxi path. We assume that the engine warmup is performed during the taxi process. Upon reaching the designated node in the takeoff queue near the runway, the truck detaches from the aircraft and goes back to its previous location. On ARENA, the truck either goes back to its initial location or waits in its current location for another aircraft. For this scenario, we assume the truck goes back to its initial location. The aircraft entity then waits to ensure the runway availability before taking off and exiting the system. Figure 29 represents the simulation diagram for this scenario. Figure 27 and Figure 28 shows the type of energy used in the processes. Unlike the previous scenario, fuel consumption will be calculated for arriving aircrafts because they used their engines for taxi operations. While fuel consumption will not be calculated for departing aircrafts because they utilized electric tow-trucks during their taxi-process.

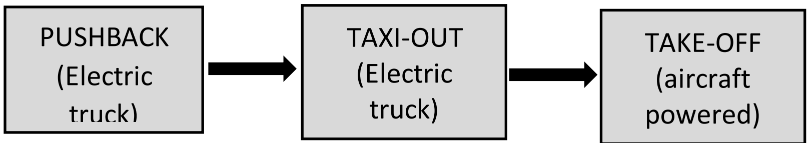


Figure 27.Series of simulated events for only departing aircraft

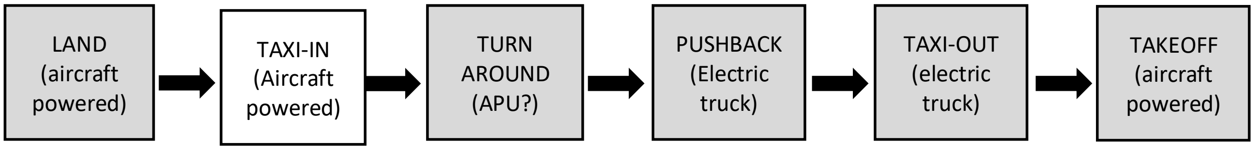


Figure 28.Series of simulated events for arriving-departing aircraft

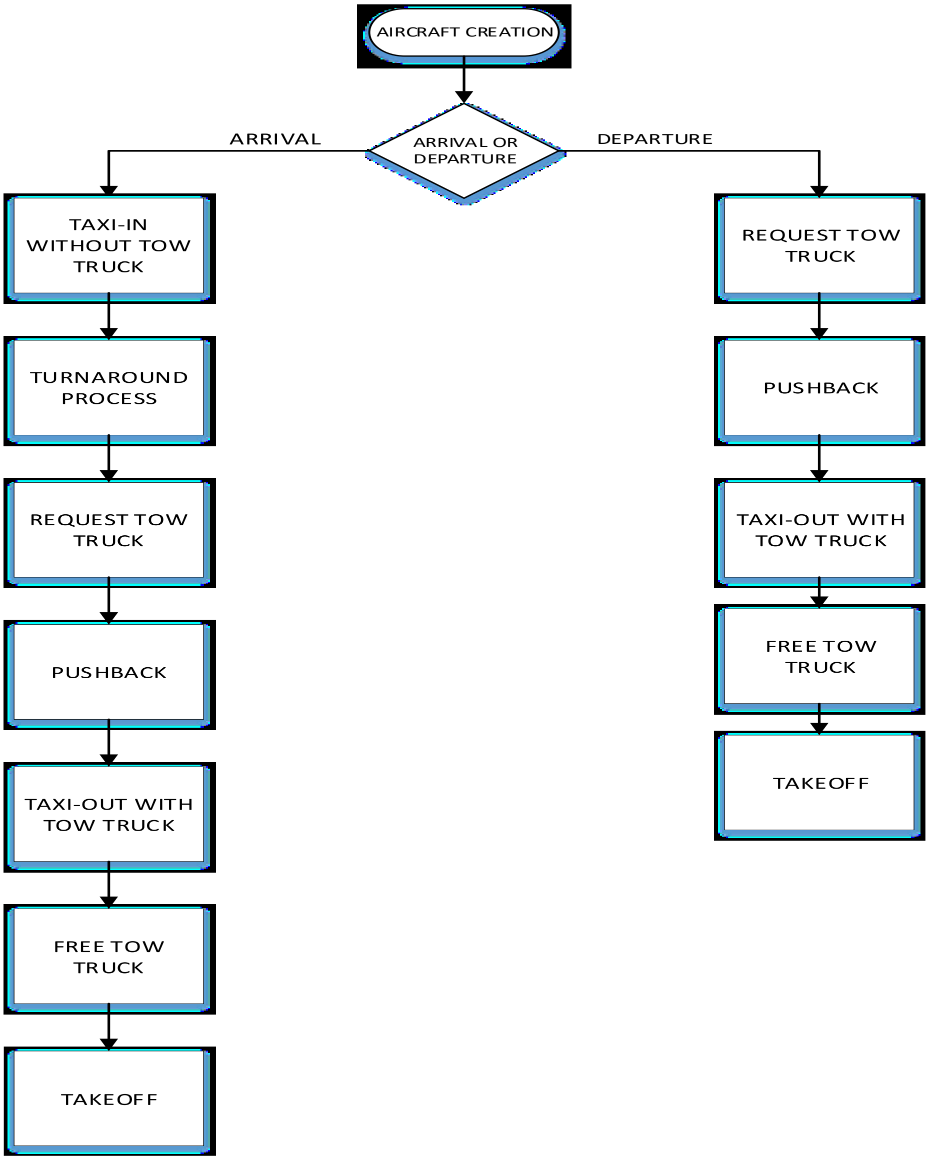


Figure 29.Aircrafts only taxi-out with trucks

2.4.5 Summary of Key Assumptions

This section provides a summary of key assumptions. For all simulations, the aircraft taxi speed is assumed to be 7 m/s when moving and 0 m/s when stopped. For scenario 1, in which pushback occurs via the baseline pushback tractor, which is likely powered using conventional fuel, we assume aircraft warm up occurs during pushback. For scenarios 1, 2, and 3, pushback and taxiing occur under the power of the electric taxi system. For these scenarios, we assume engine warmup occurs during the taxi process.

2.5 Strategy for Data collection and Analysis

To collect the appropriate data for statistical analysis, it is crucial to determine the number of replications needed to achieve results with a small margin of error. This could be achieved by using the formula below (Kelton & Sadowski, 2015)

$$N = \left[Z \times \frac{S}{E}\right]^2$$

Where:

N	Number of replications
Z	Standard normal critical value(95% confidence level)
S	Standard deviation for a random number of replications
E	Preferred margin error

As mentioned earlier, we are using an 18-hour period of the YUL flight operations' data for Monday, August 26, 2019, between 6 A.M and 12 P.M. The baseline model was simulated for 10 replications with a total of 644 flights to determine the sample standard deviation. The critical value for 95% confidence interval is 1.96 while the preferred margin error used is 50 minutes. The total taxi times was extracted from the simulation after each run. Table 4-4 provides the results for 10 replications.

Replication	**Total Taxi time(min)**
1	7201.7
2	7064.6
3	6984.5
4	7098.8
5	7133.1
6	7175.8
7	7051.1
8	7219.8
9	6909.8
10	7084.3
Standard deviation	**89.2**
Average	**7082.4**

Table 4. Simulation results for 10 replications

Therefore:

$$N = \left[1.96 \times \frac{89.2}{50}\right]^2 = 12$$

As a result, we will run our models for 12 iterations to perform our statistical analysis.

2.6 Results of Simulation Runs

Each scenario was replicated 12 times. For each replication, the taxi time, fuel consumption, fuel cost, total delay, delay cost, carbon emission and carbon tax were extracted and analyzed to identify the most economic and environmentally friendly strategy for the future market requirements.

2.6.1 Fuel Consumption

The amount of fuel consumed by an aircraft during taxing depends on the thrust level and distance travelled. Different levels of thrust are required for different taxiing states, which include stopped (idling), starting (acceleration), turning, and taxiing. Estimates for the thrust settings during these states varies between 4% while idling to 9% for accelerating standard aircrafts (Hospodka, 2014)(Nikoleris et al., 2011). Less fuel is consumed at lower thrust levels. (Nikoleris et al., 2011) use the following equation to estimate fuel consumption:

$$FC_i = \sum_{m=1}^{4} t_{m,i} \times f_{m,i}$$

where FC_i is the total fuel consumed for taxiing by aircraft i, $t_{m,i}$ is the time that aircraft i spends in state m, and $f_{m,i}$ is the fuel flow rate of the aircraft i in state. For their baseline assessment, (Nikoleris et al., 2011) assumed a 4% thrust for idling based on Wood et al.(2009) and (Dubois & Paynter, 2006), 9% thrust for acceleration based on a British Airways' study (Morris, 2005), 5% taxing thrust, and 7% turning thrust. The last two were estimated based on the understanding that both would be in between the idling and acceleration thrust levels, and turning would require more thrust than taxiing.

An alternate approach is to estimate an average taxiing thrust for all states. According to (European Union Aviation Safety Agency, 2019) , the taxi fuel consumption is most often determined using the fuel burn indices presented in the International Civil Organization (ICAO) engine emissions databank. The ICAO emissions data bank provides fuel burn rates for only four power settings which are taxi/idle at 7% thrust, approach at 30%, climb-out at 85% and takeoff at 100%(European Union Aviation Safety Agency, 2019). Since our main focus is the taxi phase for this study, a 7% thrust used to estimate fuel consumption using the simplified formula as follow

$$FC_i = t_i \times f_i$$

where FC_i is again the total fuel consumed for taxiing by aircraft i, t_i is the total time that aircraft i spends taxiing, and f_i is the average taking fuel flow rate for aircraft I, which was estimated based on a 7% thrust level. When electric trucks are used, it is assumed that the aircraft powers down and, therefore, does not consume fuel.

Several factors determine the amount of fuel consumed by an aircraft, with one major factor being the size of the aircraft. Figure 30 shows the maximum takeoff weight (MTOW) of the various aircraft going through Montreal Trudeau on 26 August 2020, shown by narrow- and wide-body aircraft. For each aircraft type, the MTOW was obtained from the FAA Aircraft Characteristics Database (Federal Aviation Administration, 2018a). The average MTOW for the narrow- and wide-body aircraft is approximately 43,000 kg and 245,000 kg, respectively.

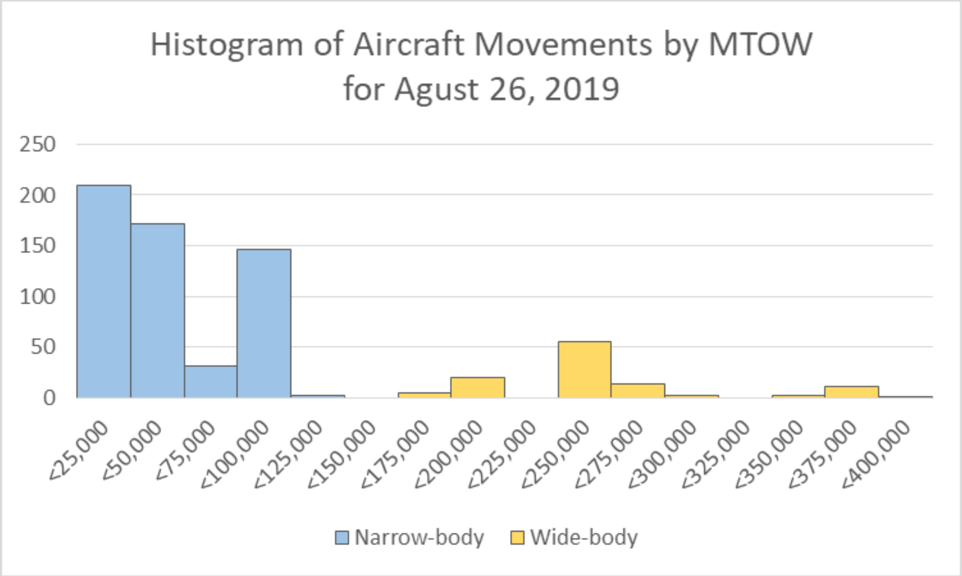


Figure 30.Aircraft movements by MTOW for august 26,2019

Of the aircraft movements occurring at Montreal-Trudeau on 26 August 2020, 187 (28%) were from the De Havilland Canada Dash 8 Series, and 77% of these were from three airlines, WestJet, Air Canada Express, and Porter Airlines. Based on the mix of Dash 8 Series aircraft and using MTOW data from the FAA Aircraft Characteristics Database, their average MTOW was estimated to be 25,000 kg. This is substantially lower than the average MTOW for all narrow-body aircraft, which was estimated to be approximately 43,000 kg. The aircraft with the closest MTOW is the Embraer 170/175 aircraft, which has a maximum MTOW of approximately 45,000 kg according to the FAA Aircraft Characteristics Database and accounted for 54 (8%) of the aircraft movements on the day for which data collected. Of the E170/E175 aircraft moving through Montreal-Trudeau, 84% were operated by Air Canada Express. According to the aifleets.net website, Air Canada Express has transferred its E170/175, all of which have two General Electric (GE) CF34-8E5A1 engines, to Republic Airlines.

The Airbus A330-300 (A333) was the most commonly used wide-body aircraft used at Montreal on August 26, 2019. According to the FAA Aircraft Characteristics Database, the MTOW for the A333 is approximately 242,000 kg. This is quite close to the average MTOW of approximately 245,000 kg for all the wide-body aircraft operating at Montreal-Trudeau. Of the E170/E175 aircraft moving through Montreal-Trudeau, 75% were operated by Air Canada. According to the aifleets.net website, all of Air Canada's A333s have two Rolls-Royce (RR) Trent 772B-60 engines.

Fuel flow data for FE CF34-8E5A1 and RR Trent 772B-60 engines were obtained from the ICAO Aircraft Emissions Databank and is provided in Table 5 and illustrated in Figure 31. ICAO provides fuel flow estimates at idle, approach (App), climb out (C/O), take off (T/O) conditions. Idle is assumed to occur at 4% thrust. This is used to calculate the fuel flow rate at 7% thrust, which is assumed to be the average thrust for taxiing operations. Since all aircraft in the study have two engines, the aircraft fuel flow rate is twice that of the engine fuel flow rate. The estimated aircraft fuel flow rate at 7% thrust is provided in Table 31. A density of 0.8 kg/l was used to covert the fuel flow rate to units of volume. This is a representative density of Jet A-1, which is one of the most commonly used commercial jet fuels. As reported by the U.S. Energy Information Administration(EIA), the US recorded an average jet fuel cost of $1.90 per gallon in 2019(Energy Information Administration, 2020). Considering the provided fuel flow rates for the given aircrafts in this study, we estimate the Wide-body and Narrow-body aircrafts to burn $35.57 and $8.70 worth of fuel per minute respectively during taxiing (see Table 6).

Type	Representative Aircraft	Common Engine	Fuel Flow Idle (kg/sec)	Fuel Flow App (kg/sec)	Fuel Flow C/O (kg/sec)	Fuel Flow T/O (kg/sec)
Narrow-body	Embraer 170/175	GE CF34-8E5A1	0.066	0.188	0.563	0.691
Wide-body	Airbus A330-300 (A333)	RR Trent 772	0.27	0.821	2.53	3.139

Table 5.Fuel Flow Rates for Representative Aircraft Engines Used for this Study (ICAO, 2019)

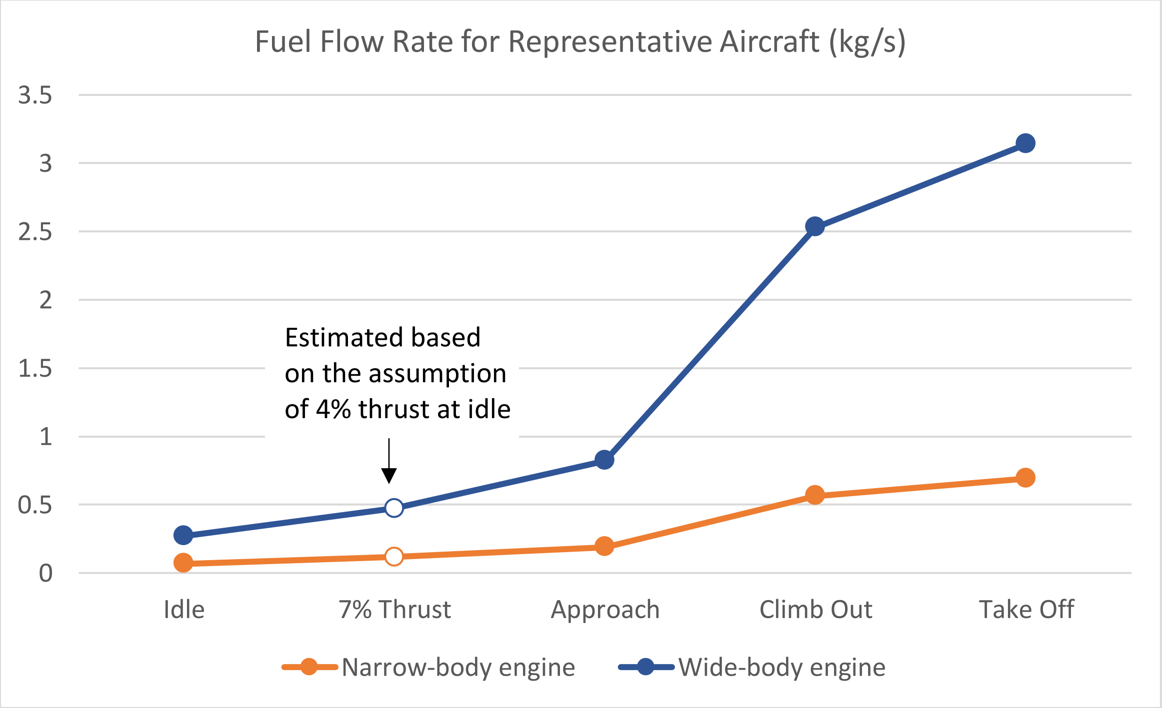


Figure 31.Fuel flow rate for the representative aircrafts

Type	Engine Fuel Flow at 4% Thrust (Idle)	Engine Fuel Flow at 7% Thrust	Aircraft Fuel Flow Rate at 7% Thrust				
			kg/sec	kg/min	l/min	gal/min	USD/min
Narrow-body	0.066	0.116	0.231	13.9	17.3	4.6	$8.70
Wide-body	0.270	0.473	0.945	56.7	70.9	18.7	$35.57

Table 6. Estimated Fuel Flow Rate at 7% Thrust

For each simulation fuel cost was calculated by multiplying the total taxi time by the cost of fuel per minute (See Table 4-2)

2.6.2 Surface Delay

The alternative taxiing system will bring about significant changes in the air traffic control procedures. Air traffic controllers will have to provide procedures to ensure efficient traffic flow of aircrafts being taxied using the tow trucks from the gate to runway and vice versa. The delay of aircrafts waiting for a truck at the runway point or at the gate could potentially lead to delay attributed to the airport, which is generally defined as “added trip time attributable to congestion at the study airport, where congestion constitutes any impediment to the free flow of aircraft and/or people through the system” (National Academies of Sciences, 2014). ss Surface delays reduce airline efficiency and increase airline operating cost,. Furthermore, various forms of congestion occur due to excess delays throughout the network; consequently this leads to over $28 billion US losses for the industry in US (Airlines for America, 2018). According to Airlines for American, the per minute direct aircraft delay cost was $47.19 in 2018. Based on the provided information in Table 7, we will calculate the direct aircraft operating cost per minute delay. The increased fuel cost associated with the delay will also be captured in the analysis since fuel consumption is calculated based on total taxi time. Since this study is focuses on the direct cost to airlines, it does not consider the cost of delays to passengers.

Item	Direct Operating cost per minute
Crew-Pilot/Flight Attendants	23.35
Maintenance	11.76
Aircraft Ownership	9.28
Other	2.80
Total Direct Operating Cost	**$47.19**

Table 7. Aircraft operating cost per minute (Airlines for America, 2018)

For each simulation delay was calculated as the time an aircraft waits for a truck to get to it's location. This time is then multiplied by the total direct operating cost per minute (See Table 7) to get the delay cost for the aircraft.

2.6.3 Towing vehicle operating cost

There are two main types of aircraft towing trucks which are the traditional towing trucks and towbarless towing trucks. The traditional tow truck connects the airplane to the towing truck using a towbar while the towbarless truck merely needs to position itself around the nose wheel and activate its capture mechanism to lift the front wheel of the airplane before towing it. Figure 32 and Figure 33 are examples of the traditional and towbarless trucks operation.

Figure 32.Traditional tow truck(Freightquip, 2020)

Figure 33.Operation of a Towbarless towing truck((Ricardo, 2011)

Although, conventional tugs have less initial purchase cost compared to towbarless tugs, airline operators have favored the use of towbarless tugs due to the following reasons;

- Taxiing process by towbarless tugs requires less manpower which leads to less operational cost
- The use of towbarless tugs increases the speed of operation
- Towbarless tugs can be used for various aircraft types
- Changing a tow bar for traditional tugs is a physical task which increases the risk of safety

According to Alibaba.com, the TK-QY400 aircraft towing truck with 450-ton (408,233 kg) towing capacity is priced at USD $355,000 and TK-QY200 with 200-ton (181,437 kg) towing capacity is priced at USD $120,000. Both vehicles operating with diesel powered engines. Given that the electric powered trucks are estimated to be 20-30% higher than the diesel powered trucks (Eagle Tugs, 2019b), we estimate an electric powered truck to be priced at $400,000 (QY400) and $150,000 (QY200). In this model, we will consider the electric powered towing truck (QY400) as the towing truck in our system. In recent years, self-driving options for passenger vehicles have gained enormous attention. Similarly, self-driving options for aircraft-towing trucks will be a possibility soon. Given that the current technology is still being developed and the air-transportation industry requires additional guaranties (both as a safety measure and public assurance), in this paper we assume towing vehicles are operated by drivers. Airports are more active from 6 AM to 10 PM (see Figure 3-6 for airport activities during the day); hence we anticipate towing trucks to be operational for 2 shifts per day (16 hours). According to available information concerning the operation of these trucks, the towing speed of a tow truck is limited to 3m/s to 4m/s with two operators required to operate a single tow truck (Quinn et al., 2012). For this study, we assume a tow speed of 4 m/s and two operators for each tow truck. Given that airports operate 365 days, we assume that the average number of people required to operate a single towing vehicle is six (6) with each costing $50,000/year salary + 50% benefits. Moreover, according to (Hooper & Murray, 2017), towing trucks require $6.65/hr for maintenance and repairs and $3/hr for insurance ($154.40/day).

2.6.4 Carbon tax

In 2019, the federal government of Canada introduced a coordinated nation-wide carbon pricing scheme to combat climate change. The carbon price began at $20 per tonne of $C0_2$ emissions in 2019, and will rise to $50 with a yearly increase of $10. For this study, we will assume a carbon tax of $20 per tonne of C02 emissions (Government of B.C, 2019). According to (U.S. Energy Information Administration, 2016) , 9.57 kg (0.00957 tonnes) of Carbon is emitted for every gallon of jet fuel burned. For this model, the carbon emissions will be calculated by multiplying the fuel consumed (gallons) by the CO2 coefficient(0.00957 tonnes).

3 Results

3.1 Scenario One: Aircraft taxi with engines

In this first scenario, we assume that all aircrafts use their engines to perform the taxi process. This aircraft taxiing strategy is what is widely used in airports globally. It should be mentioned, the existing system at the YUL airport utilizes towing trucks only for the pushback phase, and the aircrafts use their engines for the taxi operation. We ran the base model for all 644 flights and forced the aircrafts to taxi using their engines.

Flight I.D	Flight type	Aircraft size	Flight time(min)	Taxi time(min)	Fuel consumption(gallon)	Carbon emission(kg)	Fuel Cost(CAD)
128	Arrival	Large	349.6	17.6	135.9	1300.3	332.9
129	Arrival	Small	349.8	6.5	25.9	248.2	63.5
130	Departure	Small	350.5	17.5	69.3	663.6	169.9
131	Arrival	Large	350.6	12.5	96.2	921.0	235.8
132	Departure	Small	352.8	17.7	70.1	671.2	171.8
133	Departure	Small	354.2	9.9	39.4	377.4	96.6
134	Arrival	Small	361.6	15.0	59.6	569.9	145.9
135	Arrival	Small	361.7	13.0	51.6	493.9	126.4
136	Arrival	Large	362.5	20.3	156.5	1497.3	383.3
137	Arrival	Small	362.6	8.7	34.7	331.8	84.9
138	Arrival	Small	362.7	15.9	63.3	605.4	155.0
139	Arrival	Small	364.5	7.8	31.0	296.3	75.9
140	Arrival	Large	364.9	2.9	22.1	211.8	54.2
141	Departure	Large	369.5	5.1	39.6	379.3	97.1
142	Departure	Small	370.0	3.7	14.7	140.3	35.9
143	Departure	Large	370.1	6.1	46.8	448.2	114.7
144	Departure	Small	370.2	10.7	42.3	405.3	103.7
145	Arrival	Small	370.3	9.3	36.8	352.1	90.1
146	Arrival	Small	371.3	15.4	61.1	585.1	149.8
147	Arrival	Small	372.2	5.1	20.1	192.5	49.3
148	Departure	Small	376.9	17.7	70.4	673.7	172.5
149	Departure	Small	377.8	11.4	45.3	433.1	110.9
150	Arrival	Small	378.0	11.1	44.2	423.0	108.3
151	Arrival	Small	378.1	13.4	53.2	509.1	130.3
152	Arrival	Large	378.8	10.6	81.8	783.1	200.5
153	Arrival	Small	378.9	12.7	50.6	483.8	123.9
154	Departure	Small	391.4	11.2	44.5	425.5	108.9
155	Arrival	Small	397.2	21.1	83.9	802.9	205.6
156	Arrival	Large	397.4	10.8	83.4	797.9	204.3
157	Arrival	Small	398.2	9.3	37.1	354.6	90.8
158	Arrival	Small	398.3	8.1	32.0	306.5	78.5
159	Departure	Small	400.5	4.2	16.7	159.6	40.9
160	Arrival	Small	407.3	21.1	83.9	802.9	205.6
161	Arrival	Small	407.4	15.3	60.6	580.0	148.5
162	Arrival	Small	408.2	5.5	21.7	207.7	53.2
163	Arrival	Small	408.3	12.3	48.7	466.0	119.3
164	Arrival	Small	408.4	6.3	25.1	240.6	61.6

Table 8.Sample result after one day of operation

Figure 8 above shows a sample result for a random iteration. As can be seen in the table, the fuel consumed and carbon emitted during the taxi process are relatively high with the highest fuel consumption recorded at 156.5 gallons at 362.5 flight time with a carbon emission of 1497.3 Kg. While the lowest fuel consumption was 14.7 gallons at 370 flight time with a carbon emission of 140.3 kg. The high emissions observed suggests an urgent need for alternative taxiing systems.

Title	Value
Avg. Total Taxi Time (min)	7091.8
Avg. Taxi Time (min)	11
Avg. Taxi-in (min)	10.9
Avg. Taxi-out (min)	11.1
Max. Taxi Time (min)	22.7
Total Fuel Consumption (Gallon)	67,677.4
Total Fuel Cost ($)	128,587
Total Carbon Emission (kg)	647,672.4
Total Carbon Tax ($)	12,953

Table 9. Summarized numerical results of scenario one

The summarized numerical results for 1 day of operation in Table 9 shows the substantial amount of fuel consumed and carbon emitted when using the existing taxiing operations at YUL airport. After one day of operation, the total fuel consumption and carbon emission were 67,677.4 gallons and 647,672.4kg respectively. This accumulated a fuel cost of $128,587 and a carbon tax of $12,953.Based on the results, we conclude that implementing more environmentally friendly systems will provide solutions to reduce the fuel consumption and carbon emissions. The purpose of this scenario is to compare the performance parameters over a 1 year period with subsequent proposed taxiing systems. Table 10 shows the annual result for the existing system.

Title	**Value**
Fuel consumption (Gallon)	24,702,238.05
C02 emission (kg)	236,400,418.1
Fuel Cost($)	$46,934,252.3
Carbon Tax($)	$4,727,845
Total Cost	**$51,662,097**

Table 10. Annual cost result

3.1.1 Scenario Two: Aircraft taxi only with tow trucks

In this scenario, one tow truck will be assigned to arriving or departing aircraft. This operational strategy is used to assess the impact of using electric towing trucks on the taxi time, fuel consumption, carbon emission and cost. As discussed in the previous chapter, the towing trucks have a slower taxiing speed compared to aircraft taxiing using their engines. Therefore, we expect a greater total taxi time. In addition, the overall comparison of both scenarios shows both strategies ‘pros and cons.

Figure 34 shows the total taxi time for both scenarios after 12 iterations .After running the model for 644 flights with 10 towing trucks, we observed a 4.4% increase in the average total taxi time from 7091.8 min with no trucks in the system to 7405.9 min with 10 towing trucks in the system. The increase in total taxi time is precisely related to the reason we mentioned earlier regarding the towing trucks having a slower taxiing speed compared to taxiing using their engines.

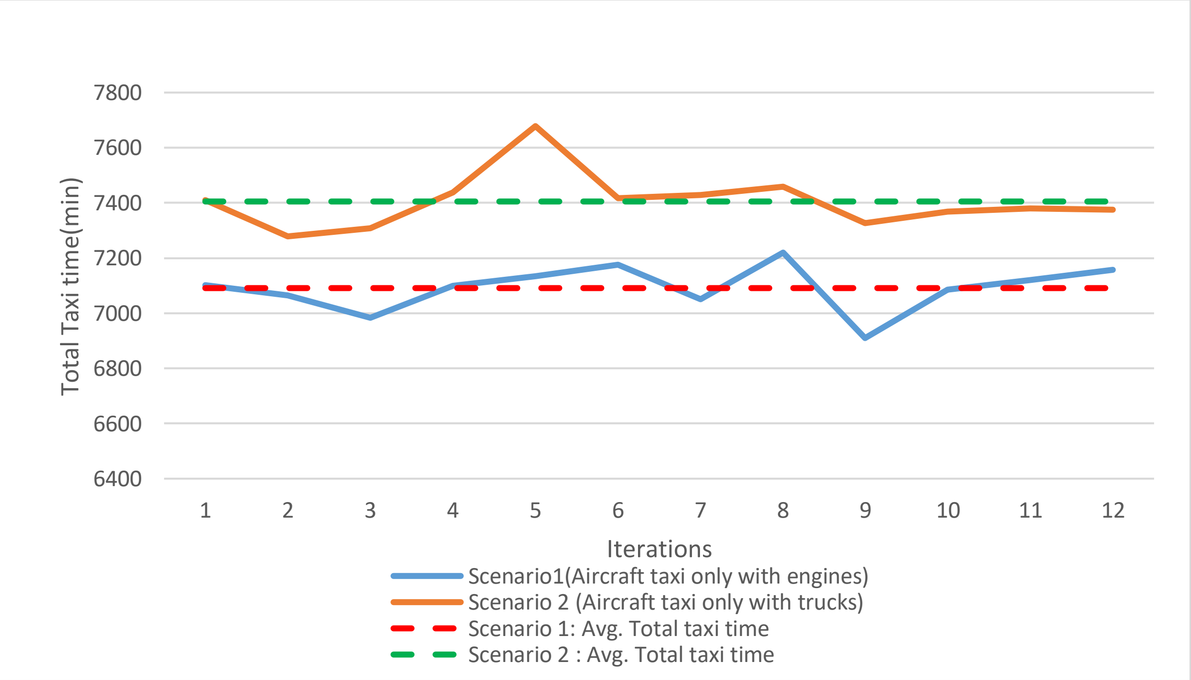
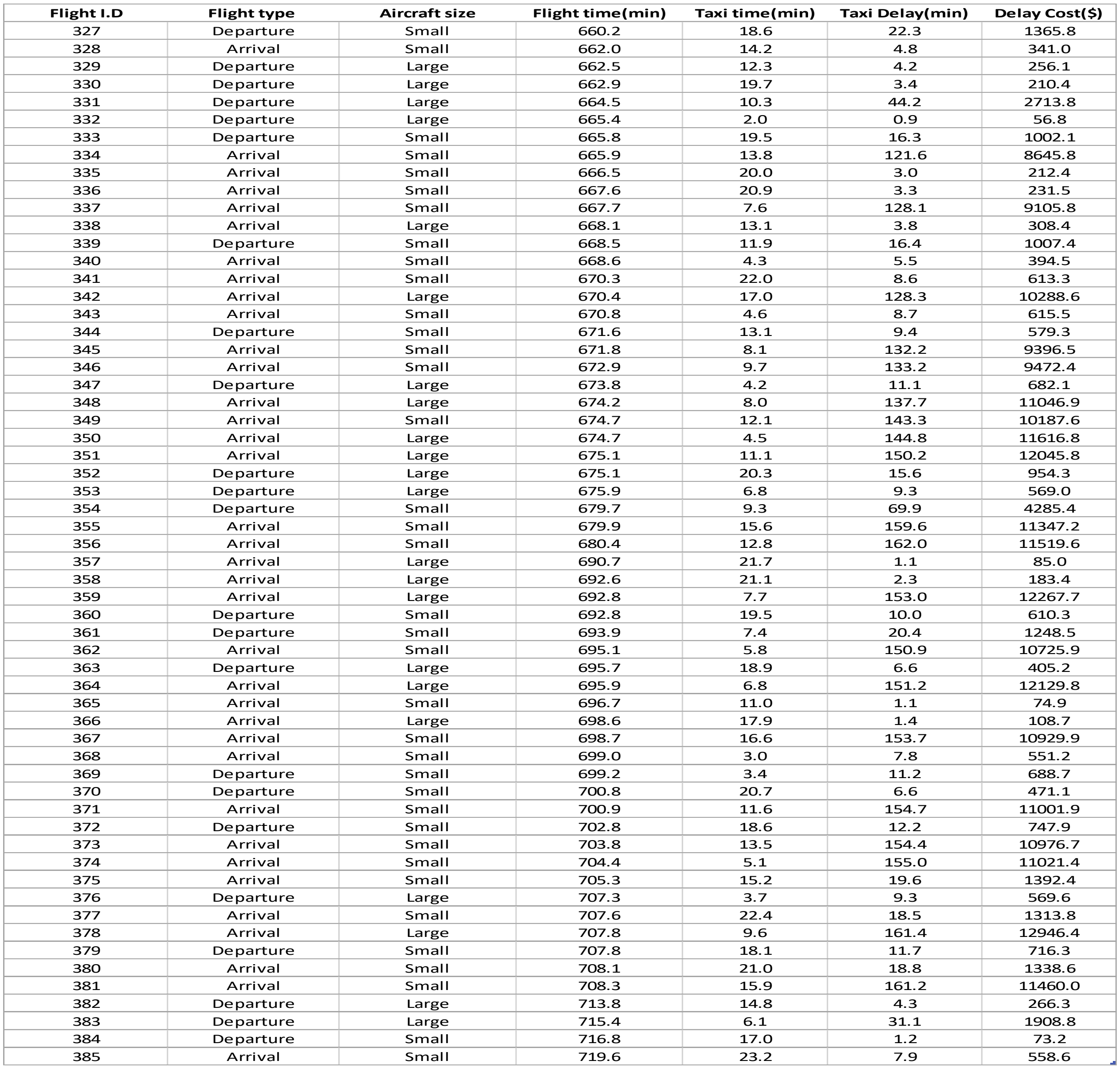


Figure 34.Total Taxi time for scenario 1 and scenario 2

We also observed a substantial amount of flights being delayed due to the unavailability of towing trucks during arrival or departures which resulted in traffic delays and associated costs. As an example, the delay of flights for a random iteration from 5 P.M to 6 P.M is provided in Table 11. As can be seen, the taxi delays recorded are substantially high with the maximum flight delay recorded at 680 simulation time with a delay of 160 minutes and an associated delay cost of $11.519.6. The enormous amount of delays and delay cost recorded makes this aircraft taxiing strategy with 10 towing trucks in the system highly inefficient and financially unsustainable.



Flight I.D	Flight type	Aircraft size	Flight time(min)	Taxi time(min)	Taxi Delay(min)	Delay Cost($)
327	Departure	Small	660.2	18.6	22.3	1365.8
328	Arrival	Small	662.0	14.2	4.8	341.0
329	Departure	Large	662.5	12.3	4.2	256.1
330	Departure	Large	662.9	19.7	3.4	210.4
331	Departure	Large	664.5	10.3	44.2	2713.8
332	Departure	Large	665.4	2.0	0.9	56.8
333	Departure	Small	665.8	19.5	16.3	1002.1
334	Arrival	Small	665.9	13.8	121.6	8645.8
335	Arrival	Small	666.5	20.0	3.0	212.4
336	Arrival	Small	667.6	20.9	3.3	231.5
337	Arrival	Small	667.7	7.6	128.1	9105.8
338	Arrival	Large	668.1	13.1	3.8	308.4
339	Departure	Small	668.5	11.9	16.4	1007.4
340	Arrival	Small	668.6	4.3	5.5	394.5
341	Arrival	Small	670.3	22.0	8.6	613.3
342	Arrival	Large	670.4	17.0	128.3	10288.6
343	Arrival	Small	670.8	4.6	8.7	615.5
344	Departure	Small	671.6	13.1	9.4	579.3
345	Arrival	Small	671.8	8.1	132.2	9396.5
346	Arrival	Small	672.9	9.7	133.2	9472.4
347	Departure	Large	673.8	4.2	11.1	682.1
348	Arrival	Large	674.2	8.0	137.7	11046.9
349	Arrival	Small	674.7	12.1	143.3	10187.6
350	Arrival	Large	674.7	4.5	144.8	11616.8
351	Arrival	Large	675.1	11.1	150.2	12045.8
352	Departure	Large	675.1	20.3	15.6	954.3
353	Departure	Large	675.9	6.8	9.3	569.0
354	Departure	Small	679.7	9.3	69.9	4285.4
355	Arrival	Small	679.9	15.6	159.6	11347.2
356	Arrival	Small	680.4	12.8	162.0	11519.6
357	Arrival	Large	690.7	21.7	1.1	85.0
358	Arrival	Large	692.6	21.1	2.3	183.4
359	Arrival	Large	692.8	7.7	153.0	12267.7
360	Departure	Small	692.8	19.5	10.0	610.3
361	Departure	Small	693.9	7.4	20.4	1248.5
362	Arrival	Small	695.1	5.8	150.9	10725.9
363	Departure	Large	695.7	18.9	6.6	405.2
364	Arrival	Large	695.9	6.8	151.2	12129.8
365	Arrival	Small	696.7	11.0	1.1	74.9
366	Arrival	Large	698.6	17.9	1.4	108.7
367	Arrival	Small	698.7	16.6	153.7	10929.9
368	Arrival	Small	699.0	3.0	7.8	551.2
369	Departure	Small	699.2	3.4	11.2	688.7
370	Departure	Small	700.8	20.7	6.6	471.1
371	Arrival	Small	700.9	11.6	154.7	11001.9
372	Departure	Small	702.8	18.6	12.2	747.9
373	Arrival	Small	703.8	13.5	154.4	10976.7
374	Arrival	Small	704.4	5.1	155.0	11021.4
375	Arrival	Small	705.3	15.2	19.6	1392.4
376	Departure	Large	707.3	3.7	9.3	569.6
377	Arrival	Small	707.6	22.4	18.5	1313.8
378	Arrival	Large	707.8	9.6	161.4	12946.4
379	Departure	Small	707.8	18.1	11.7	716.3
380	Arrival	Small	708.1	21.0	18.8	1338.6
381	Arrival	Small	708.3	15.9	161.2	11460.0
382	Departure	Large	713.8	14.8	4.3	266.3
383	Departure	Large	715.4	6.1	31.1	1908.8
384	Departure	Small	716.8	17.0	1.2	73.2
385	Arrival	Small	719.6	23.2	7.9	558.6

Table 11. Sample result

Hence, we increased the number of available tow trucks in the system to observe their impact on the performance of taxiing operations. Figure 35 shows the relationship between the number of tow trucks in the system and the delays after one day of operation. It can be observed that the total delays decreased with an increase in tow trucks. Based on our simulation results, the highest total delay recorded was 16,476.7 minutes with 10 trucks in the system. As we gradually increased the number of trucks in the system, the total delay significantly decreased by 88.8% to 1847.8 min with 16 trucks in the system. However, the decrease in total delay slowed down afterwards and stabilized with the lowest delay recorded at 1114.2 minutes with 26 trucks in the system. At this point on, the increase in tow trucks had no significant impact on the delays.

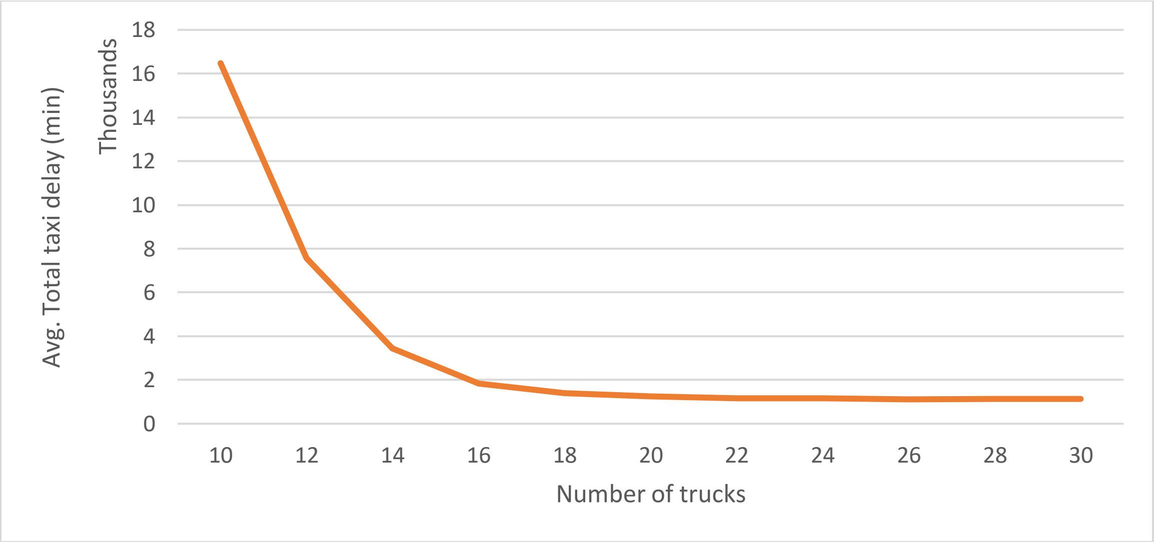


Figure 35.Relationship between the number of tow trucks and delays

Also, the significant reduction in total delay also lead to a decrease in delay cost. Table 12 shows the impact of increasing the number of tow trucks in the system on the delays and delay cost after one day of operation. As expected, the highest delay cost recorded was $712,589 with 10 trucks in the system. With an increase in tow trucks, the delay cost significantly decreased with the least delay cost recorded at $52,581.2 with 26 trucks in the system.

Number of trucks	Total Taxi Delay(min)	Total Delay Cost($)
10	16,476.7	$712,589
12	7559.7	$329,776.4
14	3446.1	$162,623.2
16	1847.8	$87,196.9
18	1398.2	$65,982.3
20	1253.1	$59,135.8
22	1168.1	$55,122.9
24	1150.5	$54,290.9
26	1114.2	$52,581.2
28	1121.7	$52,934.4
30	1120.8	$52,891.1

Table 12. Impact of the number of tow trucks on the delay and delay cost

One of the most significant advantages of applying this aircraft taxiing strategy is the potential fuel consumption reduction which leads to a decrease in carbon emission. Figure 36 below shows the impact of the number of tow trucks on the fuel consumption and carbon emission. It can be observed that the fuel consumption and carbon emission almost doubled, increasing from 67,677 gallons and 647,672.4 kg with no trucks in the system to 125,358.3 gallons and 1,199,678.9 kg with 10 trucks in the system. This drastic increase is a result of fuel consumed by delayed arriving aircrafts waiting to be assigned a tow truck. However, with 12 trucks in the system, the fuel consumption and carbon emission fell significantly by 61% to 48,636.0 gallons and 465,446.9kg. This was followed by a 60% drop to 19,533.2 gallons and 186,932.5kg with 14 trucks in the system. Afterwards, the fuel consumption and carbon emission decreased steadily, reaching a low point of 5,688.8 gallons and 54,436.0kg with 26 trucks in the system.

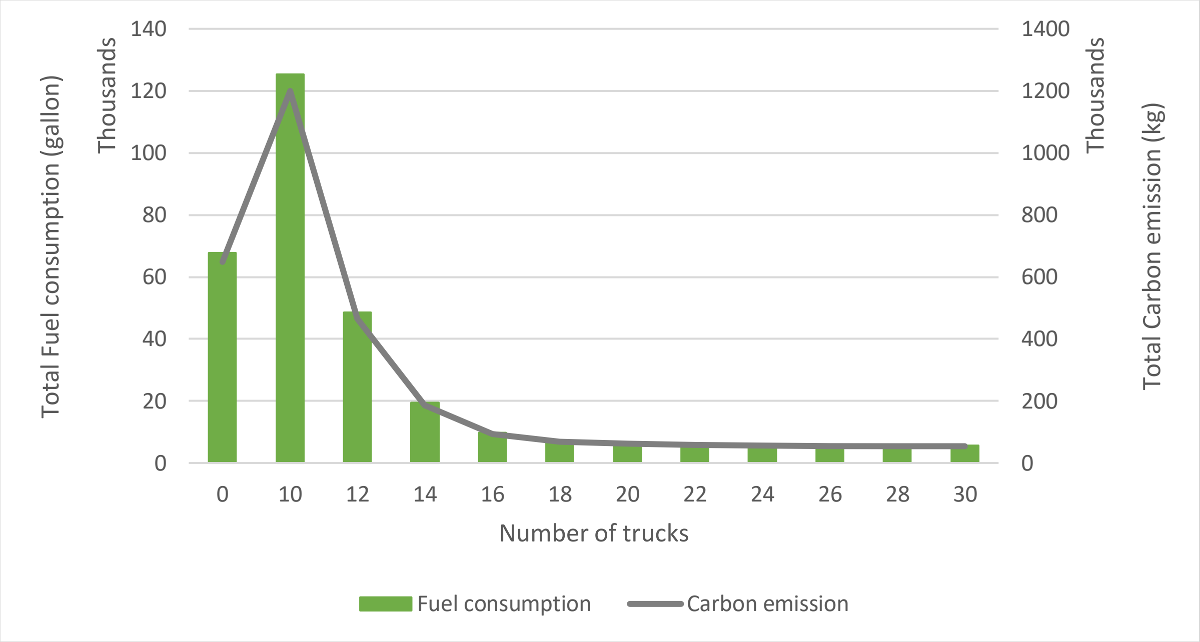


Figure 36.Impact of additional trucks on the fuel consumption and carbon emission

Moreover, it is worth mentioning that having that many trucks in the system will involve investing a substantial amount of money as the cost of an electric truck stands at around $400,000. While increasing the number of tow trucks in the system decreases the delay costs, fuel costs and improves the airport operations performance, each additional tow truck increases the operating cost. Table 13 shows the annual total cost of implementing this strategy with different number of tow trucks in the system.

Number of trucks	Number of workers	Purchase cost (7 years amortization)	Yearly Labor cost	Yearly Maintenance cost	Yearly delay cost ($47.19/min)	Yearly fuel cost	Yearly Carbon tax ($20/tonne)	Total cost
10	60	$571,426	$4,500,000	$563,560	$260,095,013	$86,935,984	$8,757,657	$361,423,640
12	70	$685,711	$5,400,000	$676,272	$120,368,401	$33,729,099	$3,397,763	$164,257,246
14	84	$799,996	$6.300,000	$788,984	$59,357,481	$13,546,257	$1,364,607	$82,157,326
16	96	$914,281	$7,200,000	$901,696	$31,826,894.5	$6,712,117	$676,157	$48,231,147
18	108	$1,028,566	$8,100,000	$1,014,408	$24,083,556.8	$4,904,227	$494,036	$39,624,795
20	120	$1,142,852.0	$9,000,000	$1,127,120	$21,584,582.4	$4,482,802	$451,583	$37,788,939
22	132	$1,257,137.2	$9,900,000	$1,239,832	$20,119,853.2	$4,173,762	$420,452	$37,111,035
24	144	$1,371,422.4	$10,800,000	$1,352,544	$19,816,196.8	$4,035,335	$406,507	$37,782,005
26	156	$1,485,707.6	$11,700,000	$1,465,256	$19,192,171.7	$3,944,765	$397,383	$38,185,283
28	168	$1,599,992.8	$12,600,000	$1,577,968	$19,321,065.3	$3,990,976	$402,038	$39,492,040
30	180	$1,714,278.0	$13,500,000	$1,690,680	$19,305,244.6	$3,971,893	$400,116	$40,582,212

Table 13. Annual cost of implementing scenario 2 (Aircraft taxi only with trucks)

It can be observed that with additional trucks in the system, the purchase cost, labor cost and maintenance cost of operating the tow trucks increases. However, the impact of this increase on the total cost is relatively small in comparison with the benefits gained in the delay cost, fuel cost and carbon tax. As can be seen, the total cost of having ten trucks in the system is $361,423,640. With additional trucks in the system, the total cost decreases, reaching a low point of $37,111,035 with 22 trucks in the system. At this point on, having additional trucks in the system increases the total cost. This is as a result of the cost of operating the tow trucks outweighing the benefits gained from the delay cost, fuel cost and carbon tax. The annual cost increases steadily to $40,582,212 with 30 trucks in the system

Table 14 shows the benefit-cost analysis for additional trucks in the system. It can be observed that the results for the benefit is sometimes positive, sometimes negative. These are due to the randomness in the simulation. It can be clearly seen that with 24 trucks in the system, the benefit-cost value becomes negative with 24 trucks in the system. Therefore, the least expensive solution is obtained with 22 trucks ($37,111,035).

Number of trucks	Benefit ($)	Cost ($)	Benefit – Cost ($)
10	-	-	-
12	$198,293,390	$ 1,126,997	$197,166,393
14	$83,226,917	$ 1,126,997	$82,099,920
16	$35,053,176	$ 1,126,997	$33,926,179
18	$9,733,348	$ 1,126,997	$8,606,351
20	$2,962,852	$ 1,126,997	$1,835,855
22	$1,804,901	$ 1,126,997	$677,903
24	$456,028	$ 1,126,997	-$670,969
26	$723,719	$ 1,126,997	-$403,278
28	-$179,760	$ 1,126,997	-$1,306,757
30	$36,825	$ 1,126,997	-$1,090,171

Table 14.Benefit-Cost analysis for scenario 2

3.1.2 Strategy three: aircraft taxi-in partially with trucks, taxi-out only with trucks

In this scenario, the model decides if an arriving flight is taxied using its engines or a truck. The decision is made based on the availability of the tow trucks on arrival of the aircraft to the airport. We run the model for different number of trucks to examine the amount of arriving flights that taxi using trucks and the amount of flights that taxi with its own engines. We then analyze the operational performance of this strategy against scenario 2 (Aircraft taxi only with trucks) and calculate the annual total cost of implementing this strategy.

Figure 37 shows the usage of tow trucks and engines through the day with 10 trucks in the system. As can be seen, 97% of aircrafts from 6am to 1pm were assigned a tow truck with only 8 aircrafts taxiing with their engines. However, as the number of flights increased through the day, the number of aircrafts that taxi with their engines increased, with the largest number recorded during the peak hours at 31 flights from 6pm to 7pm and 7pm to 8pm. This increase was due to the unavailability of enough tow trucks to serve the increasing number of flights. As expected, the number of aircrafts that taxi with its engines decreased as the time approached midnight with no aircraft taxiing with its engines from 11pm.

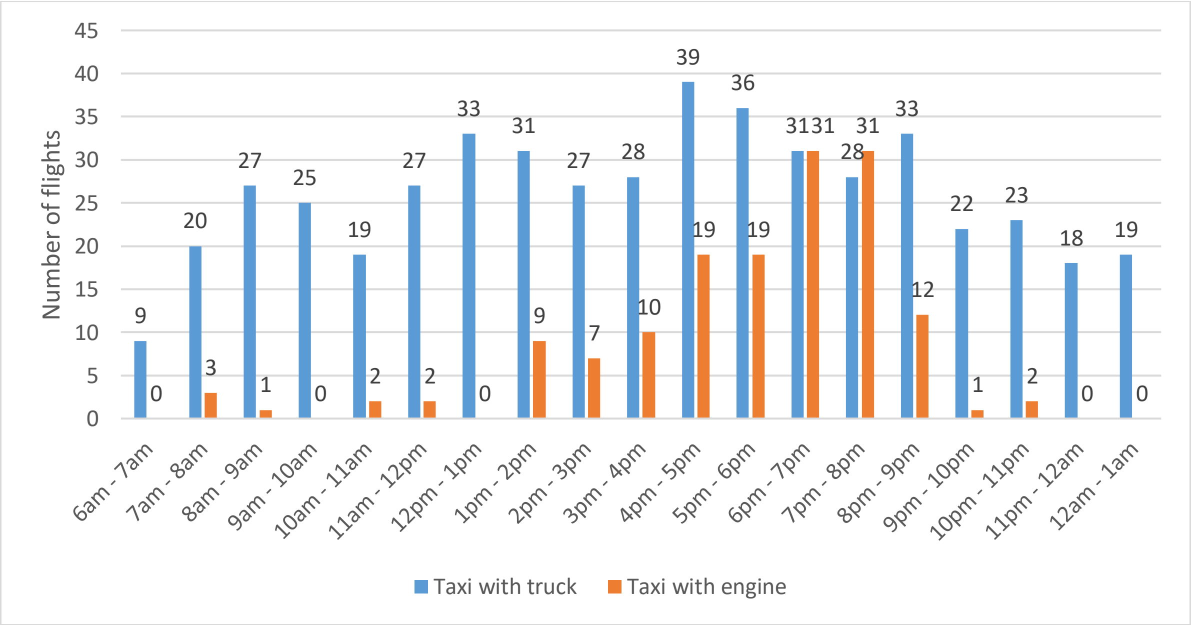


Figure 37.Movement pattern with 10 trucks

Also, Figure 38 shows the usage of tow trucks and engines through the day with 12 trucks in the system. As can be seen, only 3 aircrafts taxied using their engines from 6am to 1pm. This number increased as the time approached the busy hours of the day with the highest number recorded at 27 aircrafts from 6pm to 7pm.Similarly, the amount of aircrafts that taxi with their engines decreased as the time approached midnight. A total of 102 aircrafts taxied with their engines compared to 149 aircrafts with 10 trucks in the system. This significant decrease was due to the availability of extra tow trucks during the peak periods of the day.

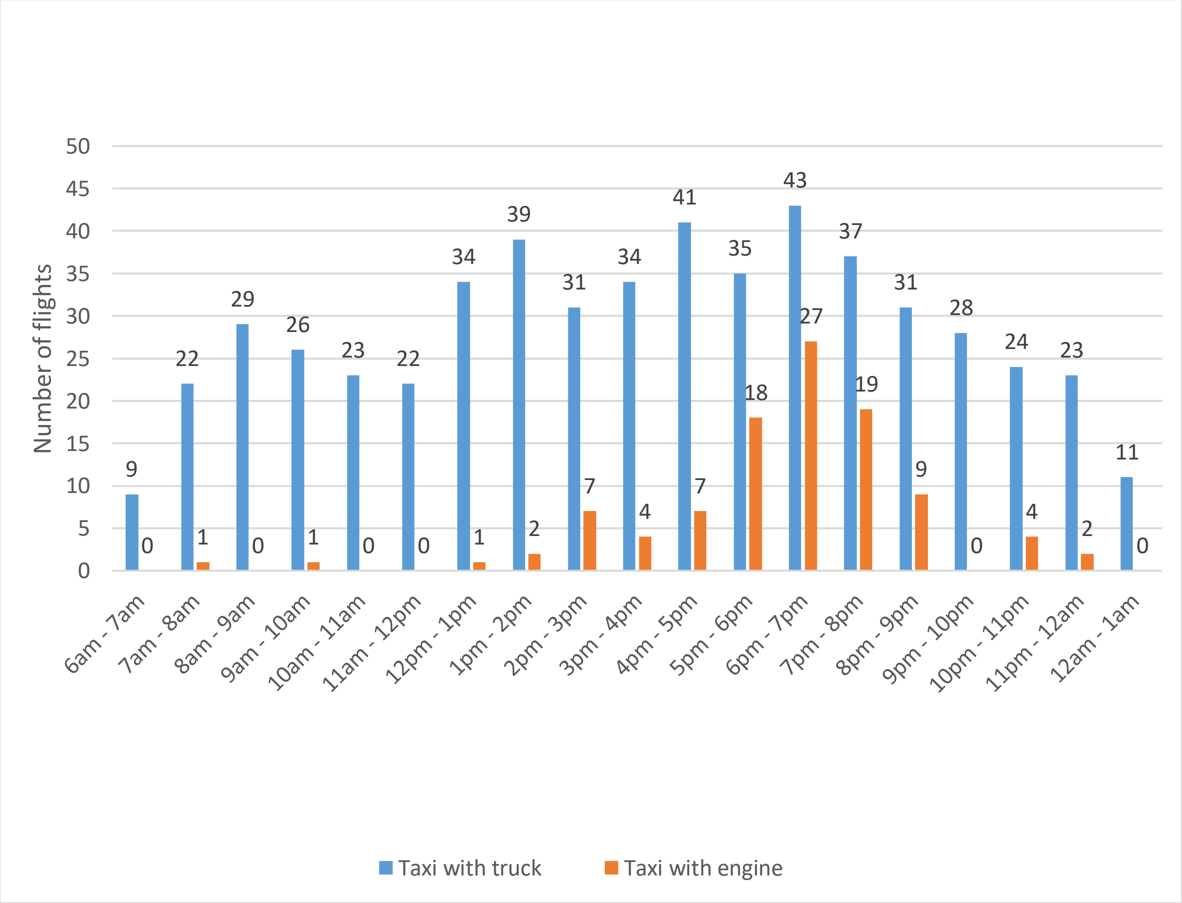


Figure 38.Movement pattern with 12 towing trucks

Figure 39 compares the total taxi delay in scenario 3 (Aircraft taxi-in partially with trucks) and scenario 2 (Aircraft taxi only with tow trucks) for different number of trucks after one day of operation. It can be observed scenario 2 has the highest number of total delays across all number of trucks considered. The lesser number of total delays for scenario 3(Aircraft taxi-in partially with trucks) results from the assumption that all arriving aircrafts taxi-in with their engines when no trucks are available. Therefore, decreasing the accumulated delays for arriving aircrafts. With 10 trucks in the system, scenario 2(Aircraft taxi only with trucks) recorded a total delay of 16,476.7 minutes. This number decreased drastically to 1847.8 with 16 trucks in the system and continued to decrease but more steadily to a low point of 1114.2 minutes with 26 trucks in the system. In contrast, scenario 3(Aircraft taxi-in partially with trucks) recorded a total delay of 1660.4 min with 10 trucks in the system. With 12 trucks in the system, this number decreased to 1109.03 minutes, and decreased again but more steadily to 891.7min with 26 trucks in the system. At this point, the additional tow trucks had no impact on the total delay

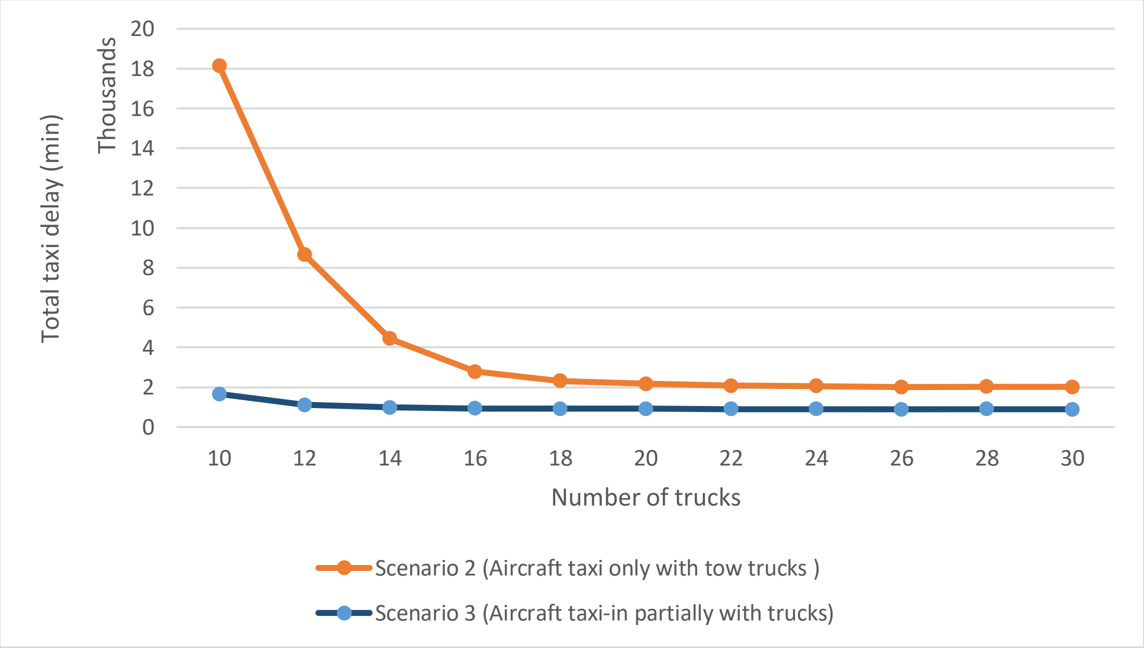


Figure 39.Relationship between the number of tow trucks and delays for Scenario 2 and Scenario 3

Also, implementing this strategy resulted in a significant decrease in total delay cost. Table 15 compares the total delay cost in Scenario 2 (Aircraft taxi only with trucks) and scenario 3 (Aircraft taxi-in partially with trucks) after one day of operation. It can be clearly seen that the total delay cost for both scenario 3 and scenario 2 decreases with additional trucks in the system.

With 10 trucks in the system, the total delay cost for scenario 2 was $712,589. This number drastically decreased, reaching a low point of $52,581 with 26 trucks in the system. In contrast, the total delay cost for scenario 3 was $78,083 with 10 trucks in the system. Like scenario 2 results, the total delay cost decreased with additional tow trucks in the system, reaching a low point of $41,771 with 26 trucks in the system. The number stabilizes afterwards.

Number of trucks	Total Delay Cost (Scenario 2: Aircraft taxi only with trucks)	Total Delay Cost (Scenario 3: Aircraft taxi-in partially with trucks)
10	$712,589	$78,083
12	$329,776	$51,976
14	$162,623	$46,367
16	$87,197	$43,416
18	$65,982	$43,168
20	$59,136	$42,965
22	$55,123	$42,242
24	$54,291	$42,309
26	$52,581	$41,771
28	$52,934	$42,159
30	$52,891	$41,794

Table 15.Impact of the number of tow trucks on the delay cost for Scenario 2 and Scenario 3

The changes in the total fuel consumption and carbon emission from implementing this strategy is found to be relatively high. This is a result of some arriving aircrafts not consuming additional fuel due to delays. Table 16 shows the total fuel consumption and carbon emission with additional trucks in the system for Scenario 2 (Aircraft taxi only with trucks) and Scenario 3 (Aircraft taxi-in partially with tow trucks) after one day of operation. With 10 trucks in the system, the total fuel consumption and carbon emission for Scenario 2 are 125,358 gallons and 1,199,679 kg. These numbers decreased drastically to 48,636 gallons and 465,447kg with 12 trucks in the system. These numbers continued to decrease, reaching 5688gallons and 54,436 kg with 26 trucks in the system. However, for Scenario 3, the total fuel consumption and carbon emission are 20,455 gallons and 195,762 with 10 trucks in the system. These numbers decreased steadily to 18,433 gallons and 176,404 kg with 18 trucks in the system. The fuel consumption and carbon emission slightly increased and remained stable afterwards.

	Scenario 2 (Aircraft taxi only with tow trucks)		Scenario 3 (Aircraft taxi-in partially with tow trucks)	
Number of trucks	Total Fuel Consumption (Gallon)	Total Carbon emission (Kg)	Total Fuel consumption (Gallon)	Total Carbon emission (Kg)
10	125,358	1,199,679	20,455	195,762
12	48,636	465,447	20,168	193,012
14	19,533	186,932	19,663	188,180
16	9,678	92,624	19,245	184,181
18	7071	67,676	18,433	176,404
20	6464	61,860	18,673	178,706
22	6018	57,596	18,661	178,591
24	5818	55,685	18,928	181,145
26	5688	54,436	19,111	182,897
28	5754	55,073	19,030	182,121
30	5727	54,810	18,898	180,860

Table 16.Total fuel consumption and carbon emission for Scenario 2 and Scenario 3

Furthermore, we will calculate the annual total cost of implementing this strategy with additional trucks in the system, considering all associated costs. Table 17 shows the annual cost of implementing this strategy with additional trucks in the system.

Number of trucks	Number of workers	Purchase cost (7 years amortization)	Yearly Labor cost	Yearly Maintenance cost	Yearly delay cost ($47.19/min)	Yearly fuel cost	Yearly Carbon tax ($20/tonne)	Total cost
10	60	$571,426	$4,500,000	$563,560	$28,500,453	$14,186,108	$1,429,064	$49,750,611
12	70	$685,711	$5,400,000	$676,272	$18,971,077	$13,986,841	$1,408,990	$41,128,892
14	84	$799,996	$6.300,000	$788,984	$16,923,859	$13,636,623	$1,373,710	$39,823,173
16	96	$914,281	$7,200,000	$901,696	$15,846,761	$13,346,867	$1,344,521	$39,554,127
18	108	$1,028,566	$8,100,000	$1,014,408	$15,756,474	$12,783,266	$1,287,746	$39,970,461
20	120	$1,142,852.0	$9,000,000	$1,127,120	$15,682,108	$12,950,117	$1,304,554	$41,206,752
22	132	$1,257,137.2	$9,900,000	$1,239,832	$15,418,388	$12,941,759	$1,303,712	$42,060,829
24	144	$1,371,422.4	$10,800,000	$1,352,544	$15,442,749	$13,126,833	$1,322,356	$43,415,904
26	156	$1,485,707.6	$11,700,000	$1,465,256	$15,246,401	$13,253,829	$1,335,149	$44,486,342
28	168	$1,599,992.8	$12,600,000	$1,577,968	$15,338,238	$13,197,566	$1,329,481	$45,693,246
30	180	$1,714,278.0	$13,500,000	$1,690,680	$15,254,669	$13,106,186	$1,320,276	$46,586,089

Table 17.Annual cost of implemeting Scenario 3

With 10 trucks in the system, the annual cost is $49,750,611. This number decreases to a low point of $39,554,127 with 16 trucks in the system. At this point on, the annual cost increases with additional trucks in the system. The number increases to $46,586,089 with 30 trucks in the system.

Table 18 shows the benefit-cost analysis of implementing this strategy. It can be observed that the benefit-cost value becomes negative with 18 trucks in the system. Hence, we obtain the least expensive solution with 16 trucks in the system ($39,554,127).

Number of trucks	Benefit ($)	Cost ($)	Benefit – Cost ($)
10	-	-	-
12	$9,748,716	$ 1,126,997	$8,621,719
14	$2,432,716	$ 1,126,997	$1,305,719
16	$1,396,004	$ 1,126,997	$269,046
18	$710,662	$ 1,126,997	-$416,334
20	-$109,293	$ 1,126,997	-$1,236,290
22	$272,920	$ 1,126,997	-$854,077
24	-$228,078	$ 1,126,997	-$1,355,075
26	$56,559	$ 1,126,997	-$1,070,438
28	-$79,906	$ 1,126,997	-$1,206,904
30	$234,154	$ 1,126,997	-$892,843

Table 18.Benefit-Cost analysis for Scenario 3

3.1.3 Scenario 4: Aircrafts only taxi-out with truck

In this scenario, all arriving aircrafts taxi with their engines and all departing aircrafts taxi using tow trucks. We run the model with different number of tow trucks in the system to examine the impact of implementing this strategy on the operational performance. Figure 40 compares the total taxi delay in scenario 4 (Aircraft only taxi-out with trucks) and scenario 3 (Aircraft taxi-in partially with trucks) for different number of trucks after one day of operation. It can be observed scenario 4 has lesser total delays with additional trucks in the system. The lesser number of total delays for scenario 4 results from the assumption that all arriving aircrafts taxi-in with their engines. Therefore, eliminating delays for arriving aircrafts. With 10 trucks in the system, scenario 3(Aircraft taxi-in partially with trucks) recorded a total delay of 1660.4 minutes. This number decreased drastically to 1109 minutes with 16 trucks in the system and continued to decrease but more steadily to a low point of 891.7minutes with 26 trucks in the system. In contrast, scenario 4(Aircraft only taxi-out with trucks) recorded a total delay of 1220.8min with 10 trucks in the system. With 12 trucks in the system, this number decreased to 819 minutes, and decreased again but more steadily to 689.6 min with 22 trucks in the system. At this point, the total delays remained constant, with additional trucks in the system having no impact.

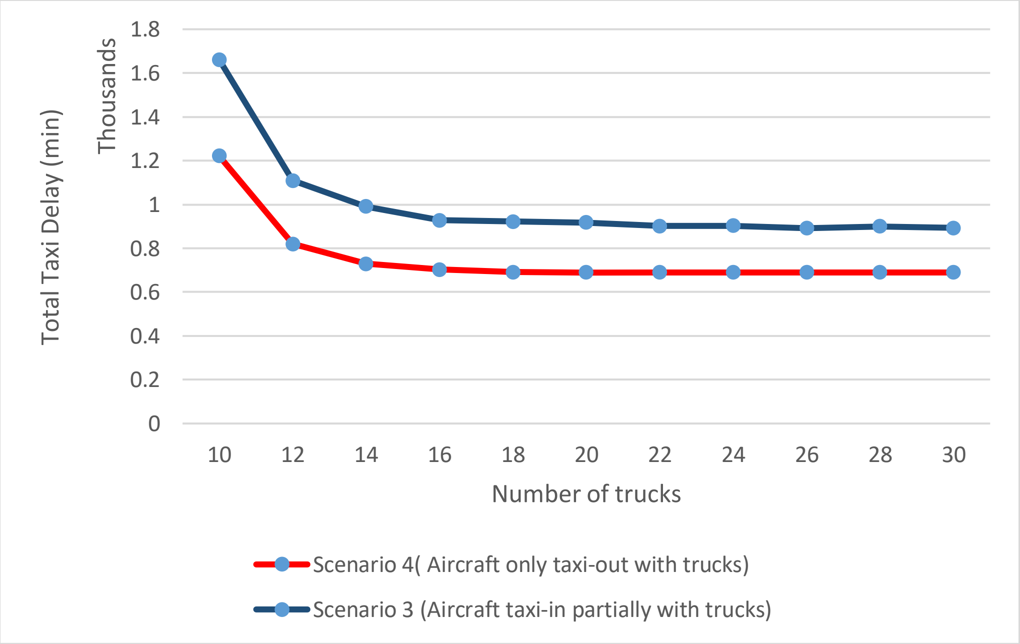


Figure 40.Relationship between the number of trucks and delays for Scenario 3 and Scenario 4

Also, implementing this strategy resulted in a significant decrease in total delay cost. Table 19 compares the total delay cost in Scenario 3 (Aircraft taxi-in partially with trucks) and scenario 4 (Aircraft only taxi-out with trucks) after one day of operation. It can be clearly seen that the total delay cost for scenario 4 is lesser than scenario 3 with additional trucks in the system. With 10 trucks in the system, the total delay cost for scenario 3 is $78,083. This number drastically decreases, reaching a low point of $41,771with 26 trucks in the system. In contrast, the total delay cost for scenario 4 is $78,083 with 10 trucks in the system. Like scenario 2 results, the total delay cost decreases with additional tow trucks in the system, reaching a low point of $32,540 with 22 trucks in the system. The number remains constant afterwards.

Number of trucks	Total Delay Cost (Scenario 3: Aircraft taxi-in partially with trucks)	Total Delay Cost (Scenario 4: Aircraft only taxi-out with trucks)
10	$78,083	$57,610
12	$51,976	$38,650
14	$46,367	$34,426
16	$43,416	$33,153
18	$43,168	$32,649
20	$42,965	$32,564
22	$42,242	$32,540
24	$42,309	$32,540
26	$41,771	$32,540
28	$42,159	$32,540
30	$41,794	$32,540

Table 19.Impact of the number of tow trucks on the delay cost for Scenario 3 and Scenario 4

Unlike the previous scenario, the fuel consumption and carbon emission recorded in this scenario remained stable with additional trucks in the system. This is because the number of aircrafts that taxi with their engines are constant in all sub scenarios considered. Table 20 shows the total fuel consumption and carbon emission with additional trucks in the system for Scenario 3 (Aircraft taxi-in partially with trucks) and Scenario 4 (Aircraft only taxi-out with trucks) after one day of operation. It can be clearly seen that the fuel consumption and carbon emission in scenario 3 is lesser than scenario 4. With 10 trucks in the system, the total fuel consumption and carbon emission for Scenario 3 are 20,455 gallons and 195,762 kg. These numbers decreased slightly to a low point of 18,433 gallons and 176,404kg with 18 trucks in the system. However, for Scenario 4, the total fuel consumption and carbon emission are 33,017 gallons and 315,976 kg with 10 trucks in the system. With additional trucks in the system, the changes in these numbers are relatively low, having no significant impact on the fuel consumption and carbon emission.

	Scenario 3 (Aircraft taxi-in partially with tow trucks)		Scenario 4 (Aircraft only taxi-out with tow trucks)	
Number of trucks	Total Fuel Consumption (Gallon)	Total Carbon emission (Kg)	Total Fuel consumption (Gallon)	Total Carbon emission (Kg)
10	20,455	195,762	33,017	315,976
12	20,168	193,012	32,765	313,556
14	19,663	188,180	33,048	316,275
16	19,245	184,181	32,996	315,778
18	18,433	176,404	33,007	315,877
20	18,673	178,706	33,125	317,009
22	18,661	178,591	33,125	317,009
24	18,928	181,145	33,125	317,009
26	19,111	182,897	33,125	317,009
28	19,030	182,121	33,413	319,771
30	18,898	180,860	33,125	317,009

Table 20.Total fuel consumption and carbon emission for Scenario 3 and Scenario 4

Like previous scenarios, we will calculate the annual cost of implementing this strategy with additional trucks in the system. Table 21 shows the annual cost of implementing this strategy with additional trucks in the system. With 10 trucks in the system, the total cost is $51,866,846. This number decreases to a low point of $45,682,668. At this point on, the total cost begins to increase, reaching $54,068,785 with 30 trucks in the system.

Table 22 shows the benefit-cost analysis of implementing this strategy. It can be clearly seen that the benefit-cost value becomes negative with 16 trucks in the system. Hence, the least expensive solution is obtained with 14 trucks in the system ($45,682,668).

Number of trucks	Number of workers	Purchase cost (7 years amortization)	Yearly Labor cost	Yearly Maintenance cost	Yearly delay cost ($47.19/min)	Yearly fuel cost	Yearly Carbon tax ($20/tonne)	Total cost
10	60	$571,426	$4,500,000	$563,560	$21,027,701	$22,897,533	$2,306,625	$51,866,846
12	70	$685,711	$5,400,000	$676,272	$14,107,475	$22,722,909	$2,289,034	$45,881,403
14	84	$799,996	$6.300,000	$788,984	$12,565,643	$22,919,233	$2,308,811	$45,682,668
16	96	$914,281	$7,200,000	$901,696	$12,100,856	$22,883,212	$2,305,182	$46,305,228
18	108	$1,028,566	$8,100,000	$1,014,408	$11,917,069	$22,890,380	$2,305,904	$47,256,330
20	120	$1,142,852.0	$9,000,000	$1,127,120	$11,886,183	$22,972,395	$2,314,166	$48,442,717
22	132	$1,257,137.2	$9,900,000	$1,239,832	$11,877,265	$22,972,395	$2,314,166	$49,560,796
24	144	$1,371,422.4	$10,800,000	$1,352,544	$11,877,265	$22,972,395	$2,314,166	$50,687,794
26	156	$1,485,707.6	$11,700,000	$1,465,256	$11,877,265	$22,972,395	$2,314,166	$51,814,791
28	168	$1,599,992.8	$12,600,000	$1,577,968	$11,877,265	$23,172,587	$2,334,333	$53,162,147
30	180	$1,714,278.0	$13,500,000	$1,690,680	$11,877,265	$22,972,395	$2,314,166	$54,068,785

Table 21.Annual Cost of implementing Scenario 4

Number of trucks	Benefit ($)	Cost ($)	Benefit – Cost ($)
10	-	-	-
12	$7,112,440	$ 1,126,997	$5,985,443
14	$1,325,731	$ 1,126,997	$198,734
16	$504,436	$ 1,126,997	-$622,561
18	$175,895	$ 1,126,997	-$951,101
20	-$59,390	$ 1,126,997	-$1,186,387
22	$8917	$ 1,126,997	-$1,118,080
24	$0	$ 1,126,997	-$1,126,997
26	$0	$ 1,126,997	-$1,126,997
28	-$220,359	$ 1,126,997	-$1,347,357
30	$220,359	$ 1,126,997	-$906,638

Table 22.Benefit-Cost analysis for Scenario 4

3.2 Summary of experimental works

The section aims to summarize and compare the recorded simulation results for the cost of implementing the least expensive solution for the four different scenarios considered in this study. Table 23 and Figure 41 summarizes the operation performance for scenario 1 with no trucks in the system, scenario 2 with 22 trucks in the system, scenario 3 with 16 trucks in the system and scenario 4 with 14 trucks in the system. It can be observed that Scenario 1 has the highest fuel cost, carbon tax and total cost. This is because all aircrafts taxi with their engines and consume more fuel, making this scenario not economically efficient and environmentally friendly. Also, scenario 2 has the lowest fuel cost and carbon tax because all aircrafts are taxied with tow trucks, therefore reducing the fuel consumed by 91.1%. On the other hand, Scenario 4 has the least delay cost and operating cost because all arriving aircrafts taxi with engines, eliminating the accumulated delays by arriving aircrafts. Although , scenario 3 and scenario 4 were introduced to reduce the total delay cost and operating cost, our model suggests that an acceptable solution which is both economically viable and has potentials to reduce emissions significantly during the on-ground taxi operation, can be achieved through implementing scenario 2 (Aircraft taxi only with trucks) with the least annual cost of $37,111,035.

	Scenario 1(Aircraft taxi with engines	Scenario 2(Aircraft taxi only with trucks)	Scenario 3(Aircraft taxi-in partially with trucks)	Scenario 4 (Aircraft only taxi-out with trucks)
Number of trucks	0	22	16	14
Fuel cost	$46,934,252	$4,173,762	$13,346,867	$22,919,233
Carbon tax	$4,727,845	$420,452	$1,344,521	$2,308,811
Delay cost	0	$20,119.853	$15,846,761	$12,565,643
Operating cost	0	$12,396,969	$9,015,977	$7,888,980
Total cost	$51,662,097	$37,111,035	$39,554,127	$45,682,668

Table 23. Summary results for all Scenarios

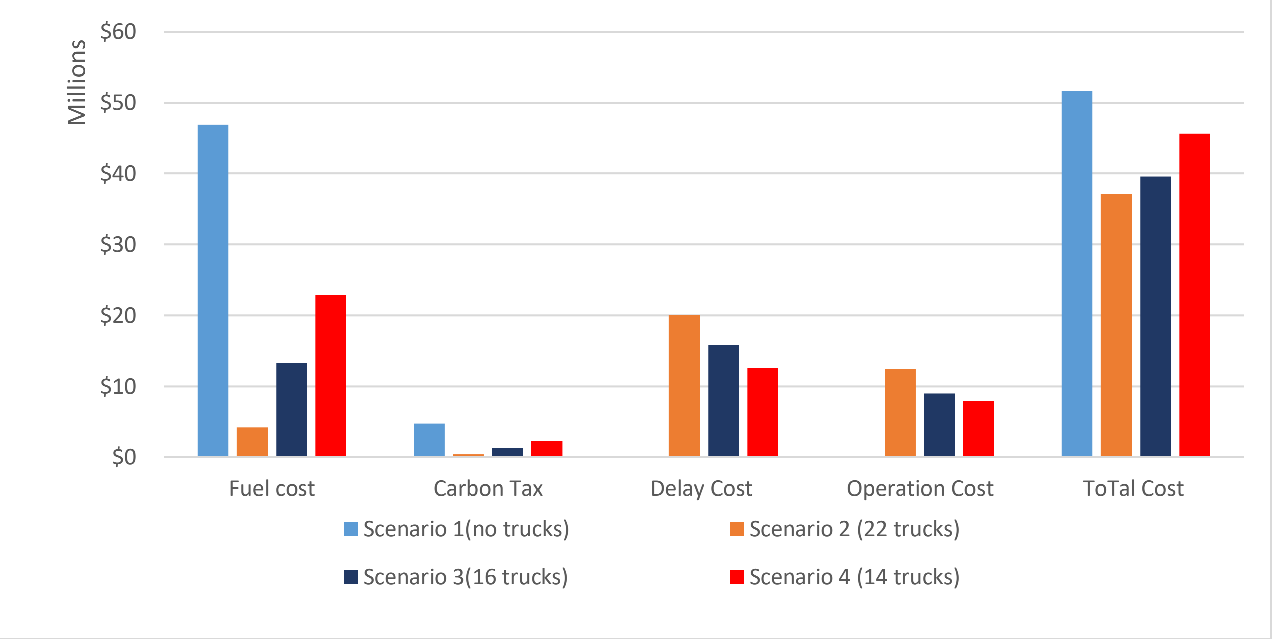


Figure 41.Summary results for all scenarios

4 Conclusions and future work

4.1 Conclusion

The goal of this thesis was to study the possibility of adopting an alternative on-ground taxiing procedure, identify a promising taxiing concept and to analyze its potential in the aviation industry while considering its economic and environmental impact. An example of the electric powered tow truck has been found and used to build three operational strategies. These operational strategies have been simulated with different number of electric powered tow trucks over a time frame of 18 hours. Output measures representing the operational, economic and environmental performance have been recorded for a total of 31 sub scenarios. Based on these output measures, the annual cost of implementing these strategies have been calculated to identify an economical and sustainable solution.

A discrete simulation model has been built and adjusted for assessing the operational performance of different operational strategies over a one-year period. It makes it a flexible tool for decision makers that enables them to quickly evaluate their alternatives and identify possible drawbacks at an early stage of the development process.

In the first strategy, all aircrafts use their engines to taxi from the gate to the runway and vice versa. In the second strategy, we introduced tow trucks in the system to perform the taxi process for all aircrafts. In the third strategy, arriving aircrafts either taxi with their engines or with a tow truck based on the availability of a tow truck. Finally, only departing aircrafts taxi with a tow truck in the fourth strategy. We adjusted the number of tow trucks in all strategies considered to assess the operational, economic and environmental impact.

It has been shown that the second strategy (All aircrafts taxi with trucks) with 22 trucks in the system profited the most from reduced fuel consumption and emission resulting in lower fuel cost and annual cost. It significantly reduces the fuel cost and environmental impact as a result of having a high number of trucks available to taxi all aircrafts. Furthermore, the cost of operating the high number of trucks in the system was relatively small compared to the benefits gained. Overall, it was identified as the least expensive solution.

On the other hand, the third strategy (Aircraft taxi-in partially with trucks) and fourth (Aircraft only taxi-out with trucks) reduces the delay cost and operating cost but have higher fuel cost and carbon tax. This is because some aircrafts perform their taxi operation with their engines. Therefore, the annual cost of implementing these strategies were found to be more expensive than the second strategy (All aircrafts taxi with trucks).

To conclude, it has been shown that electric powered tow trucks have high potentials in reducing cost and environmental emissions in the aviation industry. It is therefore expected that airports will see significant improvements in fuel consumption and carbon emissions resulting from adopting electric powered trucks to perform their on-ground taxiing process. It is not expected that the benefits resulting from utilizing the electric powered tow trucks itself would be enough to justify the initial effort. However, with a market evolving towards a greener operation, it can be expected that the opportunities of utilizing electric powered tow trucks outweigh the risks considering both, the economic as well as the environmental performance.

4.2 Limitations

This study is analyzing systems based on the assumption that all airports have required on-ground infrastructure without considering any traffic or airport network restrictions. It is the goal of the study to assess the potentials of adopting electric powered tow trucks on the long run assuming that the ideas of alternative taxiing systems would begin to change the traditional on-ground taxiing operations and the trend towards a more economical and environmentally friendly on-ground operation would intensify.

However, being at the initial stage of such a relatively young development also involves high risks. Initial efforts are high, and the direction of the trend can change rapidly driven by new inventions and unforeseen technology leaps.

Utilizing electric powered tow trucks in airports reduces the fuel consumption and emission a lot, but more motion on ground due to additional vehicles on the taxiways might yield to safety issues and concerns. This can be compensated by developing a complex and guidance control infrastructure, but it certainly increases the cost of implementing this technology.

Also, the adoption of this technology is locally limited to respective airport. Airports that do not have these advanced tow trucks cannot profit from this technology and will still face the key issues of costly and inefficient on-ground operation.

4.3 Future work

Being at an early stage of electric taxi systems developments, further work is expected to include new perceptions and study approaches of airports that attempt to implement electric tow trucks for on-ground taxi operations. With more practical operational strategies from the industry, the level of detail will increase, and questions will occur which might not be foreseeable today.

Furthermore, a more accurate cost analysis which includes the energy consumption and cost will need to be made to get a clearer picture of how the cost of electricity will impact the annual cost of implementing the taxi system.

Appendices

Appendix 1 – Estimated distances between runway nodes, taxiway nodes, and gates

Begin Node	**End Node**	**Distance (meters)**
Nd1	Nd3	282
Nd1	Nd4	297
Nd2	Nd3	96
Nd3	Nd4	79
Nd3	Nd41	131
Nd4	Nd5	170
Nd4	Nd40	80
Nd4	Nd41	155
Nd5	Nd6	362
Nd5	Nd39	93
Nd6	Nd7	209
Nd6	Nd15	270
Nd6	Nd32	74
Nd6	Nd34	251
Nd6	Nd42	209
Nd7	Nd42	83
Nd8	Nd42	100
Nd9	Nd42	139
Nd10	Nd42	178
Nd11	Nd42	217
Nd12	Nd15	57
Nd13	Nd15	23
Nd14	Nd15	51
Nd15	Nd32	193
Nd16	Nd32	109
Nd17	Nd32	137
Nd18	Nd32	180
Nd19	Nd32	209
Nd20	Nd32	212
Nd21	Nd32	234
Nd22	Nd32	237
Nd23	Nd32	312
Nd24	Nd32	346
Nd25	Nd32	346
Nd26	Nd32	386
Nd27	Nd32	260
Nd28	Nd32	241
Nd29	Nd32	210
Nd30	Nd32	200
Nd31	Nd32	190
Nd32	Nd33	65
Nd33	Nd34	126
Nd34	Nd39	110
Nd35	Nd39	352
Nd36	Nd39	253
Nd37	Nd39	199
Nd38	Nd39	85
Nd39	Nd40	190
Nd40	Nd41	80
Nd40	Nd44	190
Nd41	Nd43	189
Nd43	Nd44	81
Nd43	Nd50	278
Nd44	Nd45	61
Nd44	Nd46	97
Nd44	Nd47	170
Nd44	Nd48	262
Nd44	Nd49	280
Nd44	Nd50	352
Nd44	Nd51	267
Nd50	Nd51	124
Nd50	Nd81	294
Nd51	Nd52	77
Nd51	Nd53	99
Nd51	Nd54	136
Nd51	Nd55	199
Nd51	Nd56	207
Nd51	Nd57	333
Nd57	Nd58	25
Nd57	Nd59	62
Nd57	Nd60	105
Nd57	Nd61	134
Nd57	Nd62	235
Nd62	Nd63	55
Nd62	Nd64	21
Nd62	Nd65	70
Nd62	Nd66	114
Nd62	Nd67	172
Nd62	Nd68	197
Nd62	Nd91	329
Nd68	Nd69	180
Nd68	Nd70	145
Nd68	Nd71	73
Nd68	Nd72	46
Nd68	Nd73	65
Nd68	Nd74	105
Nd68	Nd91	214
Nd74	Nd75	214
Nd74	Nd91	295
Nd74	Nd93	380
Nd75	Nd76	114
Nd75	Nd77	80
Nd75	Nd78	46
Nd75	Nd79	76
Nd75	Nd80	80
Nd75	Nd81	171
Nd82	Nd87	309
Nd83	Nd87	256
Nd84	Nd87	200
Nd85	Nd87	175
Nd86	Nd87	129
Nd87	Nd91	122
Nd88	Nd91	91
Nd89	Nd91	70
Nd90	Nd91	86
Nd91	Nd92	144
Nd91	Nd93	264

Appendix 2 – Flight information for the simulated aircrafts

The flight information for the arrivals and departures for this study was extracted from (Flightradar24, 2019) on 26th August 2019.

Departing flights

No.	Time	Flight	To	Airline	Aircraft
1	6:00 AM	AA1516	Miami (MIA)	American Airlines	B738 (N835NN)
2	6:00 AM	AC481	Toronto (YYZ)	Air Canada	A321 (C-FGKP)
3	6:00 AM	DL5520	Atlanta (ATL)	Delta Connection	CRJ9 (N136EV)
4	6:00 AM	WS3513	Toronto (YYZ)	WestJet	DH4
5	6:00 AM	DL5479	Minneapolis (MSP)	Delta Connection	CRJ9 (N341PQ)
6	6:00 AM	YN703	Kingston (YGK)	Air Creebec	DH8A (C-FCLS)

Arriving flights

No.	Time	Flight	From	Airline	Aircraft
1	6:17 AM	AC8901	Moncton (YQM)	Air Canada Express	DH8C (C-FACT)
2	6:22 AM	AC8701	Quebec (YQB)	Air Canada Express	CRJ2 (C-GGJA)
3	6:40 AM	AC8521	Halifax (YHZ)	Air Canada Express	DH8D (C-GGOI)
4	6:42 AM	AC8970	Ottawa (YOW)	Air Canada Express	CRJ2 (C-GQJA)
5	6:46 AM	AC8791	Saint John (YSJ)	Air Canada Express	DH8C (C-GLTA)
6	6:50 AM	AC8750	Rouyn (YUY)	Air Canada Express	DH8C (C-FACF)
7	6:56 AM	AC8681	Saguenay (YBG)	Air Canada	DH3
8	7:05 AM	AC7997	Sydney (YQY)	Air Canada Express	DH8D (C-GGND)
9	7:07 AM	WS528	Edmonton (YEG)	WestJet	B737 (C-GUWS)
10	7:10 AM	AC308	Vancouver (YVR)	Air Canada	A321 (C-FJNX)
11	7:10 AM	AC396	Calgary (YYC)	Air Canada	A320 (C-FDSN)
12	7:10 AM	AC774	Los Angeles (LAX)	Air Canada	A320 (C-FKPT)
13	7:10 AM	AC776	San Francisco (SFO)	Air Canada	A320 (C-FKCO)
14	7:10 AM	AC1687	Charlottetown (YYG)	Air Canada Rouge	A321 (C-GHQI)
15	7:10 AM	4O2810	Mexico City (MEX)	Interjet	A320 (XA-TLC)
16	7:11 AM	AC334	Edmonton (YEG)	Air Canada	A320 (C-FFWJ)
17	7:12 AM	AC1858	Las Vegas (LAS)	Air Canada Rouge	A319 (C-FYIY)
18	7:16 AM	AC1521	St. John's (YYT)	Air Canada Rouge	A319 (C-FYJG)
19	7:17 AM	WS564	Vancouver (YVR)	WestJet	B738 (C-GNDG)
20	7:19 AM	AC8501	Fredericton (YFC)	Air Canada Express	DH8D (C-GGFJ)
21	7:20 AM	RJ269	Amman (AMM)	Royal Jordanian	B788 (JY-BAA)
22	7:22 AM	WS214	Calgary (YYC)	WestJet	B737 (C-FBWJ)
23	7:28 AM	AM680	Mexico City (MEX)	Aeromexico	B738 (XA-ADT)
24	7:39 AM	AC7521	Halifax (YHZ)	Air Canada Express	E75S (C-FJBO)
25	7:44 AM	AC7549	Boston (BOS)	Air Canada Express	E75S (C-FEIX)
26	7:45 AM	AC480	Toronto (YYZ)	Air Canada	A320 (C-GJVT)
27	7:52 AM	AC8703	Quebec (YQB)	Air Canada Express	DH8C (C-GABO)
28	7:55 AM	PD453	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQC)
29	7:58 AM	WS3514	Toronto (YYZ)	WestJet	DH4
30	7:59 AM	AC7737	New York (EWR)	Air Canada Express	E75S (C-FEJD)
31	8:04 AM	AC7631	New York (LGA)	Air Canada Express	E75S (C-FEKI)
32	8:10 AM	AC1580	Vancouver (YVR)	Air Canada Rouge	B763 (C-FMWQ)
33	8:15 AM	AC400	Toronto (YYZ)	Air Canada	A321 (C-GJWO)
34	8:25 AM	AC7952	Toronto (YTZ)	Air Canada Express	DH8D (C-GGFP)
35	8:35 AM	PD457	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQX)
36	8:56 AM	DL6184	Detroit (DTW)	Delta Connection	CRJ7 (N669CA)
37	8:59 AM	WS3450	Halifax (YHZ)	WestJet	DH8D (C-FHEN)
38	9:05 AM	PD458	Halifax (YHZ)	Porter Airlines	DH8D (C-GKQD)
39	9:13 AM	WS3518	Toronto (YYZ)	WestJet	DH8D (C-GENK)
40	9:15 AM	AC402	Toronto (YYZ)	Air Canada	A320 (C-FTJO)
41	9:25 AM	AC7954	Toronto (YTZ)	Air Canada Express	DH8D (C-GGNW)

42	9:29 AM	UA4703	Chicago (ORD)	Trans States Airlines	E145 (N844HK)
43	9:34 AM	PDT5009	Philadelphia (PHL)	American Eagle	E145 (N627AE)
44	9:35 AM	PD459	Toronto (YTZ)	Porter Airlines	DH8D (C-GKQI)
45	9:39 AM	DL5466	New York (LGA)	Delta Connection	CRJ9 (N348PQ)
46	9:42 AM	AA5009	Philadelphia (PHL)	American Eagle	E145 (N627AE)
47	9:45 AM	AC8976	Ottawa (YOW)	Air Canada Express	CRJ9 (C-FCJZ)
48	9:51 AM	AC7598	Chicago (ORD)	Air Canada Express	E75S (C-FEJP)
49	9:54 AM	AC7633	New York (LGA)	Air Canada Express	E75S (C-FEJF)
50	9:58 AM	QK31	Philadelphia (PHL)	Air Canada Express	CRJ2 (C-FZJA)
51	10:02 AM	UA4963	Washington (IAD)	United Express	E45X (N21154)
52	10:08 AM	AC8752	Val-d'Or (YVO)	Air Canada Express	CRJ2 (C-GQJA)
53	10:09 AM	AC8031	Philadelphia (PHL)	Air Canada Express	CRJ2 (C-FZJA)
54	10:09 AM	AC8459	Baltimore (BWI)	Air Canada Express	CRJ2 (C-FDJA)
55	10:15 AM	AC404	Toronto (YYZ)	Air Canada	A320 (C-FPDN)
56	10:25 AM	AC7956	Toronto (YTZ)	Air Canada Express	DH8D (C-GGOI)
57	10:28 AM	WS3520	Toronto (YYZ)	WestJet	DH8D (C-GENU)
58	10:40 AM	PD463	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQL)
59	10:40 AM	AC8175	Washington (IAD)	Air Canada Express	CRJ2 (C-FEJA)
60	10:40 AM	AC8756	Rouyn (YUY)	Air Canada	DH3
61	10:48 AM	AC8707	Quebec (YQB)	Air Canada Express	DH8D (C-GGND)
62	11:15 AM	AC406	Toronto (YYZ)	Air Canada	A320 (C-FGKH)
63	11:15 AM	MAX120	Montreal (YHU)	Max Aviation	BE10
64	11:17 AM	DL5152	New York (JFK)	Delta Connection	CRJ2 (N836AY)
65	11:20 AM	AC1973	Reykjavik (KEF)	Air Canada Rouge	A319 (C-FYKW)
66	11:25 AM	AC7958	Toronto (YTZ)	Air Canada Express	DH8D (C-GGFJ)
67	11:26 AM	AC8789	Saint John (YSJ)	Air Canada Express	CRJ2 (C-GGJA)
68	11:32 AM	AC8503	Fredericton (YFC)	Air Canada Express	DH8D (C-GGFP)
69	11:35 AM	AC875	Frankfurt (FRA)	Air Canada	B789 (C-FNOI)
70	11:39 AM	AC1635	Orlando (MCO)	Air Canada Rouge	A319 (C-GARO)
71	11:44 AM	AA3130	Chicago (ORD)	SkyWest Airlines	CRJ2 (N902EV)
72	11:45 AM	PD465	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQO)
73	11:45 AM	WS3438	London (YXU)	WestJet	DH8D (C-GWUE)
74	11:55 AM	AC809	Casablanca (CMN)	Air Canada	A333 (C-GHKR)
75	11:56 AM	DL6260	Detroit (DTW)	Delta Connection	CRJ7 (N317CA)
76	11:57 AM	AC8699	Sept-Iles (YZV)	Air Canada Express	DH8C (C-GKTA)
77	11:57 AM	QK7134	Iles-de-la-Madeleine (YGR)	Air Canada Express	DH8C (C-GABP)
78	11:58 AM	WS326	Winnipeg (YWG)	WestJet	B738 (C-GJWS)
79	11:59 AM	AC7553	Boston (BOS)	Air Canada Express	E75S (C-FJBO)
80	12:04 PM	AC661	Halifax (YHZ)	Air Canada	E190 (C-FNAN)
81	12:11 PM	AA4389	Philadelphia (PHL)	American Eagle	E75S (N106HQ)
82	12:14 PM	AC1560	Calgary (YYC)	Air Canada Rouge	A319 (C-GBHY)
83	12:15 PM	AC408	Toronto (YYZ)	Air Canada	A320 (C-FFWN)
84	12:17 PM	AC8903	Moncton (YQM)	Air Canada Express	DH8C (C-FACT)
85	12:19 PM	AC745	New York (LGA)	Air Canada	A320 (C-FKPT)
86	12:19 PM	AC7739	New York (EWR)	Air Canada Express	E75S (C-FEJD)
87	12:20 PM	AC833	Brussels (BRU)	Air Canada	A333 (C-GFUR)
88	12:20 PM	AC871	Paris (CDG)	Air Canada	B77W (C-FNNU)
89	12:24 PM	AC8184	Windsor (YQG)	Air Canada Express	CRJ2 (C-FIJA)
90	12:25 PM	AC7960	Toronto (YTZ)	Air Canada	DH4
91	12:25 PM	DL5521	Atlanta (ATL)	Delta Connection	CRJ9 (N901XJ)
92	12:26 PM	AC8687	Saguenay (YBG)	Air Canada Express	DH8C (C-GTAT)
93	12:27 PM	DL5472	New York (LGA)	Delta Connection	CRJ9 (N605LR)
94	12:28 PM	AC8739	Bathurst (ZBF)	Air Canada Express	DH8C (C-FJVV)
95	12:28 PM	WS3524	Toronto (YYZ)	WestJet	DH8D (C-FNEN)
96	12:39 PM	AC8735	Iles-de-la-Madeleine (YGR)	Air Canada Express	DH8C (C-FACF)
97	12:40 PM	PD467	Toronto (YTZ)	Porter Airlines	DH8D (C-FLQY)
98	12:42 PM	AC8980	Ottawa (YOW)	Air Canada Express	CRJ2 (C-FFJA)
99	12:53 PM	AC8709	Quebec (YQB)	Air Canada Express	CRJ9 (C-FCJZ)
100	12:57 PM	AC336	Edmonton (YEG)	Air Canada	E190 (C-FNAJ)
101	1:01 PM	AC8825	Washington (DCA)	Air Canada Express	CRJ2 (C-GUJA)
102	1:08 PM	AC8711	Quebec (YQB)	Air Canada	CRJ
103	1:10 PM	TS279	Paris (CDG)	Air Transat	A332 (C-GTSJ)
104	1:14 PM	AC663	Halifax (YHZ)	Air Canada	A320 (C-FKCR)
105	1:15 PM	AC410	Toronto (YYZ)	Air Canada	A320 (C-FTJO)

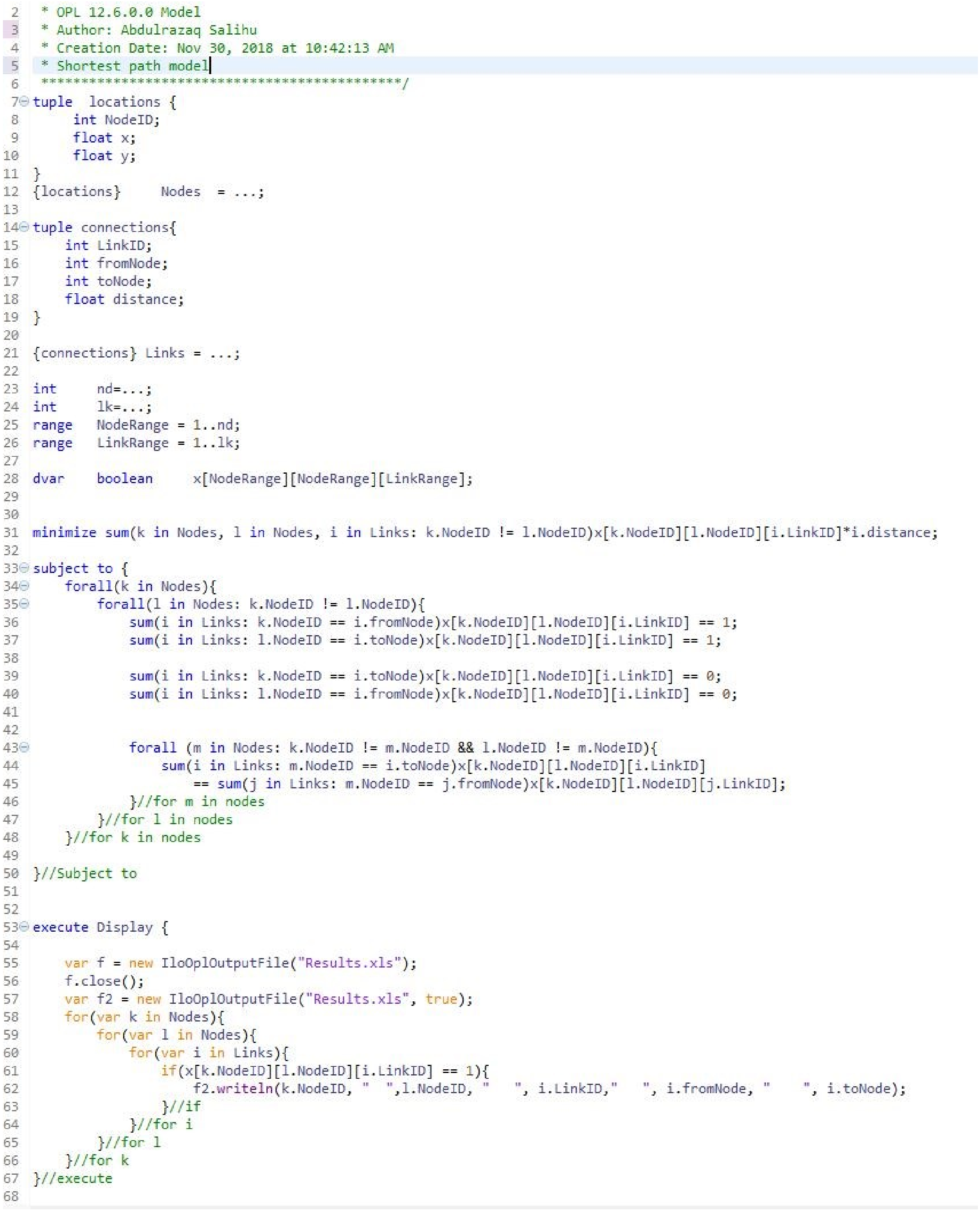
106	1:20 PM	CA879	Beijing (PEK)	Air China	B789 (B-1468)
107	1:25 PM	PD470	Halifax (YHZ)	Porter Airlines	DH8D (C-GLQX)
108	1:25 PM	AC7962	Toronto (YTZ)	Air Canada Express	DH8D (C-GGNW)
109	1:25 PM	OS73	Vienna (VIE)	Austrian Airlines	B763 (OE-LAZ)
110	1:14 PM	AC663	Halifax (YHZ)	Air Canada	A320 (C-FKCR)
111	1:15 PM	AC410	Toronto (YYZ)	Air Canada	A320 (C-FTJO)
112	1:20 PM	CA879	Beijing (PEK)	Air China	B789 (B-1468)
113	1:25 PM	PD470	Halifax (YHZ)	Porter Airlines	DH8D (C-GLQX)
114	1:25 PM	AC7962	Toronto (YTZ)	Air Canada Express	DH8D (C-GGNW)
115	1:25 PM	OS73	Vienna (VIE)	Austrian Airlines	B763 (OE-LAZ)
116	1:32 PM	AC7684	Houston (IAH)	Air Canada Express	E75S (C-FEKH)
117	1:33 PM	AA3368	New York (LGA)	American Eagle	E135 (N846AE)
118	1:45 PM	TS697	Athens (ATH)	Air Transat	A333 (C-GTSD)
119	1:46 PM	AC7590	Chicago (ORD)	Air Canada Express	E75S (C-FEKI)
120	1:48 PM	AA4426	Charlotte (CLT)	American Eagle	E75L (N127HQ)
121	1:56 PM	UA4960	New York (EWR)	United Express	E45X (N11187)
122	2:09 PM	AC7637	New York (LGA)	Air Canada Express	E75S (C-FEJF)
123	2:12 PM	AC8715	Quebec (YQB)	Air Canada	DH8D
124	2:15 PM	AC312	Vancouver (YVR)	Air Canada	A321 (C-GIUE)
125	2:15 PM	AC412	Toronto (YYZ)	Air Canada	A319 (C-FZUL)
126	2:15 PM	TU202	Tunis (TUN)	Tunisair	A332 (TS-IFM)
127	2:25 PM	AC7964	Toronto (YTZ)	Air Canada	DH4
128	2:28 PM	WS3526	Toronto (YYZ)	WestJet	DH8D (C-FWEZ)
129	2:30 PM	AC1903	Athens (ATH)	Air Canada Rouge	B763 (C-GSCA)
130	2:30 PM	AC1989	Mexico City (MEX)	Air Canada Rouge	A319 (C-GBIM)
131	2:40 PM	PB1901	Quebec (YQB)	PAL Airlines	DH8C
132	2:40 PM	QR763	Doha (DOH)	Qatar Airways	B77W (A7-BEI)
133	2:44 PM	AC8986	Ottawa (YOW)	Air Canada Express	DH8C (C-GTAQ)
134	2:49 PM	DL5527	Atlanta (ATL)	Delta Connection	CRJ9 (N299PQ)
135	2:50 PM	PD473	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQF)
136	2:50 PM	TS719	Lisbon (LIS)	Air Transat	A332 (C-GTSZ)
137	2:50 PM	AC1963	Marseille (MRS)	Air Canada Rouge	B763 (C-GHPE)
138	2:55 PM	AC1961	Lisbon (LIS)	Air Canada Rouge	B763 (C-FMLZ)
139	2:55 PM	AF344	Paris (CDG)	Air France	B77W (F-GZNG)
140	3:00 PM	AC835	Geneva (GVA)	Air Canada	A333 (C-GHKW)
141	3:00 PM	TS447	Bordeaux (BOD)	Air Transat	A21N (C-GOIF)
142	3:01 PM	AC780	San Francisco (SFO)	Air Canada	A320 (C-FFWM)
143	3:04 PM	AC1637	Orlando (MCO)	Air Canada Rouge	A319 (C-GBHO)
144	3:05 PM	AC8600	Winnipeg (YWG)	Air Canada Express	CRJ9 (C-GJAZ)
145	3:10 PM	LX86	Zurich (ZRH)	Swiss	A333 (HB-JHJ)
146	3:15 PM	AC414	Toronto (YYZ)	Air Canada	A320 (C-GKOE)
147	3:15 PM	TS157	Brussels (BRU)	Air Transat	A332 (C-GUBC)
148	3:15 PM	TS111	Paris (CDG)	Air Transat (30th Anniversary Livery	A333 (C-GKTS)
149	3:21 PM	AC7592	Chicago (ORD)	Air Canada Express	E75S (C-FUJA)
150	3:22 PM	AC8697	Sept-Iles (YZV)	Air Canada Express	DH8C (C-GABO)
151	3:25 PM	TS723	Lyon (LYS)	Air Transat	A333 (C-GTSO)
152	3:25 PM	AC7966	Toronto (YTZ)	Air Canada Express	DH8D (C-GGND)
153	3:27 PM	WS212	Calgary (YYC)	WestJet	B738 (C-GAWS)
154	3:28 PM	AC782	Los Angeles (LAX)	Air Canada	A320 (C-FTJS)
155	3:28 PM	WS3510	Toronto (YYZ)	WestJet	DH8D (C-GENU)
156	3:32 PM	AC1651	Miami (MIA)	Air Canada Rouge	A319 (C-FYNS)
157	3:40 PM	TS385	Madrid (MAD)	Air Transat	A310 (C-GSAT)
158	3:42 PM	AC8717	Quebec (YQB)	Air Canada Express	DH8C (C-FJVV)
159	3:45 PM	AC1929	Bucharest (OTP)	Air Canada Rouge	B763 (C-FMWP)
160	3:45 PM	TS261	Barcelona (BCN)	Air Transat	A332 (C-GTSI)
161	3:45 PM	AC8932	Ottawa (YOW)	Air Canada Express	CRJ9 (C-FBJZ)
162	3:50 PM	TS679	Nice (NCE)	Air Transat	A21N (C-GOIE)
163	3:51 PM	YN238	Chibougamau (YMT)	Air Creebec	DH8A
164	3:55 PM	DL5475	New York (LGA)	Delta Connection	CRJ9 (N232PQ)
165	3:59 PM	AC8847	Windsor Locks (BDL)	Air Canada Express	DH8C (C-GEWQ)
166	3:59 PM	DL5533	New York (JFK)	Delta Connection	CRJ9 (N319PQ)
167	4:04 PM	TS867	Punta Cana (PUJ)	Air Transat	A321 (C-GEZD)
168	4:05 PM	PD477	Toronto (YTZ)	Porter Airlines	DH8D (C-FLQY)
169	4:10 PM	AC83	Tel Aviv (TLV)	Air Canada	A333 (C-GHKX)
170	4:10 PM	LH478	Frankfurt (FRA)	Lufthansa (Star Alliance Livery)	A343 (D-AIGW)

171	4:12 PM	AC8507	Fredericton (YFC)	Air Canada Express	CRJ2 (C-FFJA)
172	4:12 PM	UA3986	New York (EWR)	United Express	E145 (N13903)
173	4:15 PM	AC416	Toronto (YYZ)	Air Canada	A320 (C-FFWN)
174	4:19 PM	AC1072	Denver (DEN)	Air Canada	E190 (C-FLWK)
175	4:20 PM	AC893	Rome (FCO)	Air Canada	B77W (C-FKAU)
176	4:21 PM	AC8685	Saguenay (YBG)	Air Canada Express	DH8C (C-GKTA)
177	4:22 PM	WQ6800	Atlantic City (ACY)	Swift Air	B734
178	4:24 PM	AC7728	Dallas (DFW)	Air Canada Express	E75S (C-FEJC)
179	4:25 PM	AC865	London (LHR)	Air Canada	A333 (C-GFAF)
180	4:25 PM	AC2403	Barcelona (BCN)	Qatar Airways	A332 (A7-ACM)
181	4:25 PM	AC7968	Toronto (YTZ)	Air Canada	DH4
182	4:27 PM	DL5549	Minneapolis (MSP)	Delta Connection	CRJ9 (N906XJ)
183	4:28 PM	WS3528	Toronto (YYZ)	WestJet	DH8D (C-GENO)
184	4:29 PM	AC318	Calgary (YYC)	Air Canada	A320 (C-FDSU)
185	4:33 PM	TS109	Cancun (CUN)	Air Transat	A321 (C-GEZJ)
186	4:35 PM	AC811	Algiers (ALG)	Air Canada	A333 (C-GEFA)
187	4:40 PM	WG427	Punta Cana (PUJ)	Sunwing Airlines	B738 (C-FPRP)
188	4:40 PM	AH2700	Algiers (ALG)	Air Algerie	A332 (7T-VJV)
189	4:45 PM	AC6	Tokyo (NRT)	Air Canada	B789 (C-FGFZ)
190	4:45 PM	0Q101	Rouyn (YUY)	Hydro-Quebec	DH8D
191	4:47 PM	AC7702	Houston (IAH)	Air Canada Express	E75S (C-FEIX)
192	4:47 PM	AC8909	Moncton (YQM)	Air Canada Express	DH8C (C-FACT)
193	4:50 PM	AC478	Ottawa (YOW)	Air Canada	A320 (C-FTJO)
194	4:50 PM	TS507	Rome (FCO)	Air Transat	A332 (C-GJDA)
195	4:50 PM	KL671	Amsterdam (AMS)	KLM	A332 (PH-AOC)
196	4:52 PM	AA4845	Philadelphia (PHL)	American Eagle	E145 (N642AE)
197	4:52 PM	WS542	Vancouver (YVR)	WestJet	B737 (C-FIBW)
198	4:52 PM	YN204	Val-d'Or (YVO)	Air Creebec	DH8A
199	4:53 PM	AA3126	Chicago (ORD)	SkyWest Airlines	CRJ2 (N863AS)
200	4:55 PM	AC2401	Paris (CDG)	Qatar Airways	A332 (A7-ACL)
201	4:55 PM	AC8664	London (YXU)	Air Canada Express	CRJ2 (C-GQJA)
202	5:04 PM	AC747	New York (LGA)	Air Canada	E190 (C-FNAJ)
203	5:05 PM	PD479	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQX)
204	5:05 PM	0Q103	Saguenay (YBG)	Hydro-Quebec	DH8D
205	5:08 PM	AC1684	Victoria (YYJ)	Air Canada Rouge	A319 (C-GJVY)
206	5:08 PM	TS835	Roatan (RTB)	Air Transat	B738 (C-GTQB)
207	5:14 PM	AC8463	Boston (BOS)	Air Canada Express	CRJ9 (C-FCJZ)
208	5:15 PM	7F867	Kuujjuaq (YVP)	First Air	B734
209	5:15 PM	AC418	Toronto (YYZ)	Air Canada	A320 (C-FZUB)
210	5:28 PM	AC8745	Bathurst (ZBF)	Air Canada Express	DH8C (C-FMDW)
211	5:29 PM	DL5494	Detroit (DTW)	Delta Connection	CRJ9 (N904XJ)
212	5:30 PM	SS900	Paris (ORY)	Corsair	A333 (F-HZEN)
213	5:31 PM	AC1689	Charlottetown (YYG)	Air Canada Rouge	A319 (C-FYKW)
214	5:33 PM	AA3903	New York (LGA)	American Eagle	E135 (N806AE)
215	5:34 PM	AC7525	Halifax (YHZ)	Air Canada Express	E75S (C-FEJP)
216	5:34 PM	AC1883	Cancun (CUN)	Air Canada Rouge	A321 (C-GHQI)
217	5:37 PM	AC8905	Moncton (YQM)	Air Canada Express	DH8C (C-FACF)
218	5:39 PM	AC8471	Baltimore (BWI)	Air Canada Express	CRJ2 (C-FDJA)
219	5:40 PM	AC8594	Winnipeg (YWG)	Air Canada Express	CRJ9 (C-GFJZ)
220	5:40 PM	DL5473	New York (LGA)	Delta Connection	CRJ9 (N918XJ)
221	5:41 PM	AC8793	Saint John (YSJ)	Air Canada Express	DH8C (C-GTAT)
222	5:46 PM	AC8171	Pittsburgh (PIT)	Air Canada Express	CRJ2 (C-FIJA)
223	5:46 PM	AC8827	Washington (DCA)	Air Canada Express	CRJ2 (C-FEJA)
224	5:46 PM	DL5519	Atlanta (ATL)	Delta Connection	CRJ9 (N607LR)
225	5:51 PM	AC760	San Francisco (SFO)	Air Canada	A320 (C-FFWI)
226	5:52 PM	AC1519	Quebec (YQB)	Air Canada Rouge	A319 (C-GBHY)
227	5:54 PM	0Q313	Baie Comeau (YBC)	Hydro-Quebec	DH8C
228	5:55 PM	PD481	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQQ)
229	5:59 PM	AC8033	Philadelphia (PHL)	Air Canada Express	CRJ2 (C-GUJA)
230	6:07 PM	AC332	Edmonton (YEG)	Air Canada	A320 (C-GJVT)
231	6:10 PM	3H705	La Grande Riviere (YGL)	Air Inuit	B732 (C-GSPW)
232	6:14 PM	WS3452	Halifax (YHZ)	WestJet	DH8D (C-GEEN)
233	6:15 PM	AC420	Toronto (YYZ)	Air Canada	A333 (C-GFUR)
234	6:15 PM	TS778	Vancouver (YVR)	Air Transat	B738
235	6:16 PM	WS592	Toronto (YYZ)	WestJet	B736 (C-GWSI)
236	6:20 PM	AC1987	Punta Cana (PUJ)	Air Canada Rouge	A319 (C-GBIJ)

237	6:20 PM	TS915	Quebec (YQB)	Air Transat	313
238	6:21 PM	AC8179	Raleigh-Durham (RDU)	Air Canada Express	CRJ2 (C-FZJA)
239	6:24 PM	AC8966	Ottawa (YOW)	Air Canada Express	DH8D (C-GGBF)
240	6:25 PM	AC7972	Toronto (YTZ)	Air Canada	DH4
241	6:25 PM	AC8173	Washington (IAD)	Air Canada Express	CRJ2 (C-GGJA)
242	6:33 PM	1I390	Boston (BOS)	NetJets	E55P
243	6:35 PM	TS789	Calgary (YYC)	Air Transat	B737
244	6:35 PM	FI805	Reykjavik (KEF)	Icelandair	B752 (TF-FIS)
245	6:37 PM	WS218	Calgary (YYC)	WestJet	B737 (C-FBWJ)
246	6:40 PM	AC12	Shanghai (PVG)	Air Canada	B789 (C-FVND)
247	6:40 PM	AC7594	Chicago (ORD)	Air Canada Express	E75S (C-FJBO)
248	6:43 PM	AC1727	Pointe-a-Pitre (PTP)	Air Canada Rouge	A319 (C-FYJG)
249	6:46 PM	AC1523	St. John's (YYT)	Air Canada Rouge	A319 (C-GARO)
250	6:49 PM	UA6170	Washington (IAD)	United Express	CRJ7 (N501MJ)
251	6:49 PM	AC671	Halifax (YHZ)	Air Canada	A320 (C-FKCR)
252	6:50 PM	1I738	Atlantic City (ACY)	NetJets	CL35
253	6:54 PM	AC7641	New York (LGA)	Air Canada Express	E75S (C-FEJF)
254	6:55 PM	3H821	Quebec (YQB)	Air Inuit	DH8C (C-GXAI)
255	6:55 PM	LH474	Munich (MUC)	Lufthansa	A346 (D-AIHI)
256	6:59 PM	AA3940	New York (JFK)	American Eagle	E135 (N850AE)
257	6:59 PM	AC326	Calgary (YYC)	Air Canada	A320 (C-FDSN)
258	7:00 PM	YN922	Val-d'Or (YVO)	Air Creebec	DH8A
259	7:03 PM	AC8754	Val-d'Or (YVO)	Air Canada Express	DH8C (C-GABP)
260	7:05 PM	TS475	Toronto (YYZ)	Air Transat	332
261	7:07 PM	AC1856	Las Vegas (LAS)	Air Canada Rouge	A319 (C-FYIY)
262	7:09 PM	AC7555	Boston (BOS)	Air Canada Express	E75S (C-FUJA)
263	7:09 PM	PB3051	Mont-Joli (YYY)	PAL Airlines	DH8C
264	7:10 PM	YN928	Chibougamau (YMT)	Air Creebec	DH8A
265	7:13 PM	AC834	Toronto (YYZ)	Air Canada	A333 (C-GFAJ)
266	7:13 PM	AC302	Vancouver (YVR)	Air Canada	A333 (C-GFAH)
267	7:13 PM	AC1605	Fort Lauderdale (FLL)	Air Canada Rouge	B763 (C-GHPN)
268	7:18 PM	YN704	Kingston (YGK)	Air Creebec	DH8A
269	7:24 PM	AC7743	New York (EWR)	Air Canada Express	E75S (C-FEKI)
270	7:25 PM	PD485	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQF)
271	7:25 PM	AC7974	Toronto (YTZ)	Air Canada Express	DH8D (C-GGND)
272	7:28 PM	WS3534	Toronto (YYZ)	WestJet	DH8D (C-GDEW)
273	7:30 PM	WG518	Cancun (CUN)	Sunwing Airlines	738
274	7:30 PM	3H803	Kuujjuarapik (YGW)	Air Inuit	DH8
275	7:32 PM	AC8727	Quebec (YQB)	Air Canada Express	DH8C (C-FACT)
276	7:32 PM	NDL350	Boston (BOS)	Chrono Aviation	B350
277	7:47 PM	AC8014	Ottawa (YOW)	Air Canada Express	CRJ2 (C-GJZZ)
278	7:50 PM	BA95	London (LHR)	British Airways	B789 (G-ZBKC)
279	7:53 PM	AA4863	Philadelphia (PHL)	American Eagle	E145 (N621AE)
280	7:53 PM	AC8964	Baie Comeau (YBC)	Air Canada Express	DH8C (C-GKTA)
281	8:05 PM	AC798	Los Angeles (LAX)	Air Canada (Star Alliance livery)	A333 (C-GHLM)
282	8:05 PM	AC8758	Rouyn (YUY)	Air Canada Express	DH8C (C-GABO)
283	8:15 PM	AC424	Toronto (YYZ)	Air Canada	A320 (C-FFWM)
284	8:15 PM	PD488	Halifax (YHZ)	Porter Airlines	DH8D (C-GLQL)
285	8:17 PM	AC8731	Quebec (YQB)	Air Canada Express	DH8C (C-GLTA)
286	8:25 PM	AC7976	Toronto (YTZ)	Air Canada	DH4
287	8:28 PM	WS3536	Toronto (YYZ)	WestJet	DH8D (C-GENU)
288	8:35 PM	PD487	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQO)
289	8:39 PM	UA4938	New York (EWR)	United Express	E45X (N11199)
290	8:50 PM	AT208	Casablanca (CMN)	Royal Air Maroc	B77W
291	9:00 PM	4O2820	Cancun (CUN)	Interjet	320
292	9:04 PM	AC8782	Iles-de-la-Madeleine (YGR)	Air Canada Express	DH8C (C-FJVV)
293	9:05 PM	AF348	Paris (CDG)	Air France	772
294	9:06 PM	UA4075	Chicago (ORD)	United Express	E145 (N15912)
295	9:14 PM	AC8467	Boston (BOS)	Air Canada Express	CRJ9 (C-FCJZ)
296	9:16 PM	YN5707	Chibougamau (YMT)	Air Creebec	DH8A
297	9:25 PM	AC7978	Toronto (YTZ)	Air Canada Express	DH8D (C-GGNW)
298	9:25 PM	PD491	Toronto (YTZ)	Porter Airlines	DH8D (C-GLQD)
299	9:29 PM	AC749	New York (LGA)	Air Canada	E190 (C-FNAJ)
300	9:45 PM	AC426	Toronto (YYZ)	Air Canada	A321 (C-GITY)
301	9:45 PM	AM636	Mexico City (MEX)	Aeromexico	B738 (XA-AMO)

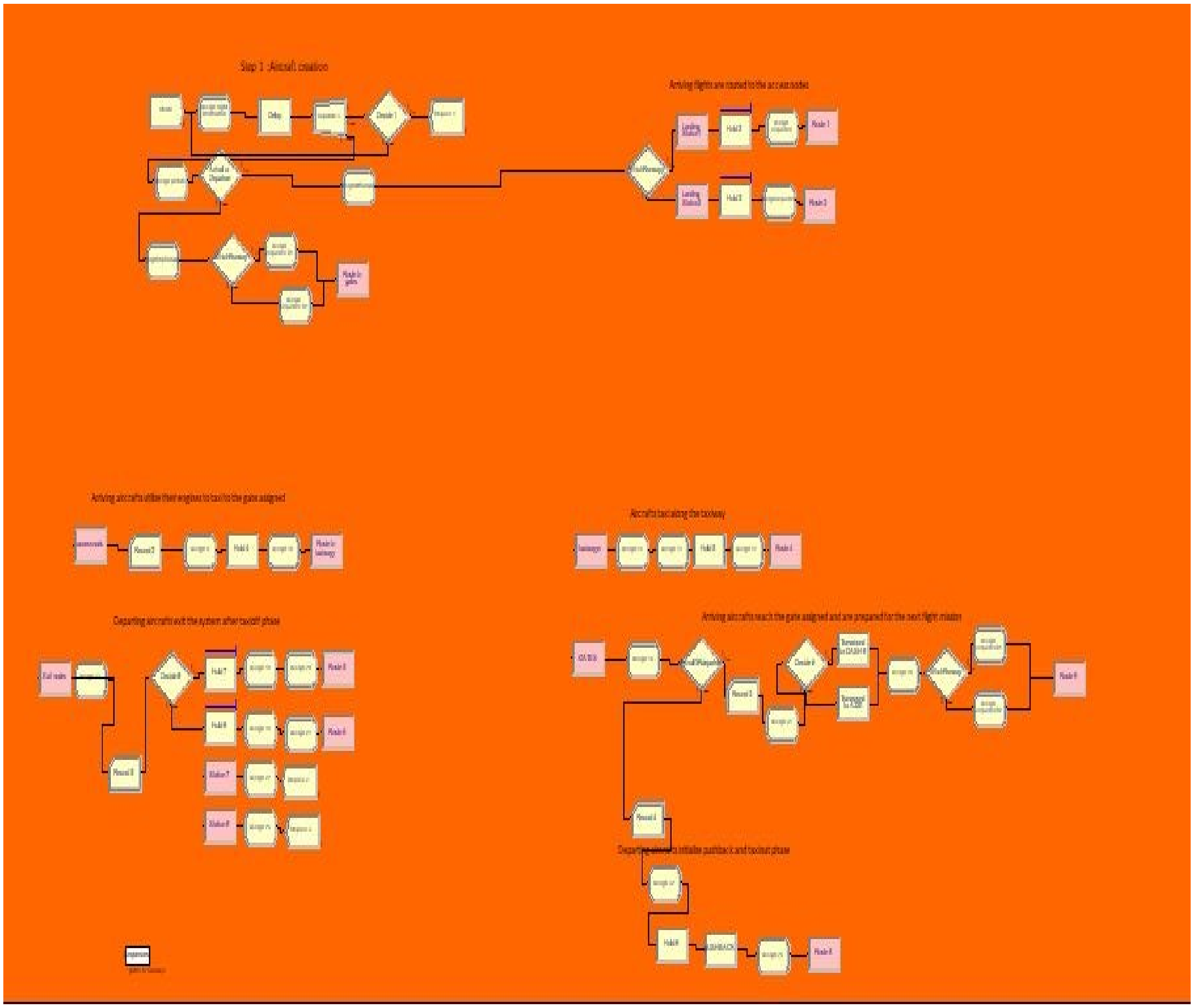
302	9:54 PM	AC1566	Vancouver (YVR)	Air Canada Rouge	B763 (C-GHLT)
303	10:07 PM	AC8907	Moncton (YQM)	Air Canada Express	DH8C (C-FMDW)
304	10:11 PM	AA4567	Charlotte (CLT)	American Eagle	E75S (N105HQ)
305	10:12 PM	DL6298	Detroit (DTW)	Delta Connection	CRJ7 (N390CA)
306	10:14 PM	AC1074	Denver (DEN)	Air Canada	E190 (C-FNAI)
307	10:16 PM	WS596	Toronto (YYZ)	WestJet (Disney's Frozen Livery)	B738 (C-GWSV)
308	10:19 PM	AC7645	New York (LGA)	Air Canada Express	E75S (C-FEJP)
309	10:20 PM	TS595	Toronto (YYZ)	Air Transat	321
310	10:25 PM	AC7980	Toronto (YTZ)	Air Canada	DH4
311	10:28 PM	AC1609	Fort Lauderdale (FLL)	Air Canada Rouge	B763 (C-GEOQ)
312	10:30 PM	AC428	Toronto (YYZ)	Air Canada	A320 (C-FDCA)
313	10:40 PM	DL5528	Atlanta (ATL)	Delta Connection	CRJ9 (N915XJ)
314	10:41 PM	AC7596	Chicago (ORD)	Air Canada Express	E75S (C-FEJC)
315	10:49 PM	AA4677	Philadelphia (PHL)	American Eagle	E75S (N101HQ)
316	10:54 PM	AC386	Winnipeg (YWG)	Air Canada	A319 (C-GAQZ)
317	10:57 PM	AA4127	New York (LGA)	American Eagle	E135 (N806AE)
318	11:20 PM	PB1909	Quebec (YQB)	PAL Airlines	DH3
319	11:21 PM	DL5470	New York (LGA)	Delta Connection	CRJ9 (N918XJ)

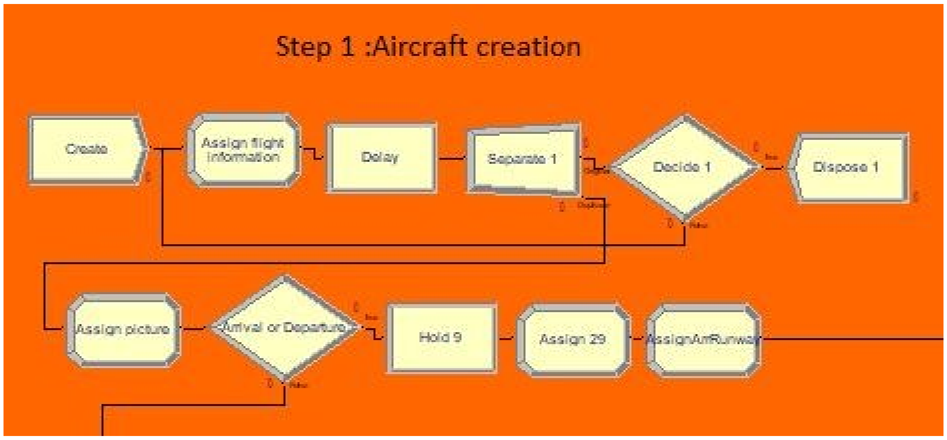
Appendix 3 – Algorithm for calculating shortest path runways and gates



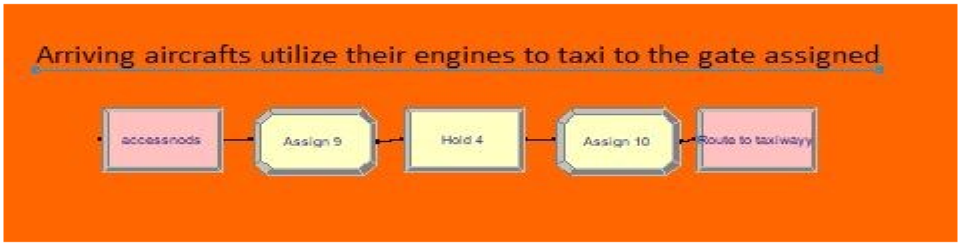
```
 * OPL 12.6.0.0 Model
 * Author: Abdulrazaq Salihu
 * Creation Date: Nov 30, 2018 at 10:42:13 AM
 * Shortest path model
 *********************************************/
tuple  locations {
     int NodeID;
     float x;
     float y;
}
{locations}     Nodes  = ...;

tuple connections{
    int LinkID;
    int fromNode;
    int toNode;
    float distance;
}

{connections} Links = ...;

int     nd=...;
int     lk=...;
range   NodeRange = 1..nd;
range   LinkRange = 1..lk;

dvar    boolean     x[NodeRange][NodeRange][LinkRange];


minimize sum(k in Nodes, l in Nodes, i in Links: k.NodeID != l.NodeID)x[k.NodeID][l.NodeID][i.LinkID]*i.distance;

subject to {
    forall(k in Nodes){
        forall(l in Nodes: k.NodeID != l.NodeID){
            sum(i in Links: k.NodeID == i.fromNode)x[k.NodeID][l.NodeID][i.LinkID] == 1;
            sum(i in Links: l.NodeID == i.toNode)x[k.NodeID][l.NodeID][i.LinkID] == 1;

            sum(i in Links: k.NodeID == i.toNode)x[k.NodeID][l.NodeID][i.LinkID] == 0;
            sum(i in Links: l.NodeID == i.fromNode)x[k.NodeID][l.NodeID][i.LinkID] == 0;


            forall (m in Nodes: k.NodeID != m.NodeID && l.NodeID != m.NodeID){
                sum(i in Links: m.NodeID == i.toNode)x[k.NodeID][l.NodeID][i.LinkID]
                    == sum(j in Links: m.NodeID == j.fromNode)x[k.NodeID][l.NodeID][j.LinkID];
            }//for m in nodes
        }//for l in nodes
    }//for k in nodes

}//Subject to


execute Display {

    var f = new IloOplOutputFile("Results.xls");
    f.close();
    var f2 = new IloOplOutputFile("Results.xls", true);
    for(var k in Nodes){
        for(var l in Nodes){
            for(var i in Links){
                if(x[k.NodeID][l.NodeID][i.LinkID] == 1){
                    f2.writeln(k.NodeID, "  ",l.NodeID, "    ", i.LinkID,"    ", i.fromNode, "    ", i.toNode);
                }//if
            }//for i
        }//for l
    }//for k
}//execute

```

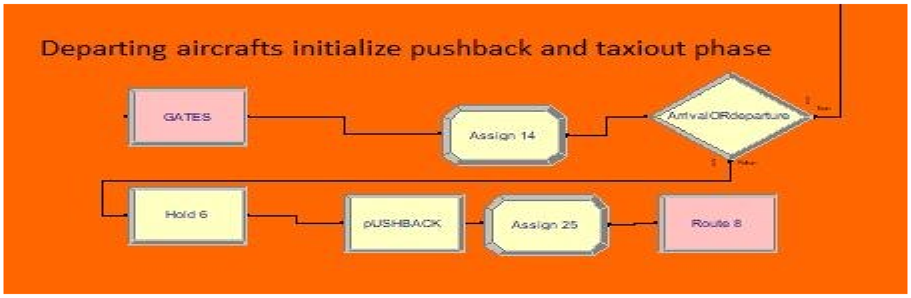
Appendix 4 – Process flowchart for the simulation model

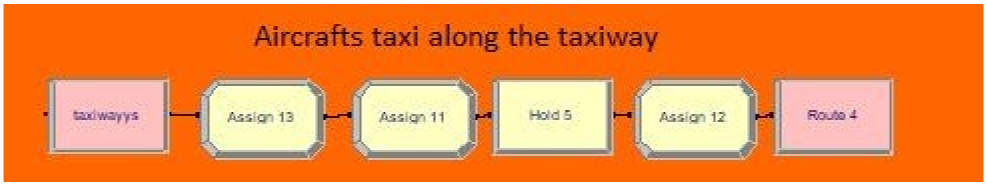


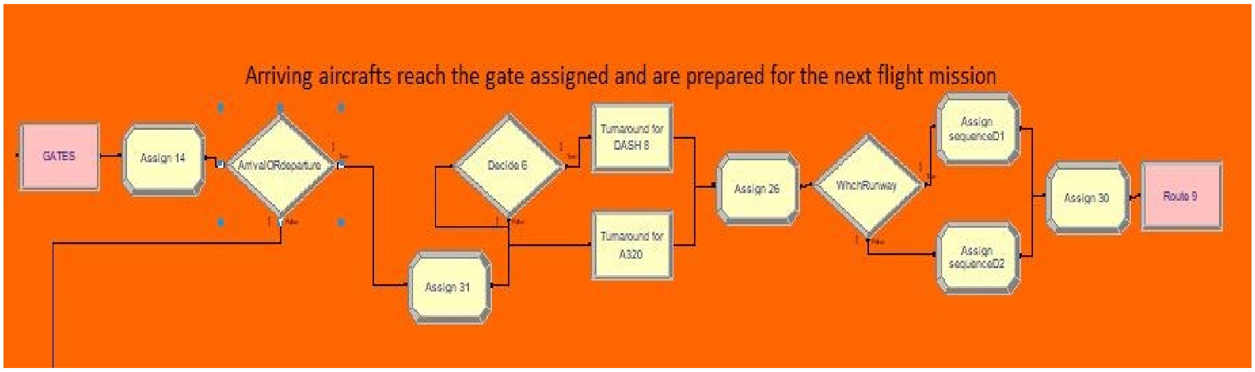

Step 1 :Aircraft creation

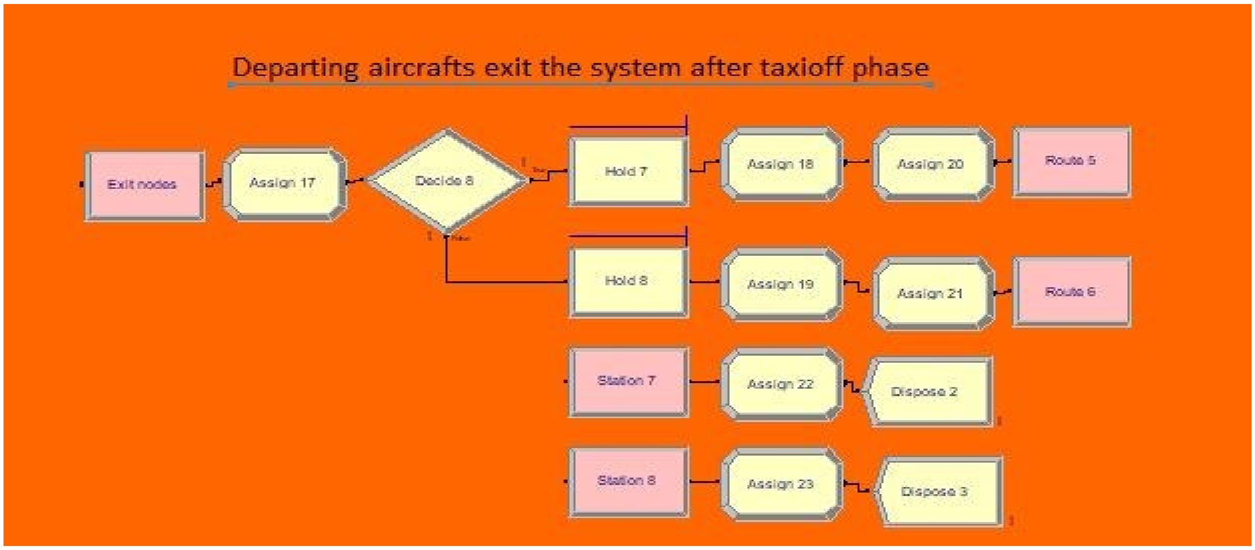

Arriving flights are routed to the access nodes


Arriving aircrafts utilize their engines to taxi to the gate assigned


Departing aircrafts initialize pushback and taxiout phase


Aircrafts taxi along the taxiway
taxiwayys
Assign 13
Assign 11
Hold 5
Assign 12
Route 4


Arriving aircrafts reach the gate assigned and are prepared for the next flight mission
GATES
Assign 14
ArrivalORdeparture
Decide 6
Turnaround for DASH 8
Turnaround for A320
Assign 31
Assign 26
WhchRunway
Assign sequenceD1
Assign sequenceD2
Assign 30
Route 9


Departing aircrafts exit the system after taxioff phase
Exit nodes
Assign 17
Decide 8
Hold 7
Assign 18
Assign 20
Route 5
Hold 8
Assign 19
Assign 21
Route 6
Station 7
Assign 22
Dispose 2
Station 8
Assign 23
Dispose 3

Bibliography

Aeroports de Montreal. (2011). Takeoff and Landing Procedures At Montréal-Trudeau.

Aeroports de Montreal. (2018). Runway use statistics at Montreal-Trudeau Airport for 2018. Soundscape Management. https://www.admtl.com/en/adm/communities/soundscape/faq

Aeroports de Montreal. (2019). Flights:Airlines and destinations. https://www.admtl.com/fr/vols

Aeroports De Montreal. (2014). Airport Guide.

Aeroports De Montreal. (2018). Annual Report 2018.

Air Transport Action Group. (2019). Facts & Figures. https://www.atag.org/facts-figures.html

Airlines for America. (2018). U.S Passenger Carrier Delay Costs. U.S Passenger Airlines. https://www.airlines.org/dataset/per-minute-cost-of-delays-to-u-s-airlines/

Airport Council International. (2019). In the balance: Global air transport demand in 2018 and 2019. International Airport Review. https://www.internationalairportreview.com/article/101952/world-airport-traffic-report-preview-aciworld/

Alliance to Save Energy. (2018). Non-road Vehicles Sector Baseline. https://www.ase.org/sites/ase.org/files/ase-50x50-non-road_vehicle_sector_baseline_report-final.pdf

Altuntas, O., Ekici, S., Yalin, G., & Karakoc, T. H. (2014). Comparison of auxiliary power unit (APU) and ground power unit (GPU) with life cycle analysis in ground operations: A case study for domestic flight in turkey. *Applied Mechanics and Materials*, *629*(October 2014), 219–224. https://doi.org/10.4028/www.scientific.net/AMM.629.219

Beinhaker, P. (2010). *Air Passenger Terminal Planning and Design.* (Vol. 1).

CAN & ICSA. (2018). Contribution of the Global Aviation Sector To Achieving Paris Agreement Climate Objectives. *Climate Action Network (CAN) and International Coalition for Sustainable Aviation (ICSA) Joint Input to the Talanoa Dialogue*, 1–7.

Civil Aviation Safety Authority. (2011). Civil Aviation Order 20.9. In Civil Aviation Regulations (Vol. 9, Issue 1).

Commercial Aviation Safety Team / Common Taxonomy Team. (2013). Phase of Flight: Definitions and Usage Notes. 1.3(April), 1–11.

Deonandan, I., & Balakrishnan, H. (2010). Evaluation of strategies for reducing taxi-out emissions at airports. *10th AIAA Aviation Technology, Integration and Operations Conference 2010, ATIO 2010*, *3*, 0–14. https://doi.org/10.2514/6.2010-9370

Dubois, D., & Paynter, G. C. (2006). "Fuel Flow Method2" for Estimating Aircraft Emissions. *SAE Transactions*, *115*(0148–7191), 1–14. https://doi.org/https://doi.org/10.4271/2006-01-1987

Eagle Tugs. (2019a). Aircraft Tugs and Airport Tugs. Aircraft Tug Ground Support Equipment. eagletugs.com

Eagle Tugs. (2019b). Why an electric aircraft tug may cost you less over time. https://eagletugs.com/electric-aircraft-tug-cost

EASA, EEA, & EUROCONTROL. (2019). European Aviation Environmental Report. In *Ege Üniversitesi Ziraat Fakültesi Dergisi* (Vol. 40, Issue 1). https://doi.org/10.20289/eüzfd.59424

EconomicTimes. (2019). Air India first in the world to use Taxibot on a commercial flight. Business News. https://economictimes.indiatimes.com/industry/transportation/airlines-/-aviation/security-check-at-airports-to-be-made-easier/3d-scanning/slideshow/66847478.cms

Energy Information Administration. (2020). U.S. Gulf Coast Kerosene- Type Jet Fuel Spot Price FOB. Independent Statictics & Analysis. https://www.eia.gov/dnav/pet/hist/EER_EPJK_PF4_RGC_DPGD.htm

Energyhub. (2020). Electricity Prices in Canada 2020. https://doi.org/10.1787/9789264279612-graph41-en

European Union Aviation Safety Agency. (2019). ICAO Aircraft Engine Emissions Databank. https://www.easa.europa.eu/easa-and-you/environment/icao-aircraft-engine-emissions-databank

Ewald Heinrich, M. T., & Heinrich, M. T. E. (2015). On the Concept of Electric Taxiing for Midsize Commercial Aircraft: A Power System and Architecture Investigation. 0–193. https://macsphere.mcmaster.ca/bitstream/11375/18085/2/Heinrich_Maximilian_TE_finalsubmission2015august_MASc.pdf

Federal Aviation Administration. (2018a). Aircraft Characteristics Database Airports. Aircraft Characteristics Database. https://www.faa.gov/airports/engineering/aircraft_char_database/

Federal Aviation Administration. (2018b). Pilot’s Handbook of Aeronautical Knowledge In Managing Airports (pp. 177–217). https://doi.org/10.4324/9781315269047-5

Flightradar24. (2019). Live air traffic https://www.flightradar24.com/data/airports/yul

Freightquip. (2020). Conventional Aircraft Tractors. https://freightquip.com/tld/conventional-aircraft-tractors/

Government of B.C. (2019). British Columbia’s Carbon Tax. https://www2.gov.bc.ca/gov/content/environment/climate-change/planning-and-action/carbon-tax

Government of Canada. (2016). Powering our future with clean electricity. https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/powering-future-clean-energy.html

Government of Canada. (2017). Government of Canada sets GHG reduction targets. https://www.canada.ca/en/treasury-board-secretariat/news/2017/12/government_of_canadasetsambitiousghgreductiontargetsforfederalop.html

Gubisch, M. (2016). FARNBOROUGH*:* Honeywell and Safran halt electric taxi project. https://www.flightglobal.com/farnborough-honeywell-and-safran-halt-electric-taxi-project/121200.article

Guo, R., Zhang, Y., & Wang, Q. (2014). Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. *Transportation Research Part C: Emerging Technologies*, *44*, 98–109. https://doi.org/10.1016/j.trc.2014.03.006

Hooper, A., & Murray, D. (2017). An Analysis of the Operational Costs of Trucking. *TRB 2010 Annual Meeting*, *October*, 51. https://doi.org/http://truckexec.typepad.com/files/atri-operational-costs-of-trucking-2013-final.pdf

Hospodka, J. (2014). Electric taxiing – Taxibot system. *MAD - Magazine of Aviation Development*, *2*(10), 17. https://doi.org/10.14311/mad.2014.10.03

Howard, S. (2013). Rock And Roll:More Options For An Electric Ground Taxi System. Airline Reporter.

https://www.airlinereporter.com/2013/07/rock-and-roll-more-options-for-an-electric-ground-taxi-system/

International Air Transport Association. (2018). IATA Forecast Predicts 8.2 billion Air Travelers in 2037. https://www.iata.org/en/pressroom/pr/2018-10-24-02/

International Civil Aviation Organization. (2016). Long-Term Traffic Forecasts. Jul*y*. https://www.icao.int/safety/ngap/NGAP8 Presentations/ICAO-Long-Term-Traffic-Forecasts-July-2016.pdf

International Civil Aviation Organization. (2019). What is CORSIA and how does it work? https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx

International Energy Agency. (2019). Tracking Transport. https://www.iea.org/reports/tracking-transport-2019

Ithnan, M., Selderbeek, T., Beelaerts van Blokland, W., & Lodewijks, G. (2015). Aircraft Taxiing Strategy Optimization. 1–9. http://rstrail.nl/new/wp-content/uploads/2015/02/izzudin_ithnan.pdf

Kelton, W. D., & Sadowski, R. P. (2015). Simulation with Arena by Kelton.*pdf* (pp. 1–700).

Khammash, L., Mantecchini, L., & Reis, V. (2017). Micro-simulation of airport taxiing procedures to improve operation sustainability: Application of semi-robotic towing tractor. *5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2017 - Proceedings*, 616–621. https://doi.org/10.1109/MTITS.2017.8005587

Lindenfeld, S., & Tran, M. (2015). An Economic & Environmental Analysis of the JetBlue Airways Ground Support Vehicles : A Proposed Implementation of a Cleaner-Burning Fleet. *May*, 1–54.

Marin, G. D., Naterer, G. F., & Gabriel, K. (2010). Rail transportation by hydrogen vs. electrification - Case study for Ontario, Canada, II: Energy supply and distribution. *International Journal of Hydrogen Energy*, *35*(12), 6097–6107. https://doi.org/10.1016/j.ijhydene.2010.03.095

Michael, G. (2017). Wheeltug reveals timeframe for planned service entry. Flightglobal. https://www.flightglobal.com/systems-and-interiors/wheeltug-reveals-timeframe-for-planned-service-entry/122729.article

National Academies of Sciences. (2014). Defining and Measuring Aircraft Delay and Airport Capacity Thresholds. *The National Acedemies Press*. https://doi.org/10.17226/22428.

Nikoleris, T., Gupta, G., & Kistler, M. (2011). Detailed estimation of fuel consumption and emissions during aircraft taxi operations at Dallas/Fort Worth International Airport. *Transportation Research Part D: Transport and Environment*, *16*(4), 302–308. https://doi.org/10.1016/j.trd.2011.01.007

Quinn, C., Ricondo & Associates, & Federal Aviation Administration. (2012). Use of Towbarless Tractors at Airports : Best Practices. In Volume 15 of Research results digest. Transportation Research board. https://doi.org/10.17226/14649

Re, F. (2012). Viability and State of the Art of Environmentally Friendly Aircraft Taxiing Systems. *Electrical Systems for Aircraft Railway and Ship Propulsion (ESARS)*, 1–6.

Ricardo. (2011). TaxiBot development. IAI Awards to Support next Phase of TaxiBot Development. Ricardo.com

Rosero, J. ., Ortega, J. ., & Aldabas, E. (2007). Moving Towards a More Electric Aircraft. *IEEE A&E Systems Magazine*.

Safran S.A and Honeywell Aerospace. (2013). Electric Green Taxiing System. June, 3.

Safran S.A and Honeywell Aerospace. (2014). EGTS Environmental Benefits (Overview). *EGTS International.*

Schmidt, M. (2017). A review of aircraft turnaround operations and simulations. *Progress in Aerospace Sciences*, *92*(January), 25–38. https://doi.org/10.1016/j.paerosci.2017.05.002

Shaheen, S. A., & Lipman, T. E. (2007). Reducing Greenhouse Emissions and Fuel Consumption. *IATSS Research*, *31*(1), 6–20. https://doi.org/10.1016/s0386-1112(14)60179-5

Smith, S. (2013). Electric GSE Buying Trends Report. *AVIATIONPROS.* https://www.aviationpros.com/gse/gse-technology/green-alternative-energy-gse/article/10889496/electric-ground-support-equipment-buying-trends-report

Soepnel, S., Roling, P., Haansta, J. O., Busink, J., & De Wilde, W. (2017). Impact of electric taxi systems on airport apron operations and gate congestion. *17th AIAA Aviation Technology, Integration, and Operations Conference, 2017*. https://doi.org/10.2514/6.2017-4391

Statista. (2020). Number of flights performed by the global airline industry from 2004 to 2020. Transportation and Logistics. https://www.statista.com/statistics/564769/airline-industry-number-of-flights/

Surgenor, C. (2014). Taxibot green taxiing vehicle receives European approval for Boeing 737 commercial operation*s*. Independent Reporting on Aviation and the Environment. https://www.greenaironline.com/news.php?viewStory=2004

Thierry, D. (2014). WheelTug, Safran-Honeywell and IAI Offer Three Rival Solutions for Airline Engines-off Taxiing. SINGAPORE AIR SHOW. https://www.ainonline.com/aviation-news/air-transport/2014-02-11/wheeltug-safran-honeywell-and-iai-offer-three-rival-solutions-airline-engine-taxiing

U.S. Energy Information Administration. (2016). Carbon Dioxide Emissions Coefficients. Independent Statistics & Analysis. https://www.eia.gov/environment/emissions/co2_vol_mass.php

Ugurlu, A., & Oztuna, S. (2015). A comparative analysis study of alternative energy sources for automobiles. *International Journal of Hydrogen Energy*, *40*(34), 11178–11188. https://doi.org/10.1016/j.ijhydene.2015.02.115

WheelTug. (2020). WheelTug makes flying faster. http://www.wheeltug.com/

WheelTug plc. (2017). Wheeltug Receives FAA Go-Ahead for Airplane E-Taxi System Certification *Plans*. AVIATIONPROS. https://www.aviationpros.com/gse/press-release/12293792/wheeltug-plc-wheeltug-receives-faa-goahead-for-airplane-etaxi-system-certification-plans

Zhou, H., & Jiang, X. (2015). Research on taxiway path optimization based on conflict detection. *PLoS ONE*, *10*(7), 1–11. https://doi.org/10.1371/journal.pone.0134522