Electrification of Airport Operations: Electric Powered Tow-Truck Utilization in Taxiing Operations

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ABSTRACT

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Civil aviation has steadily increased over the past decades and plays an essential role in connecting people and countries across the world. According to the International Civil Aviation Organization (ICAO, 2018), passenger traffic has grown with an average of 5.4% between 1995 and 2015. ICAO estimates the demand for aviation to continue increasing by an annual rate of 4.3% until 2035 and 4.1% until 2045. Among several crucial objectives of air transportation system problems, the minimization of fuel consumption has a profound impact on both the economic viability of airline companies and the impact of air-transportation in the environment.

Although aviation is not currently the leading cause of global warming, industry development, and the increase in air transportation will make it a significant factor for global warming over the coming decades. Predicting the impact of aviation on economic and environmental systems requires investigations at different stages of air transport operations. One of the strategies to reduce the fuel consumption of aviation is to optimize the fuel burn during airplane ground movement (taxiing) in airports. The main reason is that aircraft ground movement is a significant source of fuel consumption and emissions at an airport (e.g., it is estimated that aircraft burn about 7% of their fuel during this stage of the flight). Among different ways of taxiing operation in an airport, electrification of ground transportation has proven to be one of the most efficient ways which have many advantages such as reducing fuel consumption and emission of greenhouse gases with low maintenance cost. However, it should be noted that electric-powered vehicles can be a beneficial and efficient way of taxiing in airports if the electricity is clean. Clean electricity is produced from

renewable and non-emitting sources such as wind, sun, and water. Using electric-powered vehicles in airports might not be the optimal option if the electricity is produced by burning fossil fuels like coal. Nowadays, in many provinces of Canada, the produced electricity is clean, and the government is determined to have 90% clean electricity across Canada by 2030.

The presented study discusses the scheduling of aircraft towing tractors at the airport in order to minimize the fuel consumption and environmental emission of airplane engines and towing tractors. In this study, we developed a Mixed Integer-Linear Programming (MILP) model to schedule electric-powered towing vehicles (pushback Tugs) to provide taxiing services to aircraft. The proposed MILP solution enables aircraft to request a towing vehicle when it is available or perform traditional taxiing operations by using aircraft engines to minimize operating costs, which includes delay/earliness costs, fuel consumption cost, and towing cost. We concluded that the hybrid system for taxiing operation which includes both traditional engine powered solutions and the proposed electric-powered towing vehicle approaches, is the optimal solution. Through sensitivity analysis, the proposed taxiing operations planning model determines the optimum number of towing vehicles in an airport.

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1 Introduction

Over the past decades, the aviation industry has been growing all over the world and has played a crucial role in connecting people and countries across the world. To keep up with the trend, the aviation industry is growing so fast, such that the world air traffic is growing 4-5% yearly, and by 2025, it is anticipated to grow as high as 150% (SESAR, 2006). As a consequence of rapid growth in air transportation, the industry, governments, and society at large are facing growing challenges regarding fuel consumption and emissions. 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.

Given that, many large airports around the world are located in the hearts of residential areas such as Chicago's O'Hare, New York's JFK, and Montreal's Pierre Elliott Trudeau, the Greenhouse Gas Emissions (GGE) from aircraft flying through such urban airports directly impacts the health of a large population. One of the strategies to reduce fuel consumption is to minimize the fuel burn during airplane ground movement (taxiing) in airports. According to (Khadilkar & Balakrishnan, 2012b), aircraft burn anywhere between 7 to 10% of their fuels during taxing. Air Traffic Controllers (ATC) organize the movement of airplanes to ensure a safe movement with minimum delay. Therefore, ATCs can have a considerable impact on fuel consumption and emission of the airplane by controlling the speed of the aircraft on the ground, reducing surface congestion and delay. In doing so, ATC provides landing and take-off instruction in the form of speed, flight paths, and other crucial flight navigation information according to weather and air-traffic (congestion) conditions. They manage the movement of aircraft on airport surfaces for both arriving and departing aircraft and guide pilots as they travel through the skies. Since air traffic is overgrowing in recent years, ATC Controllers usually manage multiple aircraft at the same time. Due to extended operating hours, work stress, and increasing traffic conditions, more than occasionally, the controller makes crucial mistakes. While most of such mistakes are easily corrected by pilots or through sophisticated collision and conflict avoidance systems that are embedded in today's modern aircraft, their actions frequently lead to deviations from the schedules, hence causing congestions in the air and on the ground. Even under normal operating conditions, airlines emit a substantial amount of greenhouse gasses due to frequent congestions in the air, and on the ground, their contribution to greenhouse gas emission is significantly increased.

Therefore, the current ATC operating structure needs to change because of structural and operational capacity limitations, such as voice communication via radio, which can cause an error (Donciu, Octavian, & Pleter, 2009). This limitation leads to fuel inefficiencies, which in turn can cause the delay. The free-flight concept, which was proposed by NASA(Garud-Barna, 2015), is a new alternative that guides aircraft by satellite in the cockpit. To implement this concept, the Federal Aviation Administration (FAA) introduced a new digital communication system, called Next Generation Air Transportation System (NextGen), to improve the quality and speed of communications between pilots and air traffic controllers. The improved communication, therefore, makes air traffic more efficient which will lead to saving on time and fuel burn and reduce delays. FAA is also collaborating with the US government on improving NextGen to achieve emission reduction. They aim to reach around 1.4 billion gallons of fuel reductions and 14MT of CO2 emission by 2020, an initiative that is the goal of carbon-neutral growth (FAA, 2012). Considering all the critical factors that affect emissions, aviation can have a significant influence on reaching the above goal. Several factors can affect the extent of emissions from a flight, such as:

- Aircraft type (size, and number of engines)
- Flight weight
- Flight duration
- Type of taxiing on the ground
- Type of fuel used for aircraft and GSE (e.g., jet fuel, diesel, gasoline, biofuel)
- Wind speed and direction
- Weather

Examples of the programs undertaken by governments, airlines, and airports to reduce aviation emission are discussed below.

E.U. Climate Action: The Emission Trading System (ETS) in Europe controls and observes the emitted emissions from all large-scale facilities in addition to aviation systems. Based on the E.U. ETS, all airlines in Europe are obliged to monitor and report emissions produced through their operations. Also, the airlines have certain restrictions on the number of emissions they produce each year. The goal of ETS is to reduce emissions by 21% by 2020 compared to 2005 (E.U. Emission Trading System, 2016).

Canada's Action Plan: Since 2012, the government of Canada has delivered a plan called Canada's Action Plan to reduce GHG from the aviation sector. Their goal is to reduce aviation emissions by 17% (from 2005) by the end of 2020. Canada's Action Plan has also targeted to enhance fuel efficiency by 1.5% annually by the end of 2020 (Canada's Action Plan, 2012). In this plan, the goals will be achieved by applying three strategies (Government of Canada, 2012);

- Renovating the fleet by removing old airplanes from the system and using new and more efficient airplanes.
- Using upgraded and efficient air operations.

- Improving air traffic management system.

FAA Voluntary Airport Low Emission Program (VALE): The VALE is a voluntary program offered by the FAA and is focused on the reduction of all emission-related airport ground activities. The main focus of the VALE Program is to investigate the alternative-fueled ground support equipment and technologies that lead to lower emissions. To achieve their goals, they are providing financial support to airports. Since 2005, they have provided $175 million in financial supports to 37 airports in 69 different VALE plans (FAA, 2014).

Carbon Tax Plan in Canada: The government of Canada is fighting against climate changes and environmental emission by applying tax toward big businesses and companies which are using a considerable amount of fossil fuels in their operations. The government has defined a specific amount of cost per tonne of CO2 gas emission (20 dollars/tonne). In this plan, the amount of tax is increasing each year in order to force everyone to reduce the production of CO2 emission (The Globe and mail news,2019).

The aircraft operations are usually divided into two main parts with different emissions. The Landing/Take-Off (LTO) cycle, which includes all activities near the airport are happening below 3000 feet. These include taxi-in and out, take-off, climb-out, and landing, also cruise, which differs on their emission levels depending on the length of the flight(Di Bernardi, D'Iorio, Coppa, Monteagudo, & Tomassini, 2014).

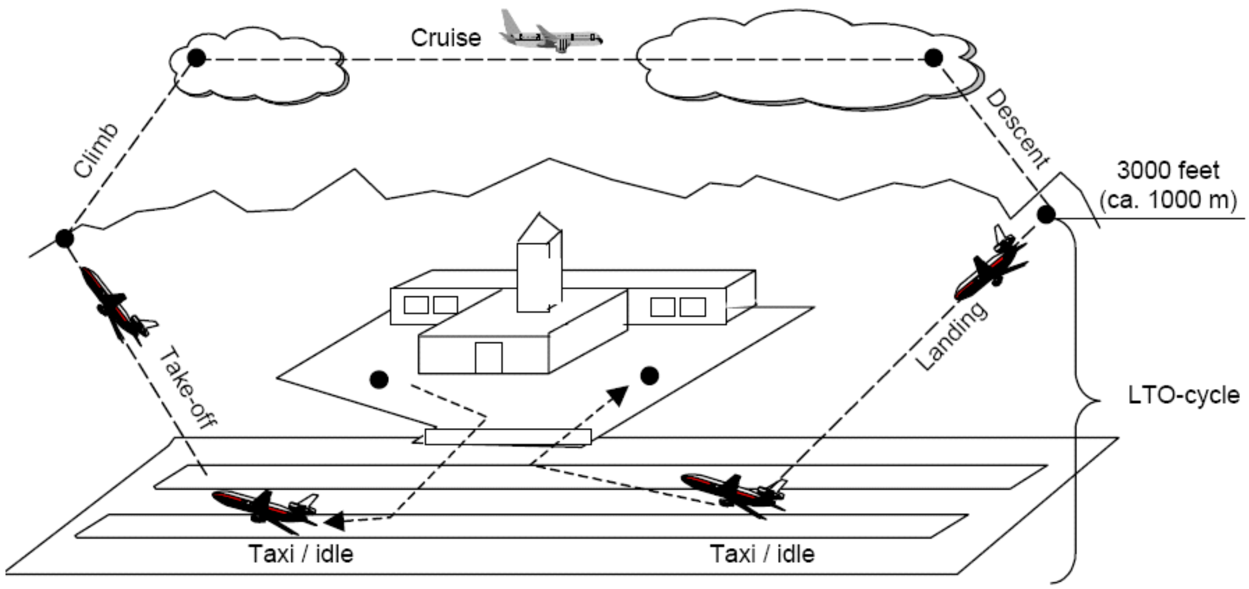


Figure 1- 1: Different phases of an aircraft operation (IPCC, 2001)

In this thesis, our focus is on reducing the emission that happens in the airport and during aircraft ground movement. It includes the movements of aircraft on airport ground, which happen between facilities. For example, arriving airplanes after landing on the runway and coming to a complete stop must be transported from the runway to the locations for maintenance or subsequent flights. Also, departing airplanes must be transported to the runway when fully loaded before take-off. All these movements occur on a network of routes called taxiways. Fuel consumption during ground movement operation is one of the areas that must be carefully investigated in order to improve fuel efficiency. Choosing an appropriate airplane taxiing method is one of the best ways to control emission as well as fuel consumption on airport ground.

There are four different ways of taxiing the airplane on the ground from the gate to the runway before departure and from runway to gate after landing. Each of these ways has its advantages and disadvantages depending on their fuel consumption, emission, safety, taxi time, and efficiency. Taxiing happens in one of the following ways(Ithnan & Selderbeek, 2013).

- All engines on during taxiing
- Single-engine taxiing
- Operational towing
- Electric taxiing

All engines on during taxiing: Most of the airplanes are capable of moving backward by their engine using reverse thrust. Taxiing on the ground when all engines are on, leads to a high level of noise, emission, and fuel cost. Also, in terms of safety, it can cause damages to the airplane engine, around buildings and people by jet blast.

Single engine taxing: If an airplane operates by less than all engines for taxing, it is called single-engine taxing. This method is useful when the taxi time is longer than the engine warm-up and cool down, which is 2-5 minutes. Through single-engine taxiing, it is possible to reduce at least 32% of the emission and fuel consumption. Average fuel reduction per flight is up to 45 gallons, which is equivalent to $137 (Luke Jensen, Brian Yutko. 2014). From the safety point of view, this method can lead to jet blast for wide-body aircraft and harm the surrounding area and people.

Operational towing: Aircraft taxiing using towing tractors reduces fuel burn and emissions created by an aircraft engine. In this method, a different type of emission and fuel is introduced. The emission and fuel consumption in this method differs based on the type of the towing tractor. The new type of towing technology developed by Tugbot is considerable in terms of fuel consumption, emission, noise, minimizing the workforce, and efficient taxing process. Taxiing the aircraft with no engine on eliminates the damages. This method has less fuel burn and emission compared to the two previous methods.

Electric taxiing: This method means moving aircraft on the ground by installing an electric motor on the landing gear. This electric motor is powered by APU (Auxiliary Power Unit) and allows the pilot to control the airplane from the cockpit. This method has the least fuel consumption and emission, among all methods.

Airline companies have been experimenting with either electric powered towing vehicles (Lufthansa with TaxiBot) or on-board systems, such as WheelTug, to eliminate fuel usage at airports. The work of (Lukic et al., 2018) provides a more comprehensive review of the current state of the electrification of taxiing operations. In this work, we provide a Mixed Integer-Linear Programming (MILP) model to optimally schedule electric-powered towing vehicles to provide taxiing services to aircraft. The proposed MILP solution facilitates aircraft's request for towing vehicle when it is available or performs traditional taxiing operations using aircraft engines. However, it should be noted that electric-powered vehicles can be an efficient way of taxiing in airports if the electricity is clean. Clean electricity is produced from renewable and non-emitting sources such as wind, sun, and water. Using electric-powered vehicles in airports might not be the optimal option if the electricity is produced by burning fossil fuels like coal. Nowadays, in many provinces of Canada, the produced electricity is clean, and the government is determined to have 90% clean electricity across Canada by 2030 (Canada Government, 2016).

1.1 Thesis contributions

This thesis brings several contributions to the aviation industry from both research and application perspectives.

- Modeling of taxiing operations as MILP

- Proposing alternative solution strategies namely: i) Centralized; and ii) Free Flight Concept: Sequential solution strategy
- Evaluation of tow-truck allocation methods: i) all engine powered taxiing; ii) all tow-truck allocation, and iii) hybrid system
- Cost-benefit analysis
- Greenhouse gas emission analysis

The remainder of the thesis is organized as follows. In section 2, a brief literature review is provided. In section 3, the formulation of the MILP model for handling the proposed hybrid taxiing operations management system is presented. Several cases are solved and discussed in section 4. Finally, in section 5, conclusions are provided.

2 Literature Review

From the health and environmental point of view, pollution from all types of transportations can be very harmful to human life across the globe. Indeed, transportation is the leading cause of carbon dioxide (CO2) and other GHG emissions (contributing to 14% global emission and 27% to the U.S. emission) (Shaheen & Lipman, 2007).

The need for modern transportation strategies in different industries is fundamental to human life. To this end, it is essential to have efficient and robust transportation systems and policies. 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 to continue to increase by an annual rate of 4.6% until 2032 and 4.5% until 2042 (Economic Development Air Transport Bureau ICAO). Although aviation is not currently is not the leading cause of global warming, industry development, and the increase in air transportation will make it a significant factor for global warming over the coming decades.

In recent years, both the automobile and rail industry has introduced several alternative power sources with the potentials to reduce their CO2 emission. Unlike these industries, advances in technology are not promising regarding a breakthrough alternative power source for the aviation industry. Therefore, both the increasing demand for air-traveling and the lack of alternatives for fossil fuels will increase the contribution of the aviation industry for the CO2 emission. In this regard, it is worthwhile to note that the global greenhouse gas emissions (GHG) have increased by 18.3 % from 2005 to 2013 (Environment and Climate Change Canada, 2012), while in 2013 alone, Canada had produced 1.6% of global GHG emissions. Also, the United States has the most extensive transportation system in the world and is the second country, after China, who is responsible for GHG emission, which is growing very fast (Greene & Schafer, 2003.).A combination of air and marine transportation is the reason for almost 5% of total GHG emissions in the United States and 3% globally (McCollum, Gould, & Greene, 2010).

IPCC (1999) predicted that aviation carbon dioxide (CO2) emissions in 2050 would be ten times more than that of 1992.

Although aviation transportation provides us with convenience, it causes a lot of major environmental concerns due to the consumption of a large amount of energy and the production of different types of emissions. Aircraft engine emissions are about 70% CO2 and around 30% H2O. Other emissions like NOx, CO, Sox, VOC, particulates, and other components are less than 1%, which 10% of these emissions happen during airport ground movements and landing and take-off operation (FAA, 2005). Therefore, optimizing airplane taxing is crucial to reduce fuel consumption and emission during ground movement. In 2011, Stettler, Eastham, and Barrett (2011) developed a code called The Aviation Emissions Inventory Code (AEIC), which allows for estimating the flight's emission in different phases with uncertainties. In 2013, Simone, Stettler, and Barrett (2013) extended this code by eliminating the complexity and using the Monte Carlo simulation. Their simulation result shows that aircraft operation near ground causes 9.1% of fuel burn, 70.6% of which is happening during the cruise.

The fuel which is burned by airplane and related emission during LTO operation is directly associated with taxi time, such that more taxi time causes more fuel consumption and emission. Most of the studies in taxiway scheduling have considered optimizing routing and timing problems by minimizing the total taxing time (Lee & Balakrishnan, 2012).

It is widely assumed that fewer taxi times leads to less environmental emissions and less fuel cost. In some studies, minimizing total waiting time and the difference between scheduled departure and arrival time and their real-time are extensively investigated (Lee & Balakrishnan, 2012), (Marin, 2006).

Khadilkar and Balakrishnan (2012a) have developed a mathematical model, using dynamic programming formulation. The findings of this study show that considering an optimal entry time to the network can help to decrease fuel consumption and delays in airports and to have a better ground movement control policy. A multi-objective model was proposed by li to analyze the relation between taxi time and fuel consumption. This study shows that this relation is very sensitive to actual fuel related to the objective function and real parameter to be used.

Smeltink and Soomer (2004) used a mixed-integer programming approach to optimize the airplane taxi scheduling in airports. Their results prove that this model works well in reducing the average delay time in airport ground movements. In (Liu, Zhang, Liu, & Xing, 2017), the main goal is to minimize airplane pushback slot control. Their results show that by controlling the slot, surface cost and delay cost will decrease. The average delay cost reduction is around 67%.

The authors in (Lulli & Odoni, 2007) assume deterministic demand and capacity, discrete-time, and equal speed of travel. Using their optimization, they concluded that the total delay and its costs could be reduced significantly by assigning delay to an airborne flight instead of flight on the ground. Andreatta, Dell'Olmo, and Lulli (2011) present a stochastic model by considering the uncertainty of airport capacity, the trade-off between airport arrivals and departures as well as the interactions between different hubs. The model identifies the number of flights that must delay in airborne and ground to minimize the total delay cost.

An assessment done in (Simaiakis, Khadilkar, Balakrishnan, Reynolds, & Hansman, 2014) shows how increasing the pushback control level can decrease airport congestion caused by aircraft movements to reach runways while the engine is on, hence reducing fuel consumption and emission.

An investigation was undertaken by Cheng (1998), in which a network-based model was developed to simulate and help analyze airplane pushback conflict on ground movements. Results show that the proposed model is valuable in minimizing delays that are caused by airplane movements while taxing.

Stergianos et al. (2015) investigate two different methods; the Quickest Path Problem with Time Windows (QPPTW) algorithm and an L.P. model to check the effect and importance of pushback delays at airports ground movements. In both methods, they concluded that considering the pushback process and its related delays can significantly help in reaching an accurate ground movement system. Note that although any type of delay is not acceptable in the airport's control system, delay in the pushback process, while the aircraft engine is running, is more costly compared to the delay of that process before the engine is on. In (Atkin, De Maere, Burke, & Greenwood, 2012), allocating pushback time was investigated. The authors conclude that reducing delay time at the runway with an engine on by changing it to delay in starting the pushback process can considerably decrease the fuel burn, hence decreasing financial and environmental burdens.

Estimation of emissions produced by aircraft during landing and take-off at Turkish airports was done by Kesgin (2006). They conclude that two minutes reduction in taxiing time could lead to a reduction of 6% in landing and take-off emissions. In the paper (Khadilkar & Balakrishnan, 2012b), the authors used a regression model to estimate the fuel burn and emission during aircraft taxing operation. The results show that the total taxi time is the main reason for fuel consumption on the ground. In (Ryerson, Hansen, & Bonn, 2010), the importance and impact of improvements in operational acts in decreasing fuel burn and emissions were studied. Their results show that for the one-minute delay in departure, 2.3-4.6 lbs. Fuel is burned. They found that the enhancement of operational activities can considerably reduce fuel costs and environmental emissions.

According to (Zou, Elke, Hansen, & Kafle, 2014), airlines focusing on operational excellence to minimize fuel usage burn up to 25-42% less fuel than those using the least efficient carriers. Furthermore, it is estimated that an aircraft burns an average of 7% of its fuel during taxiing operations. According to (Gebicki, 2018), a Boeing 747 consumes more than one-ton fuel in 15 minutes taxiing during take-off. Finally, civil aviation's contribution to global GGE is estimated to be between 3-6% (Unger, 2011). Akgunduz, Jaumard, and Moeini (2018) presented a mathematical formulation with three different solution scenarios that address an approach to avoid collision of aircraft in the air and by considering minimization of the costs associated with fuel consumption and wrong timing of airplanes movements in different parts of air routes. In this study, for the first time, the fuel consumption cost was calculated based on the aircraft's' speed in an air-traffic planning problem.

Two strategies were assessed to illustrate fuel consumption in ten U.S. airports in the 1987 process level by Fan (1990). One strategy shows that using fewer engines during aircraft ground movement would lead to saving 88 million liters of fuel. On the other hand, implementing the strategy of towing aircraft while taxing, results in savings of 278 million liters of jet fuel in those airports.

Deonandan and Balakrishnan (2009) compare two different methods of taxiing on the ground in the United States domestic flights in 2007. They evaluate single-engine taxi and towing tractors based on taxi time, fuel consumption, and emission. They concluded that fuel burn and emission decrease is above 40% for single-engine taxing and more than 75% using towing tractors. A MATLAB model was developed by Cash et al. (2019) in order to compare Internal Combustion Engines (ICE) pushback tugs with Hybrid Electric Vehicles (HEV) tugs. The results show that

HEV fuel consumption is 52% less than ICE, which means less fuel cost and less environment emission are caused by vehicles engine.

A comparison between utilization of electric and diesel pushback tractors while airplanes are taxiing in airports by Baxter, Sabatini, and Wild (2015) shows that total and direct CO2 emission is, respectively, 2.5 and five times more in diesel tugs than electric tugs. Vaishnav (2014) assesses the emission and fuel consumption of airplane taxiing on airport ground for electric taxing and tugs. To do so, four different types of taxiing were considered; all engine taxiing, single-engine taxiing, E-taxi, and tugs. Comparisons of these methods were made based on factors such as cost (operation, capital, and maintenance), fuel consumption, price, and related emission and taxing time. Results show that using tugs or E-taxi causes less emission and fuel consumption compared to using airplane engines during taxi. Both methods could reduce the emission from domestic flights in the United State by 1.5 million tons each year, which is 1.1% in total for 2006. By considering just narrow-body airplanes in the United States, there will be a decrease of 0.5 million tons of CO2 each year, which is almost $100/ton. Based on (Tld-group.com 2014), it is expected that airlines spend more than $8.7 billion just for taxiing operation in 2020. Using taxibot besides reducing fuel consumption and emission during taxi operation, this amount will decrease to $2.9 billion.

Lukic et al. (2018) compare two different kinds of electric taxing on airport ground from an environmental and operational point of view. The reduction of emission and noise resulted from wheel tug and taxibot, known as electric taxiing, is notable.

In (Hospodka, 2014), the authors conduct a comparison between three different types of electric taxing tugs. The first one is wheeltug, which is powered by APU on the front wheel. The next electric taxing tug is from Honeywell Company, which is similar to wheeltug, while the only difference is using the APU system on the main wheels. The last method is the Taxibot. The advantage of this system is that the pilot controls the tug directly from the cockpit, and compared to the other two, it can move more massive airplanes.

Based on (Mototok, 2019), the waiting time for aircraft pushback by electric pushback tug is very low. British Airways decrease the delay by more than 54% at London Heathrow by using mototok, which is a remote-control electric pushback tug. Saving maintenance and operational cost is another advantage of this system. Maintenance, repair, and energy costs for this type of tugs are less than 0, €90 for a pushback.

2.1 Literature Review Summary

In this chapter, we reviewed different studies about the effect of transportation on the environment, and the main focus was on air transportation. There are plenty of papers about the emission from the airplane engine in the air and on the ground, but the objective of airline companies is to transport passengers from an origin to a destination with minimum deviations from the schedule, safely and comfort while sustaining a profitable business. In the literature, the Air Traffic Management (ATM) problem is mostly tackled with the objective of minimizing the flight delays in the system. On the other hand, the fuel consumption management issue has not been tackled as an integral part of the overall ATM system. The fuel consumption problem is mostly seen as a technology issue where aircraft manufacturers and researchers focus on the design and development of more fuel-efficient engines, and lighter and more aerodynamic aircraft bodies. Hence, the proposed work provides airport taxiing operations planning and management with options to utilize electric powered towing vehicles while considering minimizing delay, emission, and fuel cost.

3 Formulation of Pushback Tugs Scheduling

In this study, we propose a mathematical model in order to minimize the total fuel consumption and emission caused by an aircraft engine and pushback tugs. The proposed model is based on the traditional Vehicle Routing Problem (VRP) with time-window modeled as Mixed Integer Linear Programming (MILP) to assign pushbacks tugs to airplanes with an objective to move aircraft between runways and gates through taxiways safely and efficiently with the minimum possible fuel consumption. While our objective is to minimize fuel consumption, we also focused on service quality. Hence, our mathematical model considers the minimization of delays and earliness.

In this section, the details of the mathematical model are provided. Even though the proposed MILP is capable of handling taxiing operations in all types of airports, in order to reflect the realistic flight conditions, we developed our model based on Montréal-Pierre Elliott Trudeau International Airport (YUL).

The proposed mathematical model is a type of network optimization model where the network consists of Nodes and Links. A node $v \in V$ is a location in the airports that may represent gates, runway entrance/exit points, or taxiway intersections. On the other hand, the link $l \in L$ is the taxiway connecting two nodes. Airplanes enter the system for two purposes (arrival (F_a) or departure (F_d) airplanes). The gate number of the arriving airplanes are known in advanced. Also, the gate number of the departing airplanes are known in advanced. The point of entrance or exit to runways is determined by the mathematical model based on the traffic conditions.

We also modeled pushback tugs which are available to help airplanes to complete their taxiing operations without using their full engine powers in order to minimize fuel consumption on the ground. In fact, by eliminating fuel usage during taxiing operations, airplanes have the potentials to reduce their takeoff fuel needs on board since they do not need to carry additional fuel to complete taxiing at the arrival airport. As a result, they will use less fuel during takeoff, which will further reduce fuel consumption. Let's assume that there are k pushback tugs in the system. In the model, we explore the performance of taxiing operations with a different number of pushback tugs and with varying towing strategies.

3.1 Assumptions

- The time of starting the taxi operation for departing aircraft and arriving aircraft is known and scheduled.
- The gate information is predefined.
- Aircraft speed is considered constant (300 m/min).
- Pushback tug speed is (115 m/min with load and 200 m/min without load).
- It is assumed that a specific flight can pass a node only once. Subsequently, an aircraft can travel an arc only once.
- If an aircraft leaves or arrives at the gate after the scheduled departure or arrival time, a penalty cost will be imposed.
- If an aircraft arrives or departs at the runway after the planned departure or landing time, a penalty cost will be imposed.

3.2 Parameters and Decision Variables

The sets and the parameters of the formulation are shown in Table 3-1. Table 3-2 shows the decision variables.

Table 3- 1: Sets and Parameters of the Problem Formulation

F	Set of all flights indexed by f
f_A	Set of arriving flights:
f_D	Set of departing flights:
k	Set of all vehicles indexed by k
v	Set of nodes of the network indexed by v
v_G	Set of nodes used to represent gates
v_R	Set of nodes used to represent the runways
v_T	Set of nodes used to taxiway intersections
L	Set of links of the network indexed by l
opp_l	The link corresponding the opposite of link l
v_{in}^f	The entry point of flight f
v_{out}^f	The exit point of flight f
w_v^-	Set of incoming nodes that can route airplanes to node v: $v \epsilon V$
w_v^+	Set of outgoing nodes that node v can route airplanes to $v \epsilon V$
$lenght_l$	Length of link L
T_{in}	Scheduled entry time to the taxiway
T_{out}	Scheduled exit time from the taxiway
$late_{in}^f$	Latest entry time to the taxiway system for flight f
$early_{in}^f$	Earliest entry time to the taxiway system for flight f
$late_{out}^f$	Latest exit time from the taxiway system for flight f
$early_{out}^f$	Earliest exit time from the taxiway system for flight f
$Speed_A$	Speed of aircraft
$Speed_T$	Speed of towing vehicle
TT	Travel time between each two nodes

$Size_A$	Size of aircraft
Delay cost	Cost of delay per minute
$Fuel\ cost_A$	The cost of fuel per minute traveled when aircraft is not assigned to any towing vehicle
$Fuel\ cost_T$	The cost of fuel per minute traveled for towing vehicle

Table 3- 2: Decision Variables of the Problem Formulation

$assign_k^f$	$= \begin{cases} 1, & \text{if assign vehicle k to flight f} \\ 0, & otherwise \end{cases}$
$gamma_k^{ff'}$	$= \begin{cases} 1, & \text{if vehicle k serve flight f}'\text{after serving flight f} \\ 0, & otherwise \end{cases}$
DN_k^f	$= \begin{cases} 1, & if \text{ vehicle k start towing on flight f from dummy node} \\ 0, & otherwise \end{cases}$
SN_k^f	$= \begin{cases} 1, & if \text{ vehicle k finish towing on flight f in sink node} \\ 0, & otherwise \end{cases}$
$\boldsymbol{x_f^l}$	$= \begin{cases} 1, & if \text{ assign flight f to link l} \\ 0, & otherwise \end{cases}$
d_l^f	Departure time from the beginning of link l
a_l^f	Arriving time to the end of link l
$time\ in\ sys_f^1$	time in the system when airplane moving by pushback tractor
$time\ in\ sys_f^2$	time in the system when airplane moving by its own engine
t_out_f	The time that flight f exits the system
t_in_f	The time that flight f enters the system

$Delay_F$	The total delay time of aircraft ={Delay at Origin + Delay at Destination}
$DelayOut_F$	Delay time to leave origin node
$DelayIn_F$	Delay at arriving at the destination node

The proposed mathematical model considers the minimization of total fuel and delays cost. Constraints of the model are categorized into three groups: Towing constraints, routing constraints, and timing constraints.

3.3 Objective Function

The objective of the proposed mathematical model is to minimize fuel consumption during taxiing operations. The main business objective of both airline companies and airport management is to provide on-time arrival and departure services for the customers. Therefore, in the formulation of the objective function, deviations from the scheduled arrival and departure times are also penalized.

$$min \sum_{f} \big(time\ in\ sys_f^1 * pushback\ fuel\ cost + time\ in\ sys_f^2 * aircraft\ fuel\ cost + Delay\ cost * Total\ Delay\big)$$

3.4 Aircraft towing constraints

$$\sum_{f'} gamma_k^{ff'} + SN_k^f = assign_k^f \qquad f \in F, k \in K \qquad (1)$$

$$\sum_{f'} gamma_k^{ff'} + DN_k^f = assign_k^f \qquad f \in F, k \in K \qquad (2)$$

$$\sum_{k} assign_k^f \leq 1 \qquad f \in F \qquad (3)$$

$$gamma_k^{ff'} \leq assign_k^f \qquad f, f' \in F, k \in K \qquad (4)$$

$$gamma_k^{ff'} \leq assign_k^{f'} \qquad f, f' \in F, k \in K \qquad (5)$$

$$\sum_{f} DN_k^f \leq 1 \qquad k \in K \qquad (6)$$

$$\sum_{f} SN_k^f \leq 1 \qquad k \in K \qquad (7)$$

$$t\_in_{f'} \geq traveltime^{ff'} + t\_out_f - M(1 - gamma_k^{ff'}) \qquad f, f' \in F, k \in K \qquad (8)$$

$$t\_out_f - early_f^{in} \leq time\ in\ system_f^1 + (1 - \sum_{k} assign_k^f) * M \qquad f \in F \qquad (9)$$

$$t\_out_f - early_f^{in} \leq time\ in\ system_f^2 + \sum_{k} assign_k^f * M \qquad f \in F \qquad (10)$$

Constraints (1) ensure that if a vehicle assigned to an aircraft, it can go to serve another flight or can be retired. Similarly, constraints (2) ensures that a vehicle can serve a flight from an initial node or after serving another flight. Constraint (3) forces all aircraft to be served by at most one vehicle. Inequalities (4) and (5) say that if a vehicle is assigned to a flight, it might be assigned to the next flight, or it might come after serving the previous flight. By constraint (6), (7), we assure that each vehicle brings at most one flight from the initial node or takes at most one flight to the sink node. We consider constraint (8) for the situation that the vehicle is assigned to serve two consecutive flights, so the start time of towing for the next airplane is always after finishing the towing of the previous airplane plus time that it travels to reach the next flight.

Two constraints (9) and (10) indicate the total time an airplane stays in the system after their initial arrival or departure times. The total time in the system is calculated in two different ways in order to capture if the aircraft is pushed by itself (self-powered) or towed by a pushback tug. Those airplanes self-powered consume fuel for taxiing. Hence, time in the system is calculated through constraint (10) and fuel cost is included in the objective function. However, for those airplanes towed by a tug, the time in the system is captured in constraint (9), and the taxiing cost is included in the objective function accordingly.

3.5 Aircraft routing constraints

$$\sum_{l \in W^+(V_{in}^f)} x_l^f = 1 \qquad f \in F \qquad (11)$$

$$\sum_{l \in W^-(V_{in}^f)} x_l^f = 0 \qquad f \in F \qquad (12)$$

$$\sum_{l \in W^-(V_{out}^f)} x_l^f = 1 \qquad f \in F \qquad (13)$$

$$\sum_{l \in W^+(V_{out}^f)} x_l^f = 0 \qquad f \in F \qquad (14)$$

$$\sum_{l \in W^-(v)} x_l^f = \sum_{l \in W^+(v)} x_l^f \qquad f \in F, v \in V: v = type2 \qquad (15)$$

$$x_l^f + x_{l'}^f \leq 1 \qquad f \in F, l, l' \in L: l' = opp_l \qquad (16)$$

$$\sum_{l \in W^-(v)} x_l^f \leq 1 \qquad f \in F, v \in V \qquad (17)$$

$$\sum_{l \in W^+(v)} x_l^f \leq 1 \qquad f \in F, v \in V \qquad (18)$$

$$\sum_{l \in W^-(v)} x_l^f + \sum_{l \in W^+(v)} x_l^f \leq 1 \qquad f \in F, v \in V(G, R) \qquad (19)$$

Constraints (11), (12), (13), (14) ensures that all aircraft enter or exit the taxiway system by using a single link and do not come back to their origin node while they are taxiing. Constraint (15) forces all aircraft that are entering a node, leave the node. Constraint (16) enforces aircraft to use either a link or its opposite link while taxing. Constraints (17) and (18) enforce all vehicles or aircraft to choose at most one link on each node. Inequalities (19) ensure that no aircraft can travel through the same node and link more than once.

3.6 Aircraft timing constraints

$$d_f^l \geq x_l^f * early_{in}^f \qquad l \in W^+(v), f \in F \qquad (20)$$

$$a_f^l \geq x_l^f * early_{out}^f \qquad l \in W^-(v), f \in F \qquad (21)$$

$$d_f^l \leq M * x_l^f \qquad f \in F, l \in L \qquad (22)$$

$$a_f^l \leq M * x_l^f \qquad f \in F, l \in L \qquad (23)$$

$$\sum_{l \in W^+(v_{in}^f)} d_f^l = t\_in_f \qquad f \in F \qquad (24)$$

$$\sum_{l \in W^-(v_{out}^f)} \mathrm{a}_\mathrm{f}^\mathrm{l} = t\_out_f \qquad f \in F \qquad (25)$$

$$\sum_{l \in W^-(v)} a_f^l = \sum_{l \in W^+(v)} d_f^l \qquad f \in F, v \in V \setminus \{v_{out}^f, v_{in}^f\} \qquad (26)$$

$$a_f^l \geq d_f^l + (\frac{lenght_l}{speed_A} * x_l^f) - \sum_k assign_k^f * M \qquad f \in F, l \in L \qquad (27)$$

$$a_f^l \geq d_f^l + \left(\frac{lenght_l}{speed_T} * x_l^f\right) - \left(1 - \sum_k assign_k^f\right) * M \qquad f \in F, l \in L \qquad (28)$$

$$\sum_{l \in W^-(v_{out}^f)} a_f^l - late_f^{out} \leq DelayOut_f \qquad f \in F \qquad (29)$$

$$\sum_{l \in W^+(v_{in}^f)} d_f^l - late_f^{in} \leq DelayIn_f \qquad f \in F \qquad (30)$$

$$DelayOut_f + DelayIn_f \leq Delay_f \qquad f \in F \qquad (31)$$

While constraints (22),(21) ensures that departure and arrival of the aircraft to be within the time window, constraint set (22) and (23) ensure that when an aircraft is not assigned to a link, the departure and arrival time to that link is zero. Constraints (24) and (25) specify the entry time (t_in_f) and exit time (t_out_f) to the taxiway system for each aircraft. Constraint number (26) is the relation between arriving and departing from a link. Constraint (27) (28) gives the time that a flight reaches the end of the link by either towing tractor or airplane engines on, which is related to the speed of aircraft or towing tractor, length of the taxiway and entry time. If an aircraft leaves the gate or the runway after its scheduled time, it is subjected to a delayed penalty. Constraints (29), (30), and (31) determines the duration of delays if it occurs.

4 Solutions and Results

In this section, the mathematical model that was discussed in section 3 is tested in order to minimize delay, fuel cost, and emission. Mathematical models were solved in IBM ILOG CPLEX Optimization Studio 12.2, using Optimization Programming Language (OPL) on a personnel computer with a 64-bit operating system, 3.40 GHz Intel Core i7-3770 CPU and 16.0 GB RAM.

The objective of the airport operations is to enable an uninterrupted traffic flow for both incoming and outgoing airplanes between runways and gates while all airplanes support services such as catering, fueling, luggage transportation and towing are provided effectively, so that airport capacity is utilized at the highest level. Between runways and gates, airplanes follow solid taxiway lines. Collectively, unbroken lines that guide airplanes in today's airports generate a mesh network which is suitable to write a MILP model for the aircraft scheduling problem. In Figure 1, a mesh network that approximates the taxiing paths at Montreal's Pierre Elliott Trudeau International Airport is provided.

Let us now describe the given network as a $G(V, L)$ where V is the set of nodes that represent gates, runways, and intersection points, and L is the links connecting taxiways between nodes. The objective of the taxiing operations is to move airplanes between runways and gates by following the consecutive nodes.

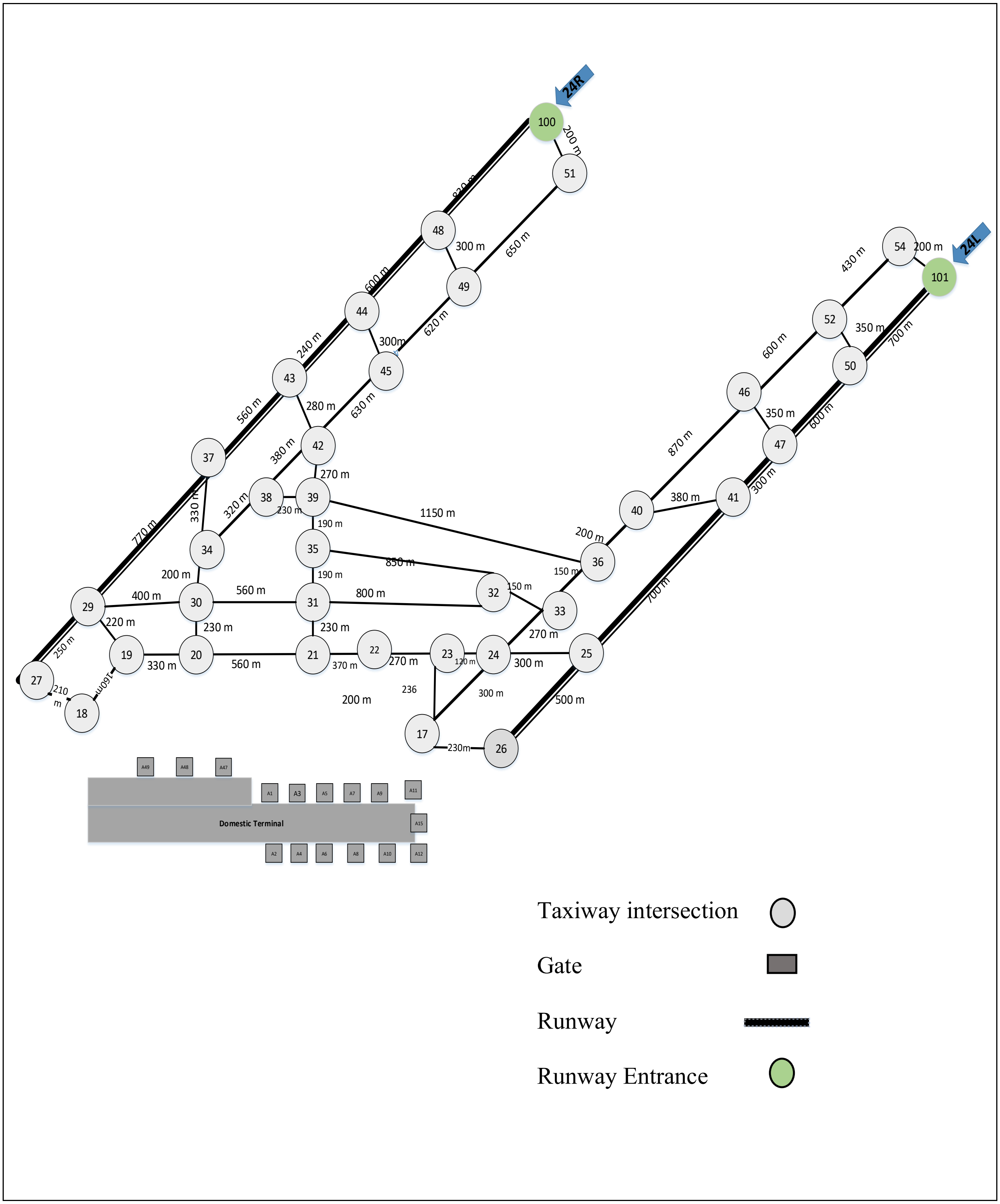


Figure 4-1: Montreal's Pierre Elliott Trudeau International Airport Network

(Montreal airport YUL Website.a, 2019) Shows the runway use statistics for different years. Table 4-1 is provided based on the statistics of 2018. As can be seen from the statistics, runway 10/28 has minimum usage to handle traffic under normal flight conditions. Between the two other runways, 24L/24R has the highest utilization. For our experiments, we only considered the domestic flights and consequently selected the 16 gates, which serve domestic flights. Finally, 54 nodes were identified from the satellite images of the airport to determine the taxiing network (Figure4-1.)

Table 4-1: Runway use statistic at YUL airport

Runways ID	Percentage of Arrival	Percentage of Departure
06L	18%	9%
06R	13%	22%
10	0%	0%
24L	17%	63%
24R	52%	5%
28	0%	0%

4.1 Flight information

In this project, airplanes are categorized into three groups according to their sizes. Accordingly, a relationship is built between the type of aircraft and the fuel and emission amounts. Based on (Montreal YUL Airport. b, 2019) at YUL airport, 68% of airplanes are the small size with less than 45,000 kg weight, and 32% are medium and heavy airplanes. Table 4-2 and 4-3 show the different models of Airbus and Boeing airplanes which operates at Montreal YUL airport. Based on a study at Zurich Airport (Fleuti, 2014), we classified airplanes according to their sizes and their fuel consumption. To represent the small size airplanes, we selected Airbus 320 and Boeing 737 due to their popularity (most frequently used aircraft-types in Montreal's YUL airport). For medium size airplanes, we decided to choose an aircraft form the Boeing family (Boeing 767), which is the most popular model in its category.

Table 4- 2: Different models of Airbus aircraft operating at YUL airport (Montreal airport YUL Website.a, 2019)

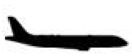
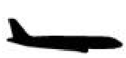
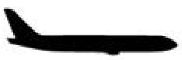
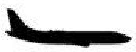
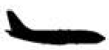
		% of flights at YUL	Take off	Approach
	**Airbus A330-300 (A333)** Chapter 4 300 seats	3.3%	91	98
	**Airbus A310** Chapter 3 250 seats	0.8%	88	98
	**Airbus A321neo (A32N)** Chapter 4 206 seats	10 flights in 2018	83	94
	**Airbus A321** Chapter 3 200 seats	1.1%	87	97
	**Airbus A220-300*** Chapter 4 150 seats	Not yet operating at YUL	80	92
	**Airbus A320** Chapter 4 150 seats	8.1%	84	96
	**Airbus A319** Chapter 4 124 seats	3.7%	84	94

Table 4- 3: Different models of Boeing aircraft operating at YUL airport (Montreal airport YUL Website.a, 2019)

	**Boeing B777 (B77W)** Chapter 4 400 seats	1.0%	90	101
	**Boeing B787-800 (B788)** Chapter 4 242 seats	1.6%	85	97
	**Boeing B767-300 (B763)** Chapter 3 211 seats	2.0%	90	99
	**Boeing B737-800** Chapter 3 160 seats	5.1%	86	97
	**Boeing B737-200** Chapter 3 112 seats	0.8%	90	97

Fuel consumption and emission during taxiing operations for the selected three airplanes are summarized in Table 4-4.

Table 4- 4: Emission and fuel burn on different airplanes during taxiing (Cook, Tanner, & Anderson, 2004), (ICAO, 2011)

			Emission (kg/ LTO)			
Aircraft type	**Fuel burn (kg/min)**	**Delay Cost($/min)**	**CO2**	**NOx**	**CO**	**HC**
Boeing 767-300	23.33 (7.72 Gallon)	23.36	5610	28.19	14.47	1.19
Boeing 737-800	15 (4.96 Gallon)	24.82	2780	12.3	7.07	0.72
Airbus A320-200	12 (3.97 Gallon)	39.42	2440	9.01	6.19	0.57

Based on the provided information in table 4-4, we can calculate the fuel cost for different airplanes and use it as a parameter in the objective function of the mathematical model (Jet fuel price in

Canada has been considered 2.77 $/Gallon). Arrival and departure times of flights for a given day is gathered from the airport webpages for one day (Montreal YUL Airport Website.c, 2019) Table 4-5 provides the sample input information for 40 flights. The first column of the table is the ID of each flight. The second column is the type of flight in the system which type 1 is for departing aircraft, and type 2 is for arriving aircraft. V_{in} and V_{out} in the next two columns show the nodes to enter and exit from the system. Here, gates are the entry node for departing aircraft, and the runway is their exit. For arriving aircraft, this is another way around. Tin_f is the scheduled time of departing and arriving for each aircraft, while $Tout_f$ is the entry time plus the taxiing time at the airport. $Early_{in}$ is the earliest time that a flight can enter the taxiway system and is the same as Tin_f . The latest time that a flight can enter the taxiway system is the $Earliest_{in}$ + taxi time. To prevent any infeasibilities, $Latest_{in}$ and $Latest_{out}$ are assumed large enough.

Table 4- 5: Flight Information from YUL airport

Flight ID	Type	V_in	V_out	T_in	T_out	Early_in	Late_in	Early_out	Late_out	Aircraft Size	Delay cost	Fuel cost
1	2	100	7	24	39.5	24	34	38.50	58.50	2	24.82	13.73
2	2	100	1	24	42.7	24	34	39.70	59.70	2	24.82	13.73
3	2	100	6	24	47.9	24	34	38.90	58.90	3	39.42	21.38
4	2	101	4	24	36.0	24	34	34.97	54.97	2	24.82	13.73
5	2	101	9	27	50.2	27	37	41.20	61.20	1	23.36	10.99
6	2	101	15	27	39.1	27	37	39.07	59.07	2	24.82	13.73
7	2	101	13	27	41.5	27	37	38.50	58.50	2	24.82	13.73
8	2	101	10	27	46.0	27	37	38.02	58.02	1	23.36	10.99
9	2	100	5	27	49.1	27	37	42.10	62.10	3	39.42	21.38
10	2	100	10	47	66.0	47	57	61.00	81.00	1	23.36	10.99
11	2	100	6	107	131.9	107	117	121.90	141.90	1	23.36	10.99
12	2	100	15	342	354.9	342	352	354.90	374.90	3	39.42	21.38
13	2	101	16	358	380.2	358	368	370.20	390.20	3	39.42	21.38
14	1	14	101	360	375.9	360	370	371.92	391.92	2	24.82	13.73
15	1	6	100	360	383.9	360	370	374.90	394.90	3	24.82	21.38
16	1	3	100	360	378.4	360	370	375.35	395.35	3	23.36	21.38
17	2	100	12	382	398.6	382	392	395.60	415.60	2	24.82	13.73
18	1	13	100	390	413.5	390	400	403.45	423.45	2	39.42	13.73
19	1	14	100	390	405.0	390	400	403.02	423.02	2	24.82	13.73
20	1	13	101	390	403.5	390	400	401.50	421.50	3	39.42	21.38
21	1	2	101	390	411.3	390	400	401.25	421.25	1	39.42	10.99
22	2	100	16	394	416.8	394	404	406.80	426.80	3	39.42	21.38
23	2	101	16	397	412.2	397	407	409.20	429.20	3	39.42	21.38
24	1	15	100	420	440.9	420	430	432.90	452.90	2	39.42	13.73
25	1	1	100	420	444.7	420	430	435.70	455.70	1	24.82	10.99
26	1	11	101	420	436.2	420	430	431.15	451.15	2	39.42	13.73
27	1	15	100	420	435.9	420	430	432.90	452.90	1	39.42	10.99
28	2	100	16	430	446.8	430	440	442.80	462.80	2	24.82	13.73
29	2	101	6	430	448.6	430	440	440.62	460.62	1	23.36	10.99
30	2	101	7	430	448.4	430	440	440.40	460.40	3	39.42	21.38
31	1	12	101	440	458.3	440	450	451.32	471.32	1	24.82	10.99
32	2	100	3	442	464.4	442	452	457.40	477.40	1	23.36	10.99
33	1	6	100	450	470.9	450	460	464.90	484.90	1	24.82	10.99
34	1	6	101	450	469.6	450	460	460.62	480.62	1	23.36	10.99
35	2	101	12	452	471.3	452	462	463.32	483.32	3	39.42	21.38
36	1	14	101	455	476.9	455	465	466.92	486.92	3	39.42	21.38
37	1	4	101	460	476.0	460	470	470.95	490.95	1	24.82	10.99
38	2	101	11	464	482.2	464	474	475.17	495.17	3	39.42	21.38
39	2	100	11	471	488.8	471	481	484.80	504.80	1	23.36	10.99
40	1	16	101	480	494.2	480	490	492.20	512.20	1	39.42	10.99

4.2 Aircraft Tugs information

Generally, there are two main categories for pushback tugs. The first one is the traditional or conventional towing tugs that connect the airplane to a towing vehicle with a tow bar. Using this kind of towing, tractors require a specific tow bar that fits the type of aircraft. As a result, each time after finishing the towing job, the tow bar should be changed if the type of aircraft is different. The second type of towing tugs is called towbarless tugs that lift the front wheel of the airplane and tow it.

Figure 4- 2: Operation of a conventional towing tug (Trepel.com, 2019)


Figure 4- 3: Operation of a Towbarless towing tug (Ricardo.com, 2011)

Figures 4-2 and 4-3 are examples of traditional and towbarless tugs operation at the airport. Conventional tugs have less initial purchase cost compared to towbarless tugs. However, many advantages come with towbarless tugs that compensate for the extra purchasing cost. For instance;

- Changing the tow bar for conventional tugs is a physical task that increases the risk of injury for operators.
- The taxiing process by towbarless tugs needs less workforce and, consequently, less operation cost.
- Working with twobarless tugs increases the speed of operation.
- Towbarless tugs are more effective since they can work with many types of airplanes.

Also, towbarless tugs are either consuming fossil fuel like diesel and gasoline, or they are electrical. In this work, we are considering electric towbarless tugs that need less maintenance cost, have more speed, and emit fewer greenhouse gasses in comparison to diesel or gasoline-powered towbarless tug options.

To calculate the total energy consumption and emission on the objective function, we need to determine the energy consumption rate and the cost of unit energy (electricity in our case). The fuel price of the pushback tugs depending on the type of tractor can be different. Electric tug's purchase cost is about 30 to 35 percent more than diesel/gasoline tugs (Eagletugs, 2019). However, it should be noted that this is a onetime cost, and an electric tug needs a new battery every few years (It is estimated that Tesla batteries are required to be replaced on average every ten years). Based on (Eagletugs, 2019) An electric tug use between 27.75 and 33.5 kilowatts per day and based on electricity cost, which is 11.85 cents/ kWh in Canada, for 24 hours operation the electricity cost will be around 3.95$.

4.3 Problem-solving strategies

In the following sections, we will introduce different strategies to solve real-life size problems. As we discussed earlier in the introduction chapter, Air Traffic Controllers (ATC) monitor all airplanes during their movement on the ground and in the air to obtain a safe and low-cost flight movement. In this situation, the behavior of each flight depends on the other flights (Centralized model). On the other hand, the Free Flight Concept (FFC) has been defined in which the control of flight is from the cockpit by the pilot, and flights are independent of each other.

First, we will discuss the complex issues related to solving our centralized mathematical model. As such, in most scheduling and sequencing models, the MILP solution to taxiing operations is an NP-Hard problem and difficulty solve optimally for real-life case problems. Consequently, a sequential approach, which is discussed later in section 4.5, has been proposed to overcome the complexity issues.

4.4 Centralized model

In the modeling of airport ground movement, all airplanes in the set F enter the system during a time window. To carry out the airplanes, there is a set of homogeneous towing tractors. In order to minimize delay, if the towing tractor was not available, flights will push by their engines. We run the model for different sizes of flights and towing tractors. The execution time increased by adding more flights to the model. For a typical airport model that includes 16 gates, 52 taxiway intersections, two runways, the proposed centralized solution strategy would not generate a feasible solution in a personal computer. Even when the problem is solved for a subset of vehicles, such as 10 airplanes and 4 towing tractors, after 3 hours of running time, only a 95% optimality gap is achieved.

Table 4-6 shows the sample result of the centralized model for 8 flights and 4 towing tractors. This table indicates the route of each flight, time to enter and exit, and the ID of the towing machine in the case that it is assigned to an aircraft. As can be seen in table 4-6, four of the flights are using towing tractors, and the rest of them are moving without tractors. The execution time for this scenario was 22:35 minutes, with the objective of 610.2.

Table 4-6: Sample Result of Centralized Model

Flight ID	Assign	Tug ID	From Node	To Node	T-in	T-out	Time in System
1			100	48	24	31.21	
1			48	44	31.21	36.43	
1			44	43	36.43	38.52	
1			43	42	38.52	40.95	
1	1	2	42	39	40.95	43.3	29.65
1			39	35	43.3	44.95	
1			35	31	44.95	46.6	
1			31	21	46.6	48.6	
1			21	7	48.6	53.65	
2			100	48	24	31.21	
2			48	44	31.21	36.43	
2			44	43	36.43	38.52	
2			43	42	38.52	40.95	
2	1	4	42	39	40.95	43.3	31.99
2			39	35	43.3	44.95	
2			35	31	44.95	46.6	
2			31	21	46.6	48.6	
2			21	1	48.6	55.95	
3			100	48	24	31.21	
3			48	44	31.21	36.43	
3			44	43	36.43	38.52	
3			43	42	38.52	40.95	
3	1	3	42	39	40.95	43.3	30.76
3			39	35	43.3	44.95	
3			35	31	44.95	46.6	
3			31	21	46.6	48.6	
3			21	6	48.6	54.76	

4			101	50	24	26.33	
4			50	47	26.33	28.33	
4			47	41	28.33	29.33	
4	0	_	41	25	29.33	31.66	10.95
4			25	24	31.66	32.66	
4			24	17	32.66	33.66	
4			17	4	33.66	34.95	
5			101	50	27.81	30.15	
5			50	47	30.15	32.15	
5	0	_	47	41	32.15	33.15	10.85
5			41	25	33.15	35.48	
5			25	24	35.48	36.48	
5			24	9	36.48	37.85	
6			101	50	27	33.08	
6			50	47	33.08	38.3	
6			47	41	38.3	40.91	
6	1	1	41	25	40.91	46.99	28.52
6			25	24	46.99	49.6	
6			24	23	49.6	50.65	
6			23	15	50.65	55.52	
7			101	50	27.53	29.86	
7			50	47	29.86	31.86	
7			47	41	31.86	32.86	
7	0	_	41	25	32.86	35.2	11.5
7			25	24	35.2	36.2	
7			24	17	36.2	37.2	
7			17	13	37.2	38.49	
8			101	50	27	29.33	
8			50	47	29.33	31.33	
8	0	_	47	41	31.33	32.33	11.02
8			41	25	32.33	34.66	
8			25	24	34.66	35.66	
8			24	10	35.66	38.02	

Based on the result from the centralized model for eight flights, Figure 4-4 shows the traveling time on the system for different airplanes.

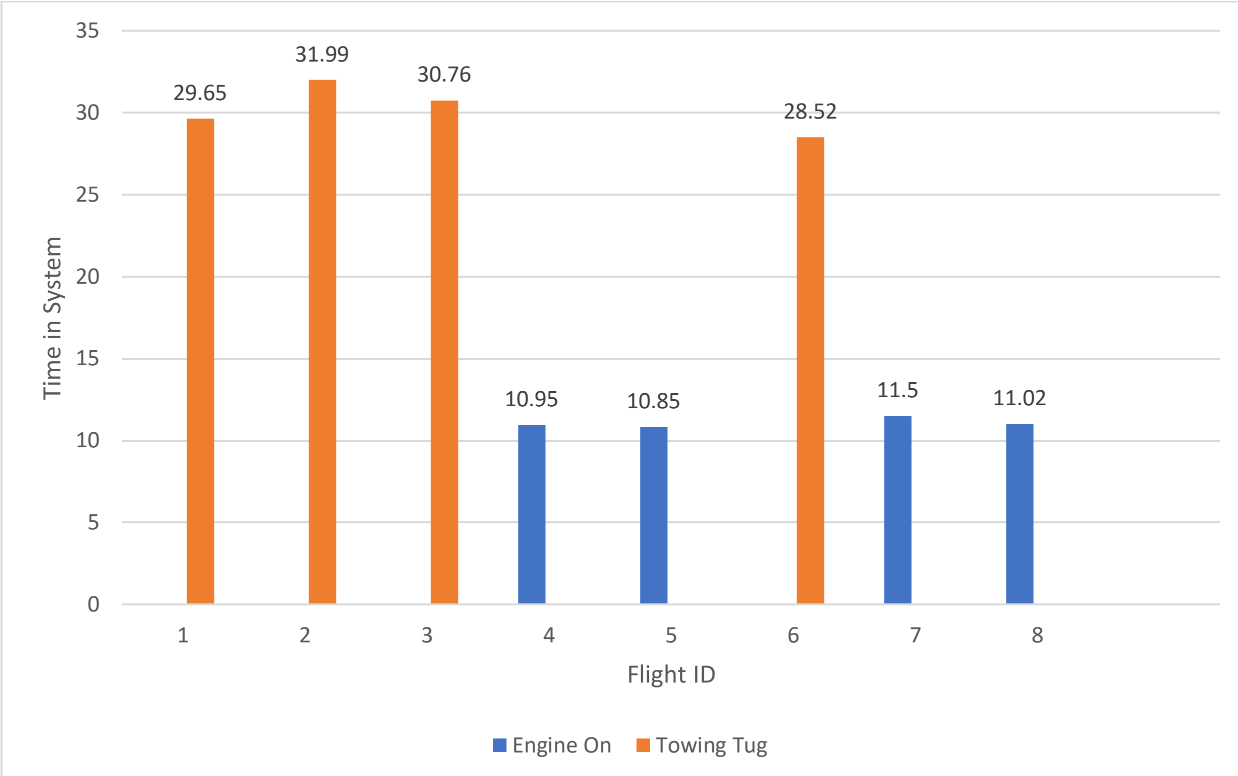


Figure 4-4: Time in the system of towing tractors vs. airplane engine on

4.5 Sequential Taxiing Operations Planning (Free Flight Concept)

Airlines determine its flight schedules based on a number of factors. Foremost essential criteria are the existence of demand. Next, the availability of the air-corridors (the allocation of airport capacity at the departure and arrival airports and in the air during the given time-window). These air-corridors, which correspond to flight-rights, must be acquired by the airline companies. Finally, the availability of resources, such as aircraft, pilots, and flight attendances. Based on these criteria, all airlines prepare a flight schedule that follows a sequential order throughout a day. In our work, we use the flight schedules as determined by the airlines as an input.

Let the flight set F be $F = \{f_1, f_2, \dots, f_F\}$ where arrivals and departures to/from an airport are indexed according to their scheduled arrival or departure times. Given that arrivals and departures are realized during a given day sequentially according to their original schedules, flights are grouped according to their arrival and departure times as $F = \{F_1, F_2, \dots, F_N\}$ where F_j include a subset of flights in F as $\left(F_j = \left\{f_{i+L_{j-1}}, f_{(i+1)+L_{j-1}}, \dots, f_{BS+L_{j-1}}\right\}\right)$,Where L_j is the last flight in F_j , $i = 1$, and subsequently $f_{i+L_{j-1}}$ is the first flight of subset F_j .In addition, BS is the batch size (number of flights in each subset F_j). Earliest flights in F_{j+1} enters the system later than the last flight in F_j. The first departure is realized in the early morning. Since all resources (taxiways, towing vehicles, and runways) are free at the beginning of the day, earlier airplanes do not need to compete for the resources. Later, flights slowly start being affected by the limitations of resources. Finally, at some point during the day, the airport reaches a steady-state operation level, and all are arriving and departing airplanes start competing for limited resources. In the sequential solution strategy, the model is first solved for flights in F_1. A solution for a given flight (s^f) includes the path-plan $\left(x_l^f\right)$, arrival and departure times at each link $\left(a_l^f \text{ and } d_l^f\right)$, the assignment of towing vehicle on a flight $\left(assign_k^f\right)$ and the next assignment for the towing vehicle $\left(gamma_k^{ff'}\right)$. Hence $S^f = \left\{x_l^f, a_l^f, d_l^f\ \forall l \in L: x_l^f = 1;\ assign_k^f\ \forall k \in K;\ gamma_k^{ff'}\ \ \forall k \in K, f' \in F\right\}$. The outcome of the first solution is included in the set $S_1 = \left\{s_1^1, s_1^2, \dots, s_1^f\ \right\}$ is generated for $\forall f \in F_1$. In the consecutive step, flights in F_2 are added to the problem and the new problem is solved for $\forall f \in F_2$ in consideration with the previous information from S_1. By the time flights in F_2 enter the system, some of the resources such as towing vehicles and taxiways are already allocated for airplanes in F_1. Therefore, the information available in S_1 is introduced in the second problem as constraints for flights in F_2. Below flow-chart depicts the overall strategy implemented for the sequential solution method (Figure 4-5).

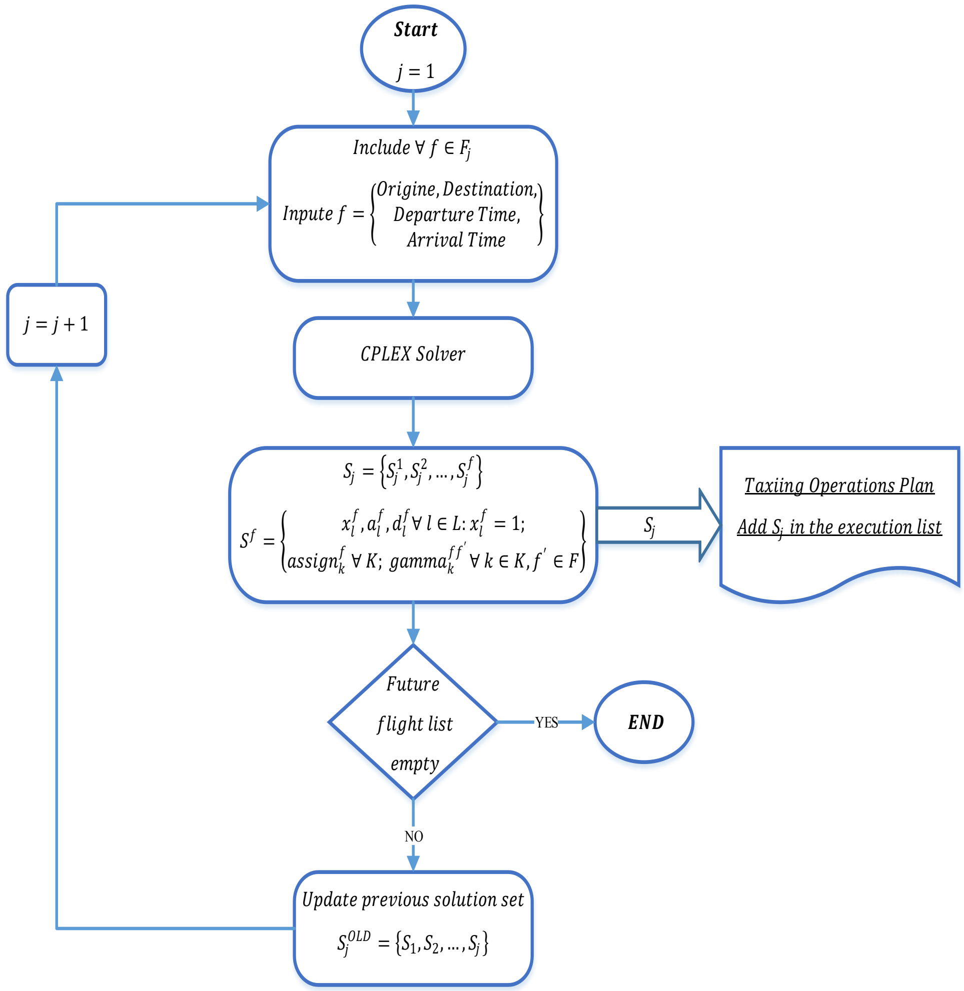


Figure 4- 5: Sequential solution method

4.6 Free Flight Concept (FFC)

In this part, we run the model for 205 flights. In order to demonstrate the traffic conditions in the airport, we summarized the arrival and departure rates in a bar chart by creating 30 minutes intervals, as shown in Figure 4-6. As can be seen, the airport is most active during the day from 5 AM to 5 PM.

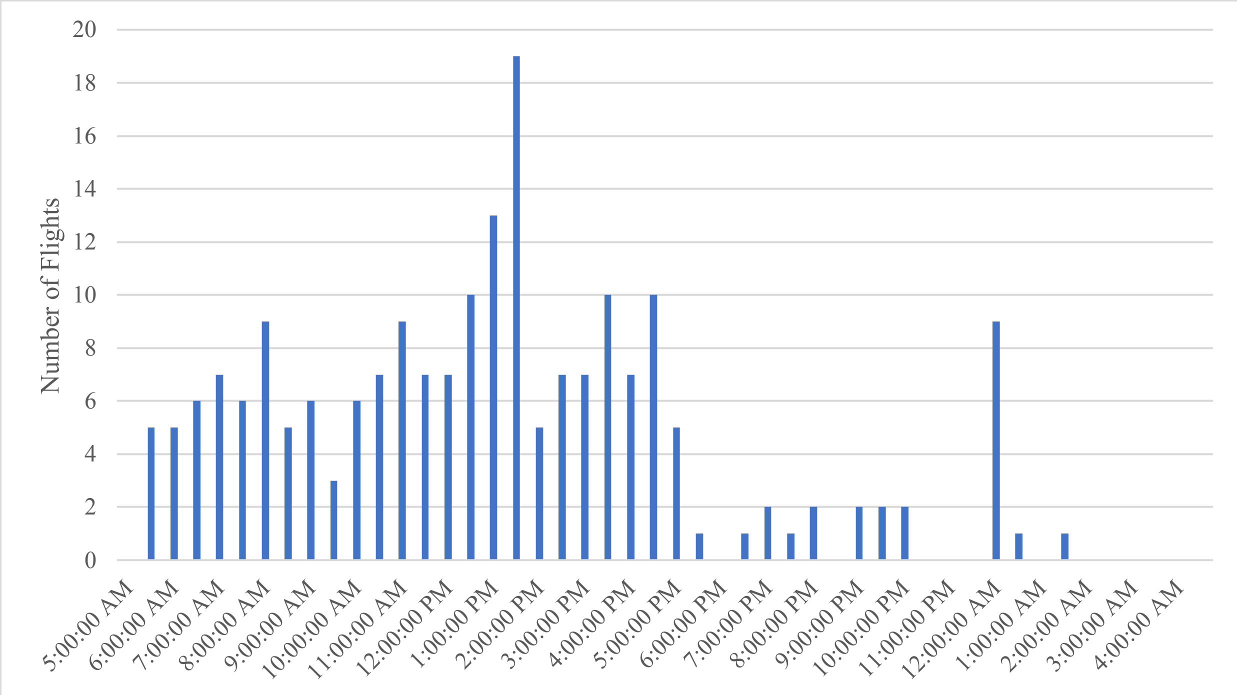


Figure 4-6: Distribution of flights during a day

We have decided to run our mathematical model batch by batch (Sequential Taxiing Operations). In order to know the batch size in our model, we have calculated the average number of flights based on Figure 4-6. Each time, the model will be run with a batch size of five airplanes. Flights are independent of each other, and the model will be solved within a set of constraints. After getting the result for the first batch of flights, the results will be used as an input for the next batch. We run the FFC model for three different scenarios: i) All flights move by towing tractors ii) Hybrid system iii) All Flights move by the engine on, Finally, results will be compared to find the best methodology for moving airplanes on the ground.

4.6.1 Scenario 1: All flights are moved by towing tractors

In this scenario, we force all airplanes to move by a towing tractor. So, in this case, $assign_k^f$ must be equal to 1. We run the model for the different number of towing tractors. After running the model for 205 flights and using only five tractors, we observed a substantial amount of flights are being delayed. As an example, the delay of 40 flights with 5 tugs is provided in table 4-7. As expected, when the number of towing vehicles is increased, delay times are decreased. However, increasing the number of towing vehicles will require a substantial amount of fixed and variable investment. Hence, the decision must be made not only based on the delay reduction but also on its impact on the overall finances of involved parties.

Table 4- 7: Sample result of delayed flights in S.c1

F ID	Tug ID	Assign	time in system	delay(min)	Delay cost($/min)	Total delay cost
6	4	1	52.83	35.08	24.82	$870.69
7	2	1	56.77	44.27	24.82	$1,098.88
8	1	1	52.48	38.11	23.36	$890.26
9	5	1	58.09	39.14	39.42	$1,542.93
10	3	1	36.03	2.03	23.36	$47.33
17	2	1	34.09	0.47	24.82	$11.59
19	2	1	55.01	30.26	24.82	$751.02
21	3	1	65.03	52.98	39.42	$2,088.32
25	1	1	59.60	29.50	24.82	$732.19
26	4	1	64.58	53.06	39.42	$2,091.57
27	2	1	78.51	77.52	39.42	$3,055.76
28	2	1	41.55	13.81	24.82	$342.69
29	5	1	49.33	31.78	23.36	$742.40
31	1	1	94.97	113.20	24.82	$2,809.67
32	3	1	45.03	12.70	23.36	$296.72
33	5	1	61.09	35.51	24.82	$881.35
34	3	1	65.06	55.24	23.36	$1,290.42

35	1	1	55.01	41.29	39.42	$1,627.60
36	4	1	87.57	95.86	39.42	$3,778.94
37	3	1	110.97	145.69	24.82	$3,616.13
38	4	1	47.54	26.97	39.42	$1,063.26
39	2	1	55.60	39.31	23.36	$918.35
40	2	1	78.23	76.15	39.42	$3,001.74
41	1	1	79.53	92.80	39.42	$3,657.99
42	4	1	74.13	82.00	39.42	$3,232.33
43	5	1	44.04	19.98	23.36	$466.79
44	1	1	96.81	115.34	24.82	$2,862.81
45	5	1	71.50	66.26	24.82	$1,644.69
46	2	1	80.63	92.54	23.36	$2,161.75
47	2	1	107.72	135.14	24.82	$3,354.15
48	5	1	118.32	146.95	24.82	$3,647.20
49	3	1	121.41	153.77	23.36	$3,592.09
50	4	1	83.09	84.82	23.36	$1,981.30
51	2	1	158.16	227.27	39.42	$8,958.87
52	1	1	84.98	102.94	24.82	$2,554.97
53	1	1	106.35	133.41	23.36	$3,116.34
54	4	1	120.21	161.13	39.42	$6,351.74
55	4	1	70.63	71.97	39.42	$2,836.86
56	3	1	102.76	127.95	39.42	$5,043.63
57	5	1	118.332	161.783	23.36	$3,779.25

In the next step, we increased the number of towing tractors in the system to observe their impact on the performance of taxi operations. Table 4-8 shows that adding more aircraft tugs to the system, decrease the number of flights with delay, total delay, and total cost of delay.

Table 4- 8: Comparing delay with the number of tugs

Number of Tugs	Number of delayed flights	Total delay(min)	total delay cost (Dollars)
5	188	88173.72	$2,593,109.85
6	184	45856.76	$1,341,325.96

7	143	24078.56	$710,958.10
8	117	15259.15	$443,955.89
9	98	9272.69	$266,044.50
10	85	5169.52	$144,242.55
12	46	1506.80	$38,872.89
15	23	477.03	$12,064.77
18	9	144.99	$3,502.89
20	8	87.00	$2,100.56

In this scenario, our final decision is a trade-off between the cost of adding more tractors and delay costs. Figure 4-7 shows that adding towing tractors to the system results in fewer delays. To see which of these sub-scenarios in the long term is more economical, we will compare the cost of adding tractors with the cost of delay.

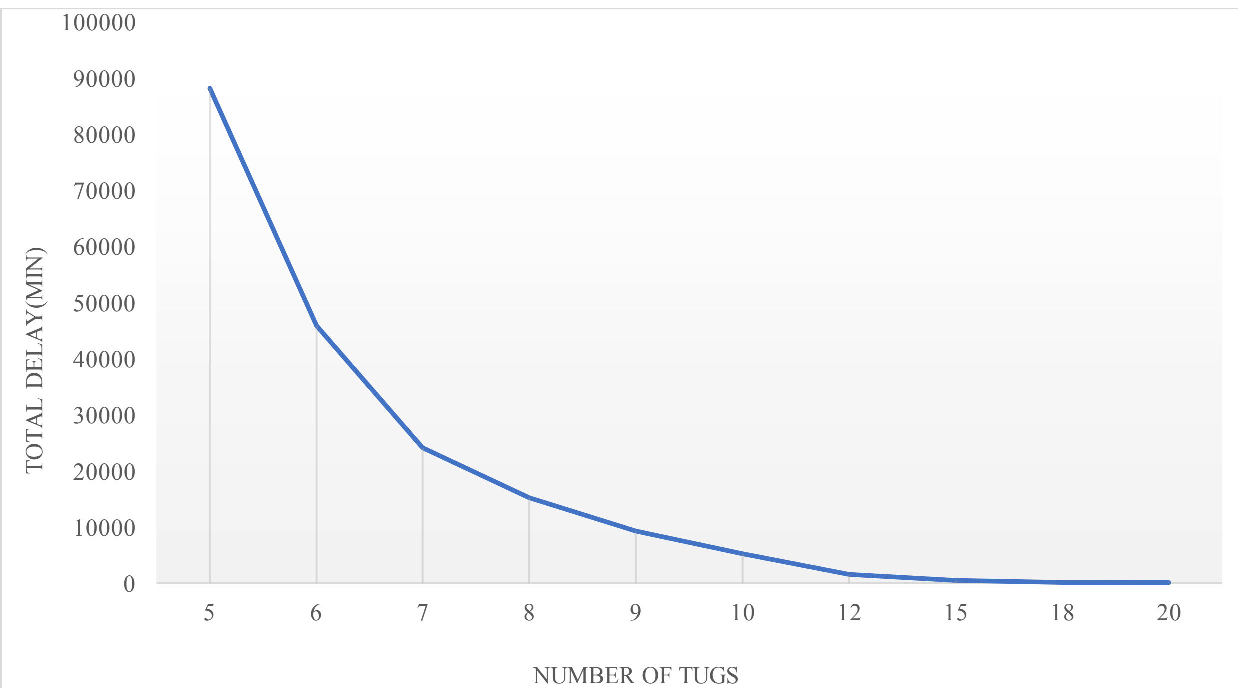


Figure 4-7: Relationship between delay and number of tugs

For aircraft tugs, we have purchase, operation, and fuel (energy) costs. We were not able to find the exact price of new towing tractors from selling companies. Based on (Alibaba, 2019) The cost of buying a diesel towing tractor is around 100k and for a new one around 600k, and as we discussed in section 4.2, electric tugs purchase cost is about 30 to 35 percent more than diesel/gasoline tugs. So, we have assumed buying a new electric towing tractor, costs around 800K. Besides, airplanes are departing and arriving from 12 AM to 11.30 PM, so there are two working shifts, and in each shift, two persons are working on one towing tractor. Assume that the salary of each worker is 40K per year.

Based on the gathered information, we have run the model for 205 flights and each time with a different number of tugs to calculate the energy and delay cost. Table 4-9 shows the average and total flight time in the system versus the number of aircraft tugs. As shown in this table, a higher number of tugs means less time in the system for flights, which causes less energy cost.

Table 4- 9: Relationship between energy cost and number of tugs

Number of Tugs	Average Time in the system(min)	Total Time in the system(min)	Energy cost(dollars)
5	274.19	56,208.35	$154.57
6	146.56	30,044.44	$82.62
7	94.21	19,312.04	$53.11
8	69.58	14,263.78	$39.23
9	54.31	11,133.03	$30.62
10	43.90	9,000.47	$24.75
12	33.56	6,879.41	$18.92
15	30.16	6,183.03	$17.00
18	28.89	5,922.99	$16.29
20	28.70	5,883.60	$16.18

In table 4-10, we provide a summary of cost analysis for seven years. In this table, we calculated the cost of purchasing and operating tugs, the cost of delays and cost of fuel consumption, as well as the total cost of performing taxiing operations.

Table 4- 10: Costs of operation for 7 years S.c1 (dollars)

Number of Tugs	Number of workers	Purchase cost	Energy cost(dollars)	operation cost	Total Tug Costs	total delay cost (Dollars)	Total cost
5	20	$4,000,000.0	$394,933.9	$5,599,538.0	$9,994,471.9	$6,625,395,694.5	$6,635,390,166.4
6	24	$4,800,000.0	$211,099.8	$6,719,445.6	$11,730,545.4	$3,427,087,808.6	$3,438,818,353.9
7	28	$5,600,000.0	$135,691.2	$7,839,353.2	$13,575,044.4	$1,816,497,933.5	$1,830,072,977.9
8	32	$6,400,000.0	$100,220.9	$8,959,260.8	$15,459,481.7	$1,134,307,297.5	$1,149,766,779.2
9	36	$7,200,000.0	$78,223.5	$10,079,168.4	$17,357,391.9	$679,743,708.4	$697,101,100.3
10	40	$8,000,000.0	$63,239.5	$11,199,076.0	$19,262,315.5	$368,539,732.9	$387,802,048.5
12	48	$9,600,000.0	$48,336.5	$13,438,891.2	$23,087,227.7	$99,320,242.2	$122,407,469.9
15	60	$12,000,000.0	$43,443.5	$16,798,614.0	$28,842,057.5	$30,825,480.5	$59,667,538.0
18	72	$14,400,000.0	$41,616.4	$20,158,336.8	$34,599,953.2	$8,949,886.6	$43,549,839.8
20	80	$16,000,000.0	$41,339.6	$22,398,152.0	$38,439,491.6	$5,366,922.1	$43,806,413.7

In addition, to see the pattern of cost changing, we have provided Figure 4-8. By checking the delay cost, we can see that adding more tugs to the system, leads to less delay cost. Therefore, as it is illustrated in Table 4-10, the total cost is decreasing by adding more tugs to the system, but after 18 tugs, the cost will increase again. In this case, having more than 18 tugs is not economical anymore. So, the best number of tugs in this scenario will be 18 tugs in order to minimize the total cost.

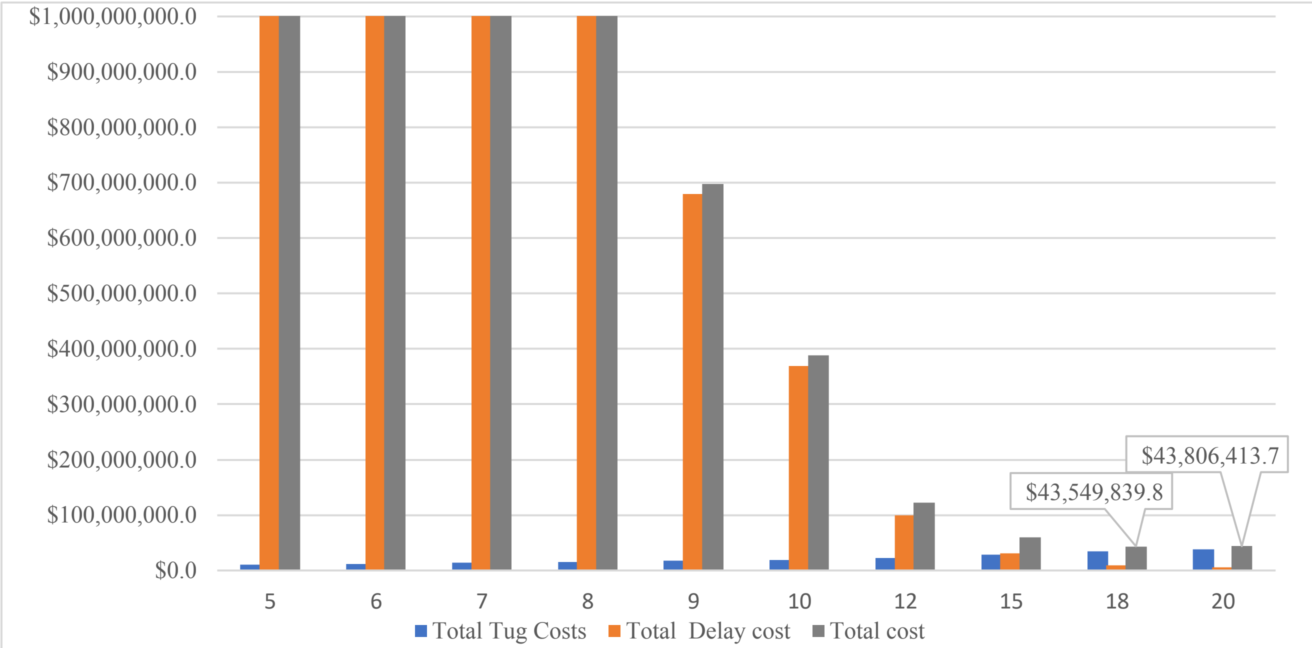


Figure 4- 8: Relationship between the delay cost and the tug cost with the number of tugs

4.6.2 Scenario 2: Hybrid system: Flights have the option to us towing tractor

In this scenario, the model decides if a flight is towed by a towing tractor or its engines push it. The decision is made based on two major factors: i) the availability of towing tractors, and ii) the size of the airplane, which impacts the fuel consumption rate. We run the model for the different number of towing tractors to see how many flights use towing tractors and how many of them move by their engines. Consequently, we calculate the costs and emission rates for each scenario for further assessment.

The following Table 4-11 is the sample results of the running model with six towing tractors. In this scenario, out of 205 flights, 60 of them use their engines for taxing, and the remaining 145 airplanes are assigned to these six towing tractors. As an example, flight number 1 is assigned to tug number 5 and starts its taxing from runway 100 and goes through the following path: 100 →

$48 \rightarrow 44 \rightarrow 43 \rightarrow 42 \rightarrow 39 \rightarrow 35 \rightarrow 31 \rightarrow 21 \rightarrow 7$ and finish its taxing after 29.7 minutes without any delay.

Table 4- 11: Sample result of 6 tugs S.c.2

Flight ID	Arc ID	From	To	Tin	Tout	Tug ID	Assign	Time in the system (Tug)	Time in the system (engine on)	Delay
1	54	21	7	48.6	53.7	5	1	29.7	0	0
	172	31	21	46.6	48.6	5	1	29.7	0	0
	198	35	31	45.0	46.6	5	1	29.7	0	0
	210	39	35	43.3	45.0	5	1	29.7	0	0
	222	42	39	41.0	43.3	5	1	29.7	0	0
	230	43	42	38.5	41.0	5	1	29.7	0	0
	234	44	43	36.4	38.5	5	1	29.7	0	0
	238	48	44	31.2	36.4	5	1	29.7	0	0
	252	100	48	24.0	31.2	5	1	29.7	0	0
2	4	21	1	48.6	56.0	3	1	32.0	0	0
	172	31	21	46.6	48.6	3	1	32.0	0	0
	198	35	31	45.0	46.6	3	1	32.0	0	0
	210	39	35	43.3	45.0	3	1	32.0	0	0
	222	42	39	41.0	43.3	3	1	32.0	0	0
	230	43	42	38.5	41.0	3	1	32.0	0	0
	234	44	43	36.4	38.5	3	1	32.0	0	0
	238	48	44	31.2	36.4	3	1	32.0	0	0
	252	100	48	24.0	31.2	3	1	32.0	0	0
3	44	21	6	48.6	54.8	4	1	30.8	0	0
	172	31	21	46.6	48.6	4	1	30.8	0	0
	198	35	31	45.0	46.6	4	1	30.8	0	0
	210	39	35	43.3	45.0	4	1	30.8	0	0
	222	42	39	41.0	43.3	4	1	30.8	0	0
	230	43	42	38.5	41.0	4	1	30.8	0	0
	234	44	43	36.4	38.5	4	1	30.8	0	0
	238	48	44	31.2	36.4	4	1	30.8	0	0
	252	100	48	24.0	31.2	4	1	30.8	0	0
4	26	17	4	49.2	51.3	6	1	27.3	0	0
	154	24	17	46.6	49.2	6	1	27.3	0	0
	178	25	24	44.0	46.6	6	1	27.3	0	0
	182	41	25	37.9	44.0	6	1	27.3	0	0
	228	47	41	35.3	37.9	6	1	27.3	0	0
	246	50	47	30.1	35.3	6	1	27.3	0	0
	254	101	50	24.0	30.1	6	1	27.3	0	0

5	80	24	9	49.6	53.2	2	1	26.2	0	0
	178	25	24	47.0	49.6	2	1	26.2	0	0
	182	41	25	40.9	47.0	2	1	26.2	0	0
	228	47	41	38.3	40.9	2	1	26.2	0	0
	246	50	47	33.1	38.3	2	1	26.2	0	0
	254	101	50	27.0	33.1	2	1	26.2	0	0
6	140	23	15	36.1	39.1	Engine on	0	0.0	12.07	0
	176	24	23	35.7	36.1	Engine on	0	0.0	12.07	0
	178	25	24	34.7	35.7	Engine on	0	0.0	12.07	0
	182	41	25	32.3	34.7	Engine on	0	0.0	12.07	0
	228	47	41	31.3	32.3	Engine on	0	0.0	12.07	0
	246	50	47	29.3	31.3	Engine on	0	0.0	12.07	0
	254	101	50	27.0	29.3	Engine on	0	0.0	12.07	0
7	120	23	13	36.1	38.5	Engine on	0	0.0	11.5	0
	176	24	23	35.7	36.1	Engine on	0	0.0	11.5	0
	178	25	24	34.7	35.7	Engine on	0	0.0	11.5	0
	182	41	25	32.3	34.7	Engine on	0	0.0	11.5	0
	228	47	41	31.3	32.3	Engine on	0	0.0	11.5	0
	246	50	47	29.3	31.3	Engine on	0	0.0	11.5	0
	254	101	50	27.0	29.3	Engine on	0	0.0	11.5	0
8	88	23	10	37.2	38.0	Engine on	0	0.0	11.02	0
	176	24	23	35.7	37.2	Engine on	0	0.0	11.02	0
	178	25	24	34.7	35.7	Engine on	0	0.0	11.02	0
	182	41	25	32.3	34.7	Engine on	0	0.0	11.02	0
	228	47	41	31.3	32.3	Engine on	0	0.0	11.02	0
	246	50	47	29.3	31.3	Engine on	0	0.0	11.02	0
	254	101	50	27.0	29.3	Engine on	0	0.0	11.02	0

Figure 4-9 shows the usage of towing tractors and airplanes engine on, during the day. As can be seen, from 5 am until 5:30 pm. 125 flights are using towing tractors for taxing, which is 60% of all flights during the day. This rate for a flight with an airplane engine is 27%. The most significant number of flights moving with the engine on is from 1:30 pm to 2:00 pm which is the rush hour of YUL airport during the day. After 5:30 pm we have 24 flights that only 3 of them are using an airplane engine for taxing.

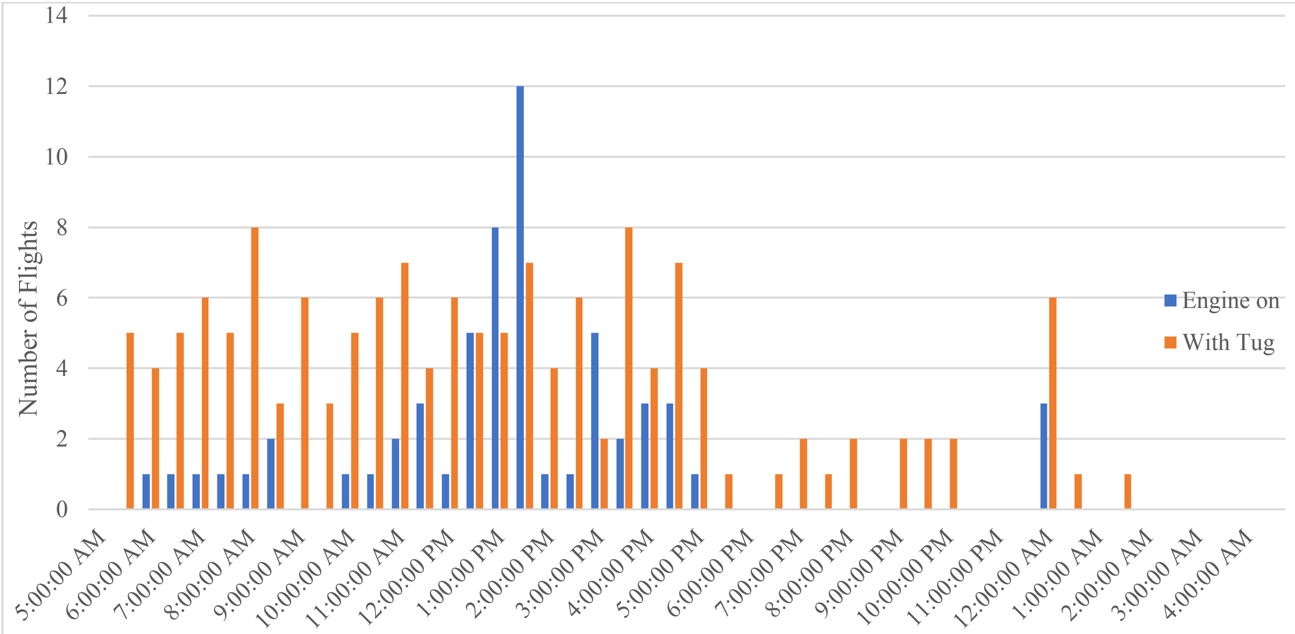


Figure 4- 9: Movement pattern with 6 Tugs

Below there are the results of running the model for 9 and 12 towing tractors (Figures 4-9 and 4-10). As indicated, by adding only 3 other towing tractors to the system each time, the number of flights using their engine to move decreases from 28% with 6 tugs to 9% and 6%, respectively, with 9 and 12 tugs.

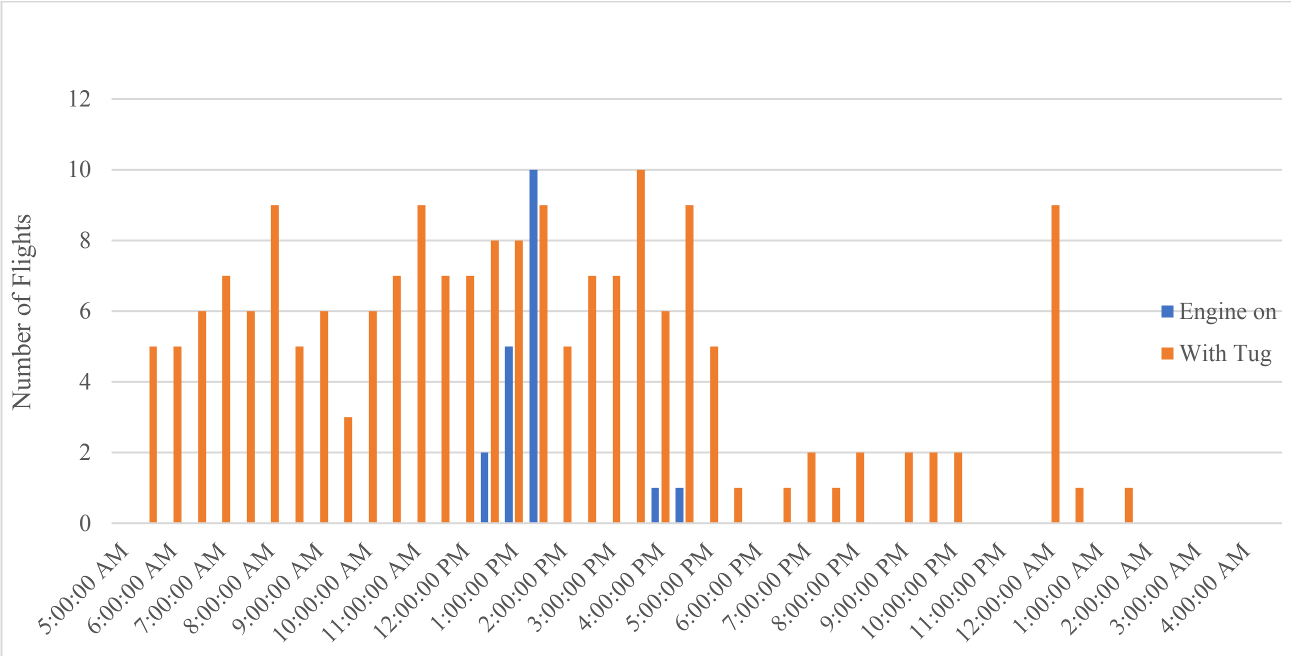


Figure 4- 10: Movement pattern with 9 Tugs

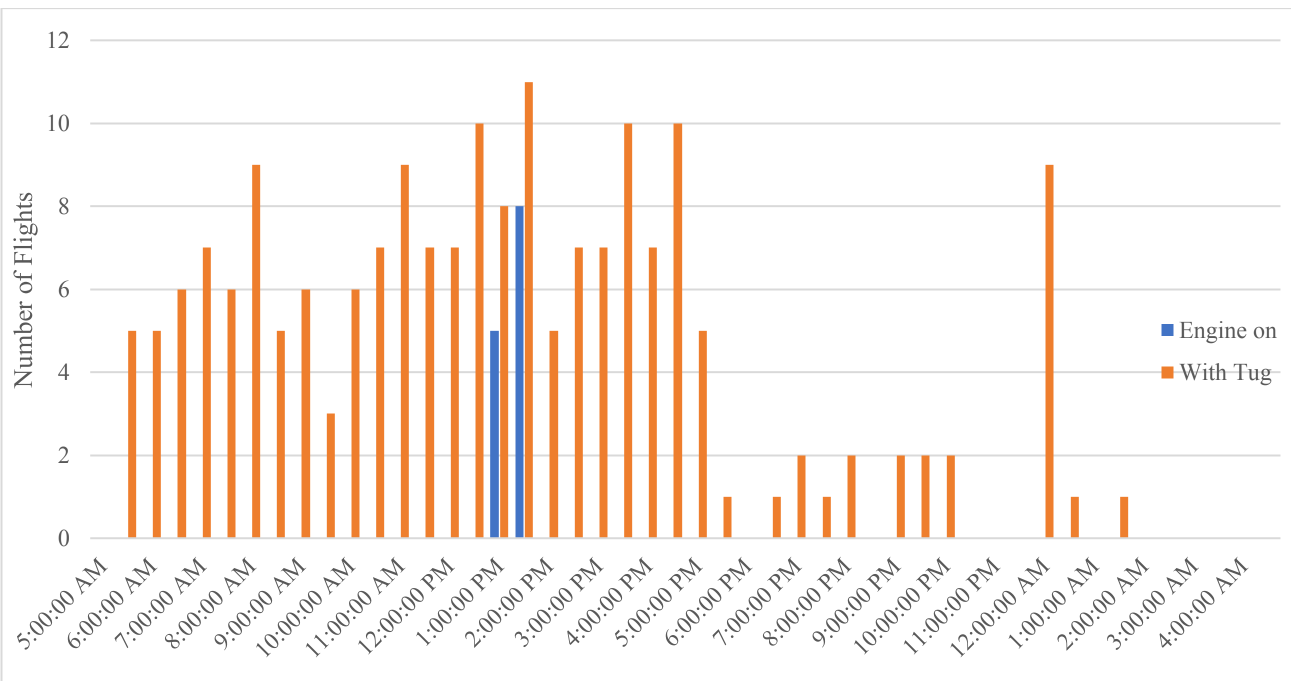


Figure 4- 11: Movement pattern with 12 Tugs

Figure 4-12 shows out of all 205 flights during the day, how many airplanes are using their engine for taxing. As it is clear, from 12 pm to 3:30 pm, we have most numbers of movements through the engine. Also, by adding more towing tugs to the system, the model chose fewer flights to use their engine to move.

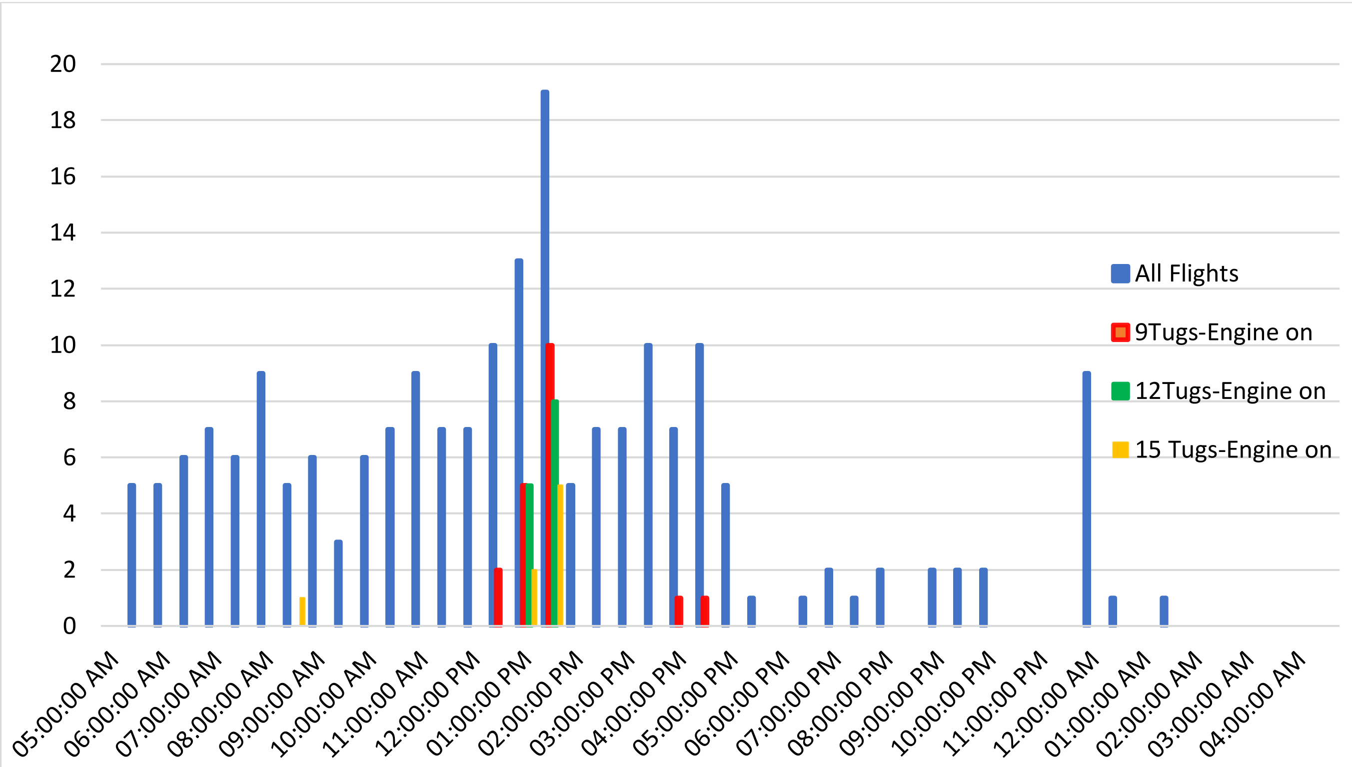


Figure 4- 12: Movement pattern with different number of Tugs during rush hours

In the case that flights using their engine on to move, we have the emission from airplane engines. In part 4.1, we indicated the emission for each type of airplane. Figure 4-13 shows the emission with 6 tugs and 205 flights as an example.

Here we have;

Total CO_2 emission from airplane engine= 258,600 kg

Total NO_x emission from airplane engine= 1,235.49 kg

Total CO emission from airplane engine = 664.36 kg

Total HC emission from airplane engine = 57.23 kg

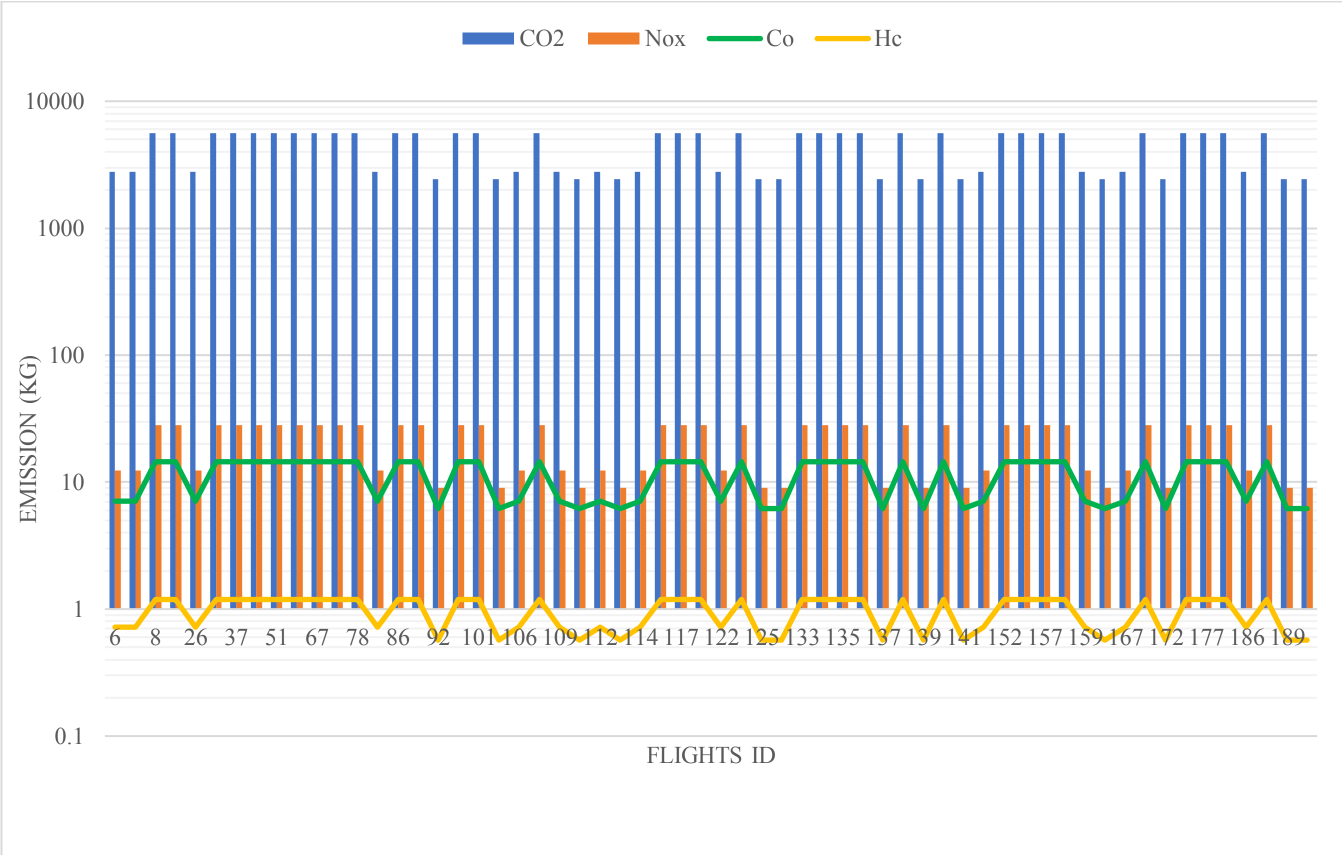


Figure 4- 13: Amount of emissions with 6 Tugs

As it is illustrated in Figure 4-13, the amount of CO_2 gas emission is notably higher than other gases.

In order to compare the effect of the different number of tugs on costs and emission, we need to calculate these costs for long term operation, which in this case we are considering seven years as the lifetime of a new pushback tug. To start, we have provided table 4-12 that shows different costs in a one-day operation per different sub-scenarios. Here, purchase cost and operation cost are the same as scenario one. All the costs are based on 1-day operations at the airport. In this case, we are not considering the cost of purchasing a new tug, but it will be considered in a long-term view. Fuel and delay cost is gathered from the results of the mathematical model. For carbon cost, as we explained in the introduction chapter, for releasing each tonne of CO_2, there is a 20$ tax penalty, and each year there is a 10$ increase in carbon tax. Also, we performed the same analysis for the duration of one year to operate an airport. Table 4-13 illustrates the mentioned costs for one year, and it is showing that when the number of towing tractors is increased, the operating cost increases yet, the fuel and other emission-related costs are decreased.

Table 4- 12: Costs of operation for 1 day

		6 Tugs	9 Tugs	11 Tugs	12 Tugs	15 Tugs	18 Tugs	20 Tugs
Tug Costs	purchase cost	$4,800,000.0	$7,200,000.0	$8,800,000.0	$9,600,000.0	$12,000,000.0	$14,400,000.0	$16,000,000.0
	operation cost	$2,629.9	$3,944.9	$4,821.5	$5,259.8	$6,574.8	$7,889.8	$8,766.4
	Energy cost	$12.2	$15.2	$14.8	$15.2	$15.5	$15.4	$15.5
	delay cost	$3,499.7	$2,940.9	$503.6	$789.9	$736.4	$285.8	$9.1
	Total Cost	$6,141.8	$6,900.9	$5,339.9	$6,065.0	$7,326.7	$8,191.0	$8,791.0
Airplane Costs	fuel cost	$10,422.2	$3,410.6	$2,918.6	$2,430.6	$1,280.0	$1,255.6	$895.3
	CO_2 (kg)	258600	88200	74200	51760	36050	30100	24830
	NO_x(kg)	1235.49	423.52	354.84	242.08	174.56	143.08	118.18
	CO (kg)	664.36	226.68	190.67	132.79	92.68	77.33	63.74
	HC (kg)	57.23	19.44	15.89	11.58	7.96	6.62	5.58
	Carbon Tax ($)	$5,172.0	$1,764.0	$1,484.0	$1,035.2	$721.0	$602.0	$496.6
	Total Cost	$15,594.2	$5,174.6	$4,402.6	$3,465.8	$2,001.0	$1,857.6	$1,391.9

Table 4-13: Costs of operation for 1 Year

		6 Tugs	9 Tugs	11 tugs	12 Tugs	15 Tugs	18 Tugs	20 Tug
Tug Costs	purchase cost	$4,800,000	$7,200,000	$8,800,000	$9,600,000	$12,000,000	$14,400,000	$16,000,000
	operation cost	$959,920.8	$1,439,881.2	$1,759,854.8	$1,919,841.6	$2,399,802.0	$2,879,762.4	$3,199,736.0
	Energy cost	$4,468.8	$5,540.6	$5,400.8	$5,544.8	$5,673.5	$5,636.2	$5,668.2
	delay cost	$1,277,383.0	$1,073,418.5	$183,810.5	$288,324.8	$268,775.1	$104,331.6	$3,317.9
	Total Cost	$2,241,772.6	$2,518,840.4	$1,949,066.1	$2,213,711.2	$2,674,250.6	$2,989,730.2	$3,208,722.0
Airplane Costs	fuel cost	$3,804,099.8	$1,244,881.2	$1,065,289.5	$887,185.6	$467,199.9	$458,276.4	$326,770.0
	CO2 (kg)	94389000	32193000	27083000	18892400	13158250	10986500	9062950
	NOx(kg)	450953.85	154584.8	129516.6	88359.2	63714.4	52224.2	43135.7
	CO (kg)	242491.4	82738.2	69594.55	48468.35	33828.2	28225.45	23265.1
	HC (kg)	20888.95	7095.6	5799.85	4226.7	2905.4	2416.3	2036.7
	Carbon Tax ($)	$1,887,780.0	$643,860.0	$541,660.0	$377,848.0	$263,165.0	$219,730.0	$181,259.0
	Total Cost	$5,691,879.8	$1,888,741.2	$1,606,949.5	$1,265,033.6	$730,364.9	$678,006.4	$508,029.0

Finally, in Table 4-14, cost breakdowns for the 7 years of operations are summarized. As illustrated, we have the highest cost when only 6 towing tugs are operating and the least cost by using 12 towing costs.

As a result, airport and airline authorities would benefit most if they provide taxing services with 12 towing tractors in service.

Table 4-14: Costs of operation for 7 Years

		6 Tugs	9 Tugs	11 tugs	12 Tugs	15 Tugs	18 Tugs	20 Tugs
Tug Costs	purchase cost	$4,800,000	$7,200,000	$8,800,000	$9,600,000	$12,000,000	$14,400,000	$16,000,000
	operation cost	$6,719,446	$10,079,168	$12,318,984	$13,438,891	$16,798,614	$20,158,337	$22,398,152
	Energy cost	$31,281	$38,784	$37,806	$38,813	$39,714	$39,453	$39,677
	delay cost	$8,941,681	$7,513,930	$1,286,673	$2,018,274	$1,881,425	$730,321	$23,225

	Total Cost	$20,492,408	$24,831,883	$22,443,463	$25,095,978	$30,719,754	$35,328,112	$38,461,054
Airplane Costs	**fuel cost**	$26,628,699	$8,714,168	$7,457,027	$6,210,299	$3,270,400	$3,207,935	$2,287,390
	CO2 (kg)	660723000	225351000	189581000	132246800	92107750	76905500	63440650
	NOx(kg)	3156676.95	1082093.6	906616.2	618514.4	446000.8	365569.4	301949.9
	CO (kg)	1697439.8	579167.4	487161.85	339278.45	236797.4	197578.15	162855.7
	HC (kg)	146222.65	49669.2	40598.95	29586.9	20337.8	16914.1	14256.9
	Carbon Tax ($)	$33,036,150	$11,267,550	$9,479,050	$6,612,340	$4,605,388	$3,845,275	$3,172,033
	Total Cost	$59,664,849	$19,981,718	$16,936,077	$12,822,639	$7,875,787	$7,053,210	$5,459,423
	Sum of costs	$80,157,257	$44,813,601	$39,379,540	$37,918,618	$38,595,541	$42,381,321	$43,920,477

4.6.3 Scenario 3: All Flights move by the engine on

In this scenario, we force all airplanes to move by their engine, so in this case, $assign_k^f$ must be equal to 0 for all flights. We run the model for 205 flights without considering any towing tractors in the system. In this case, flights will reach from gate to runway or runway to the gates much faster than previously discussed two cases. Moreover, we observe that, under normal working conditions, we did not realize delay related costs. The major drawback of this policy in comparison to the previous two cases is the consumption of substantially more fuel and consequently emit more greenhouse gasses. Table 4-15 shows a sample result for this scenario. For instance, in this scenario, flight number one, is moving through the same path that we mentioned in scenario 2 when it was taxiing by a tug, however here the taxiing time is reduced by 51 % from 29.7 to 14.5 minutes.

Table 4- 15: Sample Result of S.c.3

Flight ID	Arc ID	from	to	Tin	Tout	Time in system
1	54	21	7	33.43	38.5	14.5
	172	31	21	32.66	33.43	
	198	35	31	32.03	32.66	
	210	39	35	31.4	32.03	
	222	42	39	30.5	31.4	
	230	43	42	29.56	30.5	
	234	44	43	28.76	29.56	
	238	48	44	26.76	28.76	
	252	100	48	24	26.76	
2	4	21	1	36.63	39.7	15.7
	165	20	21	34.76	36.63	
	168	30	20	34	34.76	
	194	34	30	33.33	34	
	206	38	34	32.26	33.33	
	220	42	38	31	32.26	
	232	45	42	28.9	31	
	240	49	45	26.83	28.9	
	250	51	49	24.66	26.83	
	256	100	51	24	24.66	
3	44	21	6	36.54	38.9	14.9
	172	31	21	35.77	36.54	
	198	35	31	35.14	35.77	
	210	39	35	34.50	35.14	
	222	42	39	33.60	34.50	
	232	45	42	28.9	33.60	
	240	49	45	26.83	28.9	
	250	51	49	24.66	26.83	
	256	100	51	24	24.66	
4	26	17	4	34.6	35.4	11.4
	154	24	17	33.6	34.6	
	178	25	24	32.6	33.6	
	182	41	25	30.26	32.6	
	228	47	41	29.26	30.26	
	241	46	47	28.1	29.26	
	244	52	46	26.1	28.1	
	258	54	52	24.66	26.1	
	260	101	54	24	24.66	

5	74	21	9	39.7	41.2	14.2
	172	31	21	38.93	39.7	
	196	32	31	35.66	38.93	
	200	33	32	35.16	35.66	
	202	36	33	34.66	35.16	
	214	40	36	34	34.66	
	226	46	40	31.1	34	
	244	52	46	29.1	31.1	
	258	54	52	27.66	29.1	
	260	101	54	27	27.66	

In addition, we have provided the number of emissions of greenhouse gasses and related costs under the condition of scenario three in Figure 4-14 and Table 4-16. As it is shown in the figure, the amount of emission for all gasses has jumped significantly. For instance, the average CO2 emission in scenario three is 3690 kg for a one-day operation, which, in comparison to scenario two, by using only 6 tugs, this number drops by 65% to 1261 kg. This comparison has proven the value of using towing tugs in such operations from an environmental point of view.

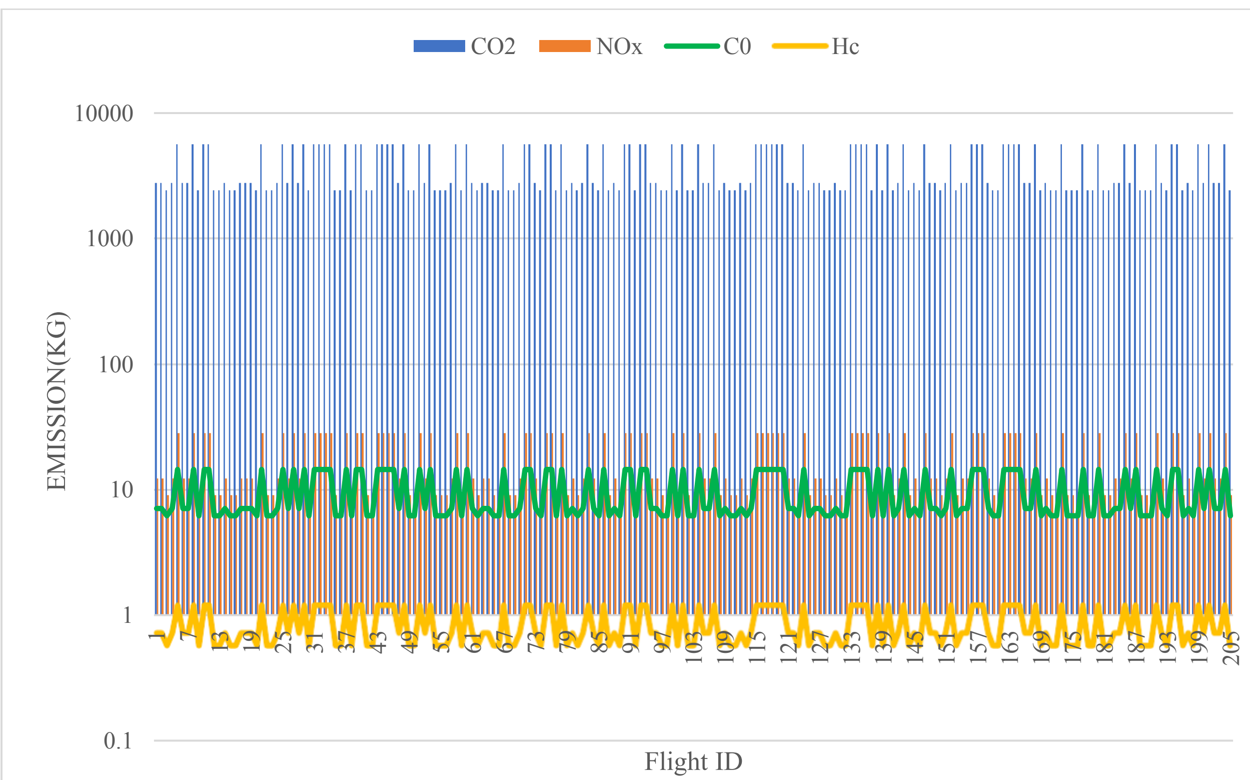


Figure 4- 14: Emission of moving all airplanes by their engine

Table 4- 16: Costs of operation by moving with an airplane engine

	1 Day	1 Year	7 Year
Fuel cost $	$41,059.13	$14,986,580.90	$104,906,066.32
CO2 (kg)	756650	276177250	1933240750
NOx (kg)	3466.5	1265272.5	8856907.5
CO (kg)	1938.35	707497.75	4952484.25
HC (kg)	171.6	62634	438438
Carbon Tax $	$15,133.00	$5,523,545.00	$96,662,037.50
Total Cost $	$56,192.13	$20,510,125.90	$201,568,103.82

Now let's compare the cost of two latest scenarios for 7 years operation. As was mentioned before, in a hybrid system scenario, between all sub-scenarios, the most economical one was using 12 tugs for the long term. The results of the comparison between this sub-scenario and scenario three show that having a hybrid system would lead to a 79% saving in total cost.

As a result, it was proven that using an airplane engine for ground movement is not only detrimental to the environment but also not economical.

4.6.4 Summary of Experimental Works

Table 4-17 and Figure 4-15 shows the summary result of all three scenarios together. As can be seen in Scenario one, among all sub-scenarios, the optimal number of towing tractors is 18 tugs, and after that, we have an increase in the total cost. Also, in scenario two, by 12 towing tugs, we can have the best solution, and buying more tugs is not economical anymore. For the last scenario in which all the airplanes are moving by using their engines, we have the highest total cost and it is not an optimal way of moving airplanes on the ground. So, just by considering scenario one (all move by tug) and two (hybrid system), we can see that the fuel cost of scenario two is more than the first scenario, and the reason is that some of the flights use their engine to move. On the other hand, in the second scenario, if towing tractors are not available, in order to minimize the total delay, the airplane will be pushed by running their own engines, which results in less delay cost compared to the first scenario. Another difference between these two scenarios is the emission cost. In the first scenario, the emission is assumed to be zero because all planes use electric-powered towing tugs to complete their taxiing operations. Besides, the second scenario leads to emission due to airplane engine usage during taxiing.

While the first scenario may be more beneficial to the environment, it may not be the most attractive solution to airline companies and airport authorities (companies) due to its cost. On the other hand, our model suggests that an acceptable solution that is both economically viable and has the potentials to reduce greenhouse gas emissions significantly during the taxiing phase can be achieved through the proposed hybrid operations model.

Table 4- 17: The Summary result of all Strategies

	Scenario 1 (18 Tugs)	Scenario 2 (12 Tugs)	Scenario 3 (Engine On)
Fuel Cost	_	$6,210,299.00	$104,906,066.32
Energy Cost	$41,616.41	$38,813.00	_
Emission Cost	_	$6,612,340.00	$96,662,037.50
Delay cost	$8,949,886.59	$2,018,273.71	_
Purchase cost	$14,400,000.00	$9,600,000.00	_
Operation Cost	$20,158,336.80	$13,438,891.20	_
Total Cost	$43,549,839.80	$37,918,617.50	$201,568,103.82

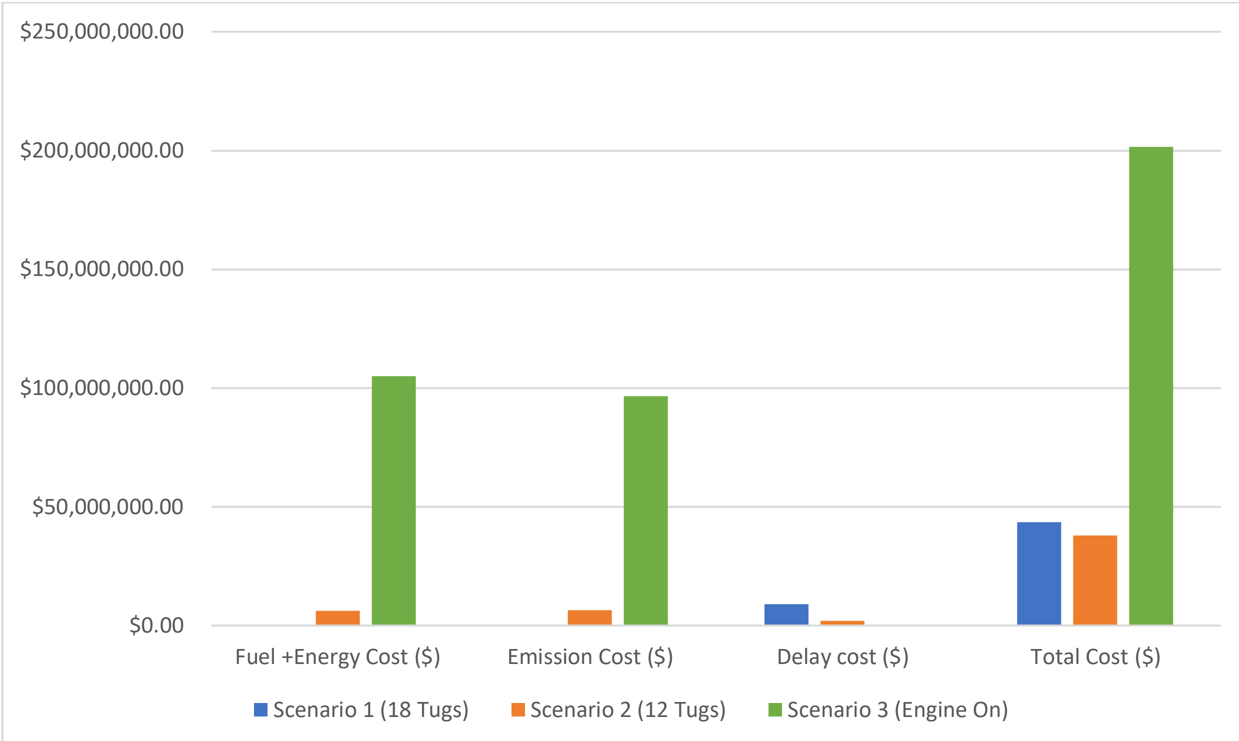


Figure 4- 15: Summary results of all strategies

5 Conclusion and future work

The objective of this Master's thesis is to study the possibility of adopting electric-powered towing options to handle entire taxiing operations between gates and runway with an objective to minimize the fuel consumption and emission during airport taxiing operations while continue proving the best customer service for the passengers and airline companies (on-time departure and arrival). In order to achieve our objectives, we studied the impacts and benefits of utilizing electric powered towing tractors for handling aircraft ground movements through a mixed-integer linear programming model.

The developed mathematical models to solve the proposed airport taxiing operations problem are computationally complex and require unique solution strategies to apply to real-life problems. Hence, we developed a sequential solution method that takes advantage of airlines' business practices. Consequently, we were able to handle a large airport (Montreal's Pierre Elliott Trudeau International Airport) daily traffic. We tested different towing options (100% towing, optional towing-Hybrid Solution, and no-towing option). In the first strategy, we are forcing all airplanes to use towing tugs in order to move from gates to runways and the other way around. The second strategy allows the model to either taxi the airplanes by towing tugs or lets them use their engine for ground movements. Finally, in the third strategy, all airplanes use their engine for taxing. Hybrid solutions that give an option to the aircraft to complete its taxiing with its own engine power performed better in comparison to no-towing or 100% towing options. While hybrid option provides the most economical solution, it also helps airlines to reduce their greenhouse gas emissions during taxiing drastically (average 70% CO_2 reduction in comparisons to no-towing option).

While our results indicate that a hybrid system is not only environmentally friendly solution but also provides substantial cost-saving opportunities; yet, it must be noted that purchasing and operating related costs for towing tractors are rough estimates from a limited number of sources. Hence, we do not make a claim that the results are readily applicable for the Montréal-Pierre Elliott Trudeau Airport (YUL) airport. In this thesis, we only demonstrated the capabilities of our MILP model and provided a good discussion point for the civil aviation authorities to consider the electrification of taxiing operations at airports in Canada and the rest of the world to fight against global warming.

In order for this mathematical model to be fully implemented, a more accurate cost analysis for operating towing vehicles is necessary. Furthermore, collision and conflict issues during taxiing operations must be included in the mathematical model to reflect the actual traffic conditions at airports better.

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