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An eco-friendly aircraft taxiing approach with collision and conflict avoidance

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ABSTRACT

Among several crucial objectives of the air transportation system, minimization of fuel consumption has a profound impact on the economic viability of airline companies and their effect on the environment. Given that many large airports around the world are located in the heart of residential areas such as Chicago's O'Hare, New York's JFK, and Montreal's Pierre Elliott Trudeau, the Greenhouse Gas Emissions (GGE) released by aircraft flying through such urban airports directly impacts the health of nearby residents. In this paper, we propose a hybrid taxiing solution to reduce the airports' impact on GGE where part of the taxiing operations is handled by tow-trucks powered by renewable energy while some other aircraft continue using their engines to complete taxiing. The main contribution of the work presented in this paper is the inclusion of collision of conflict avoidance in the formulation of taxiing operations planning with an objective to minimize fuel consumption and to maximize the desired service quality. The conflict-free taxing operations planning model is tested on Montreal's Pierre Elliott Trudeau airport. Furthermore, the detailed economic analysis on the adoption of electric-powered tow-trucks is provided.

1. Introduction

Demand for civil aviation has been steadily increasing for many decades. According to the International Civil Aviation Organization (ICAO), passenger traffic has grown an average of 5.2% per year between 1995 and 2012. ICAO estimates demand for aviation to continue to increase at an annual rate of 4.6% until 2032 and 4.5% until 2042 (ICAO, 2016). Despite its current contribution to global GGE being estimated to be only around 3–6%, increasing demand on air travel suggests that, in near future, aviation's contribution to the global GGE will increase significantly. In recent years, both automobile and rail industry have introduced several alternative power sources with potentials to reduce their CO_2 emission. Unlike for the automobile and rail industry, advances in technology is not promising a breakthrough alternative power-source for the aviation industry. Both increasing demand on air-travelling and lack of alternatives for the fossil fuel-powered engines will only increase the contribution of aviation industry for the CO_2 emission.

The objective of airline companies is to transport passengers or cargo from an origin to destination with minimum deviations from the schedule, safely and comfortably while sustaining a profitable business. In the literature, the Air Traffic Management (ATM) problem is mostly tackled as an operations research problem with an objective to minimize flight delays. Outputs of such mathematical models include departure times from origins (gates or runways), set of air sectors to be visited during flight, and the arrival and

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Abstract

Among several crucial objectives of the air transportation system, minimization of fuel consumption has a profound impact on the economic viability of airline companies and their effect on the environment. It is estimated that aircraft roughly burn 7% of their fuel during taxiing. Given that many large airports around the world are located in the heart of residential areas such as Chicago's O'Hare, New York's JFK, and Montreal's Pierre Elliott Trudeau, the Greenhouse Gas Emissions (GGE) released by aircraft flying through such urban airports directly impacts the health of nearby residents. In this paper, we propose a hybrid taxiing solution to reduce the airports' impact on GGE where part of the taxiing operations is handled by towing trucks powered by renewable energy while some other aircraft continue using their engines to complete taxiing. The main contribution of the work presented in this paper is the inclusion of collision of conflict avoidance in the formulation of taxiing operations planning with an objective to minimize fuel consumption and to maximize the desired service quality. The conflict free taxing operations planning model is tested on Montreal's Pierre Elliott Trudeau airport. Furthermore, the detailed economic analysis on the adoption of electric powered towing vehicles is provided.

Keywords: Airport operations; Greenhouse gas emission; collision and conflict free taxiing; MILP.

1. Introduction

Demand for civil aviation has been steadily increasing for many decades. According to the International Civil Aviation Organization (ICAO), passenger traffic has grown an average of 5.2% between 1995 and 2012. ICAO estimates demand for aviation to continue to increase at an annual rate of 4.6% until 2032 and 4.5% until 2042 (ICAO, 2016). Despite its current contribution to global GGE being estimated to be only around 3-6%, increasing demand on air travel suggests that, in near future, aviation's contribution to the global GGE will increase significantly. In recent years, both automobile and rail industry have introduced a number of alternative power sources with potentials to reduce their CO_2 emission. Unlike for the automobile and rail industry, advances in technology is not promising a breakthrough alternative power source for the aviation industry. Both increasing demand on air-travelling and lack of alternatives for the fossil fuel powered engines will only increase the contribution of aviation industry for the CO_2 emission.

The objective of airline companies is to transport passengers from an origin to destination with minimum deviations from the schedule, safely and comfortably while sustaining a profitable business. In the literature, the Air Traffic Management (ATM) problem is mostly tackled as an operations research problem with an objective to minimize flight delays. Outputs of such mathematical models include departure times from origins (gates or runways), set of air sector to be visited during flight, and the arrival and departure times at these air-sectors. At the operation level on the other hand, the foremost important objective of the Air Traffic Controllers (ATCOs) is the management of collision and conflict free air traffic. Consequently, significant deviations from the suggested flights plans (outcome of ATM models) are frequently observed in practice.

While flight safety will continue to be the foremost important aspect of air transportation, both as a significant cost item for airline companies and as an important contributor to the global GGE (estimated to be between 3-6% (Unger, 2011)), the fuel consumption problem is a noteworthy challenge for the civil aviation industry. It has been observed that operations management has the potential to improve airlines' fuel consumption (Zou et al., 2014). However, the fuel consumption management issue has not been tackled as an integral part of the general ATM models in the literature. It 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. In addition, for the technological advances and choice of materials used to manufacture aircraft, flight operation conditions such as speed, wind impact, take-off load, flight-altitude, and congestion management significantly impact on the fuel consumption performance of aircraft (Ryerson 2011). In particular, the congestion both in the air and on the ground considerably impact the unplanned fuel usage. According to Zou et al. (2014), those airlines focus on operational excellence with an objective to minimize fuel consumption burn by up to 25-42% less fuel than those less efficient carriers. Furthermore, it is estimated that an aircraft burns an average 7-10% of its fuel during taxiing operations (Khadilkar, 2012). According to Gebicki (2018), a Boeing 747 consumes more than one ton of fuel in 15 minutes taxiing during take-off.

In this paper, we introduce an alternative taxiing method to reduce fuel consumption during taxiing. In another words, this paper discusses the scheduling and operation of electric powered towing vehicles similar to the TaxiBot (Lukic et al., 2018) to enable collision and conflict-free taxiing operations. Airline companies have been experimenting with either electric-powered towing vehicles (Lufthansa with TaxiBot), or on-board systems such as the 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 paper we introduce a Mixed Integer-Linear Programming (MILP) model for operating electric powered towing vehicles to provide taxiing services for airline companies. The output of the proposed MILP includes the assignment of towing vehicles to aircraft, pick-up time, drop-off time and the set of taxiways to complete the taxing operations. The main contribution of this paper is its capability of incorporating collision and conflict avoidance as part of the taxing operations planning while using electric powered towing vehicles. To the authors' knowledge, the research presented in this paper is the first of its kind.

The remainder of the paper 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 discussed. Sample cases are solved and discussed in section 4. Finally in Section 5, conclusions are provided.

2. Literature Review

Climate change is one of the greatest challenges of our time. Scientific communities predominantly agree (more than 97% of the published works) that human activities are the main cause for the rapid changes on climate around the globe (Cook, 2016). GGE from human activities such as manufacturing, household heating, transportation and farming are found to be the leading causes for climate change. While several different sources contribute to the GGE globally, according to World Health Organization (WHO), the transportation industry accounts for more than 23% of all carbon dioxide (CO_2) production in the world. With the increasing globalization, existence of complex supply chain networks and increasing desire to travel around the world, the demand for various transportation mediums from personal cars to large container ships will continue to play a significant role in human lives for the foreseeable future. Based on these realities, both researchers and manufacturers of transportation vehicles have been focusing on designing and developing more efficient and less polluting technologies to mitigate the transportation industry's impact on the climate change.

Electrification and automation of transportation vehicles have gained enormous attention in recent years. While electrification has become a viable solution for the automobile, trains and in some extend for the trucking industry, such a breakthrough has not been realised for the aerospace industry. According to UN's Intergovernmental Panel on Climate Change, air-transportation constitutes 3.5% of all greenhouse produced in the world. A study made for UK further suggests that, aviation industry contributes to 6% of all greenhouse gas produced in UK (Chapman, 2007). Due to increasing demand on air-transportation and lack of technological breakthroughs to mitigate from carbon based fuel sources, the contribution of air transportation for the GGE will continue to increase significantly (Kousoulidou, 2016).

Aircraft engine emissions account for about 70% CO_2 and slightly less than 30% H_2O. Other emissions such as nitrogen oxides, carbon monoxide, oxides sulfur or unburned fuel constitute less than 1% (Wey and Lee, 2017; Aviation & Emissions, 2015). Given that aircraft may burn up to 7% of their fuel during taxiing (Khadilkar, 2012), CO_2 emitted on the ground not only negatively contributes to the global climate change, but also impacts the health of residents living near airports. In recent years, in order to offset the carbon emissions from airport operations, the electrification of airport operations concept has been proposed. The goal is to minimize or completely eliminate the usage of aircraft engines during taxiing. Two promising solutions (towing vehicles and on-board propulsion systems) have been discussed in the literature (Lukic et al., 2018; Re, 2012) and some experimental work has been tested by various airline companies (Lufthansa with TaxiBot and WheelTug with SunExpress and Kenya Airways). Most experts acknowledge the potentials of both technologies to reduce the aircraft GGE during taxiing. Yet, neither technology has been fully adopted by the industry. Towing options, both driverless and driver-on-board solutions, where aircraft are transported between runways and gates by electric-driven towing vehicles lead to slower taxiing operations. Coupling with an aircraft, towing and decoupling from the aircraft requires either non-value added delays or slower flow. When a transporter is requested for the next assignment, depending on its current location, there is a possibility for idle travelling which causes significant efficiency losses. Onboard solutions such as WheelTugs are more efficient than towing technologies. Since they are embedded within the aircraft's landing gears, they are not causing delays due to coupling and decoupling. However, on-board push systems add permanent weight on an aircraft not only during taxiing, but also during the flight. Consequently, aircraft carry and burn extra fuel to compensate for the additional weight of the on-board propulsion systems.

Airport operations management deals with the effective usage of gates, runways and taxiways in order to provide an on-time service to all customers (passengers and airlines). However, aircraft movements within the airport and in the air-sectors are controlled by the Air-Traffic Controllers (ATCOs). Due to high volume of traffic, ATCOs focus mostly becomes a *safety-first* approach, and they frequently neglect the business and environmental objectives of air transportation. Since the current airport operations management models do not include strong collision and conflict avoidance features, ATOs intervention in order to avoid collision and conflict lead to significant deviations from the planned optimum solutions at the execution level. In the literature, collision and conflict avoidance are studied using simulation models (Jones et al., 2010; Alam, 2008) or technological solutions (Holland, 2013) independently from scheduling and taxiing operations. Sophisticated collision avoidance systems such as traffic-alert and collision avoidance systems (CAASD 200), collision avoidance radar able to discriminate objects (Swaer, 1997) and NASA's millimeter-wave radar forward system (Mewhinney, 1996) embedded in today's modern aircraft to help offset various human (pilotage or air traffic controller) and modeling (mathematical or computational) errors. In recent years, due to increasing popularity of unmanned aerial vehicles, various control models have been proposed for collision and conflict avoidance (Lin, 2017; Chen 2013) to safely separate UAVs from other UAVs and other commercial and military aircraft. Akgunduz (2017) introduced a set of constraints to tackle the collision problem during flight for both UAVs and commercial aircraft. These conflict avoidance techniques currently available in the literature for air-traffic collision and conflict avoidance only focus on real-time decision support. Based on the current information from the surrounding traffic, current models either dispatch conflict warnings or suggest new collision free path plan. Since these collision avoidance tools and methods cannot be embedded in the air-traffic planning algorithms where airline and passengers' business and personal objectives are considered, most air-traffic control and airport operations management models produce poor results at the implementation level. Frequently, significant deviations from the planned en route flight plans are observed in order to avoid collision and conflict situations.

In this paper, we study the impact of electric-driven towing vehicles usage to facilitate taxiing operations. Airport operations have been well studied in the literature as gate scheduling problems (Dorndorf, 2007, Capa, 2015), runway scheduling problems (Clare, 2011) and ground delay management problems (Navazio, 2007). As mentioned earlier, one of the main shortcomings of the current air-traffic management tools is their lack of inclusion of collision and conflict avoidance as part of the overall airport operations management. In the context of airport operations, the outputs of mathematical models which are gate and runway sequencing and scheduling, and route plans for ground operations, cannot be executed as desired when collision and conflict avoidance is not imbedded in the model. The foremost important concern in aviation operations is the safety. Hence the developed mathematical models should not only be addressing the airline, airport and customer expectations in terms of cost and on-time performance; but also should include strong collision and conflict avoidance features.

3. Modeling of the hybrid taxiing operations

The objective of airport operations is to enable an uninterrupted traffic flow for both incoming and outgoing aircraft between runways and gates while all aircraft 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, aircraft follow physical taxiway lines. Collectively, physical lines that guides 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.

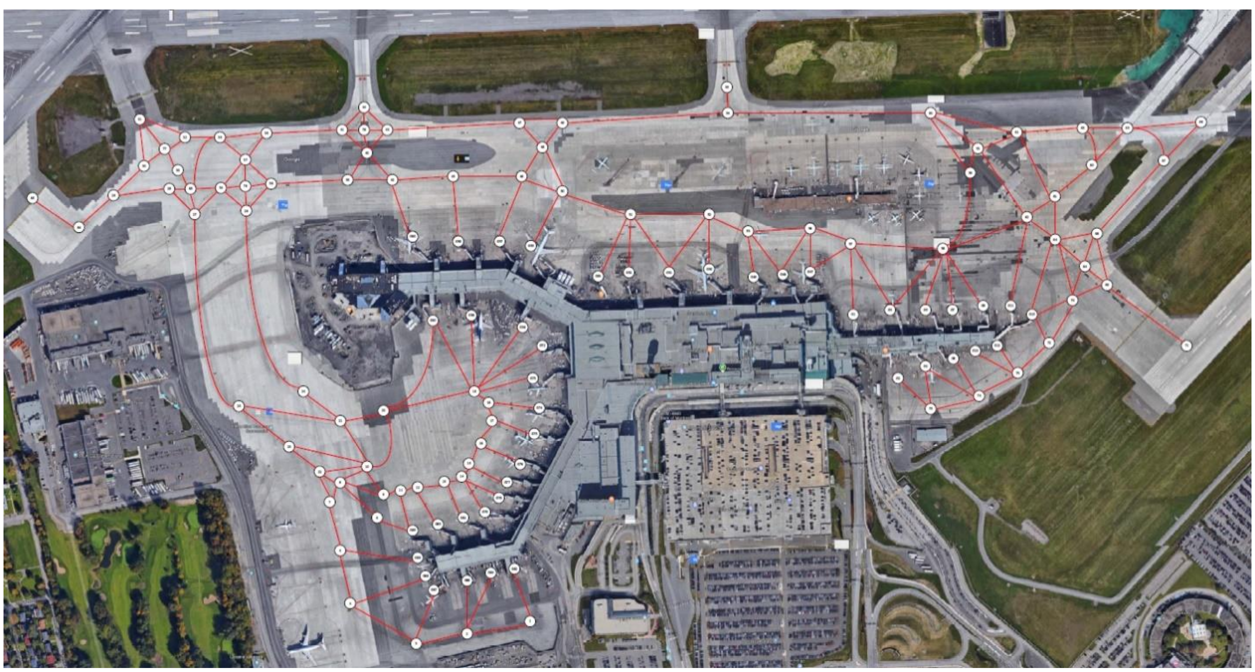


Figure 1: Montreal's Pierre Elliott Trudeau International Airport Taxiing Network

As seen in Figure 1, using gate locations and taxiway lines on the ground, a mesh network between runways (3 in Figure 1) and gates (total 52 gates from Figure 1 – gates 17-34 are excluded) is established.

Let's now describe the given network as a $G(N, V)$ where N is the set of nodes that represents gates, runways and intersection points and V is the set of links (connecting taxiways) between nodes. The objective of the taxiing operations is to move aircraft between runways and gates by following the consecutive nodes. In order for any mathematical model to be considered as a viable solution to the taxiing management problem, the following conditions should be included in the formulation.

- A gate can only be used by a single aircraft at a time:
    a. If an aircraft leaves or arrives at the gate after the scheduled departure or arrival time, a penalty will be imposed.
    b. If an aircraft arrives or departs at the runway after the planned departure or landing time, a penalty will be imposed.
- Aircraft can follow each other on the taxiways (on $v \in V$) while respecting the separation distances.
- No two aircraft can travel from opposite directions on a taxiway $(v \in V)$ at the same time

3.1 Assumptions

In order to formulate the taxiing operations problem in consideration with conflict and collision avoidance and towing-service between runways and gates options, the following assumptions were made:

i. As long as an aircraft is on the taxiway, it will not be in a collision situation with other aircraft travelling on different links.
ii. As long as aircraft respect the separation distances both on edges when they follow each other, and on nodes when they are transferred to the next taxiway, they will not be in a collision situation (separation distances between aircrafts are aircraft-type specific).
iii. Traffic due to auxiliary services is ignored. It is assumed that they always clear the way for aircraft.
iv. When they are not serving an aircraft, towing vehicles movements are ignored. It is assumed that they always clear the way for aircraft.

3.2 Model parameters and decision variable

In the model, four different sets are introduced. Moreover, links arriving to a node and departing from a node are defined as sets.

<u>Sets</u>

F	Set of aircraft
V	Set of towing vehicles
N	Set of nodes, including flight origin (ORG^f) and destination ($DEST^f$)
L	Set of links connecting nodes indexed as $l \in L$. When stated as $l(ij)$, it represents a link from $Node\ i$ to $Node\ j$

$L(n)^+$	Set of links arrive to node n
$L(n)^-$	Set of links leaves node n

In order to formulate the proposed taxiing operations, following parameters are considered.

Parameters

$t^f_{EARLY\_LEAVE}$	Scheduled earliest departure from origin node
$t^f_{EARLY\_ARRIVE}$	Scheduled earliest arrival to destination node
$t^f_{LATE\_LEAVE}$	Scheduled latest departure time from origin node
$t^f_{LATE\_ARRIVE}$	Scheduled latest arrival to destination node
t_l^{SELF}	Travelling time on link l when aircraft self-taxi
t_l^{TOW}	Travelling time on link l when aircraft is towed
$t^{SP}_{nn'}$	Travelling time for the towing vehicle when travelling alone between two nodes (n, n'). Assumed that, vehicles always travel on the shortest path between given nodes (n, n')
$\Delta^{ff'}$	The minimum separation distance between aircrafts in terms of time
$LENGTH_l$	Link length in meters
$FUEL^f$	Fuel consumption per unit distance when f is not towed.
$COST_{FUEL}$	Unit fuel cost
${COST_{DELAYS}}^f$	Penalty cost for deviation from schedule ($ per minute)
M	A large real number

The following decision variables are introduced in order to formulate the proposed taxiing operations management problem.

Decision Variables

$$x_l^f = \begin{cases} 1, & if\ aircraft\ travels\ on\ link\ l \\ 0, & otherwise \end{cases}$$

$$y_v^f = \begin{cases} 1, & if\ towing\ vehicle\ v\ is\ assigned\ to\ flight\ f \\ 0, & otherwise \end{cases}$$

$$z_v^{ff'} = \begin{cases} 1, & if\ towing\ vehicle\ v\ is\ assigned\ to\ flight\ f\ immediatly\ after\ f' \\ 0, & otherwise \end{cases}$$

a_l^f The time aircraft enters the $link\ l$

d_l^f The time aircraft leaves the $link\ l$

$$\varphi_l^{ff'} = \begin{cases} 1, & a_l^{f'} - a_l^f \geq \Delta^{ff'} \\ 0, & otherwise \end{cases}$$ Collision and conflict avoidance control variable I

$$\pi_l^{ff'} = \begin{cases} 1, & a_{l(ij)}^{f'} - d_{l(ji)}^f \geq \Delta^{ff'} \\ 0, & otherwise \end{cases}$$ Collision and conflict avoidance control variable II

$$\tau_n^{ff'} = \begin{cases} 1, & \sum_{l \in L(n)^+} d_l^{f'} - \sum_{l \in L(n)^+} d_l^f \geq \Delta^{ff'} \\ 0, & otherwise \end{cases}$$ Collision and conflict avoidance control variable III

$DELAY^f$ Total delay time of aircraft = {Delay at Origin + Delay at Destination}

$DELAY\_ORIGIN^f$	Delay time to leave origin node
$DELAY\_DEST^f$	Delay at arriving to destination node
$TOTAL\_FUEL^f$	Total fuel consumed by flight f

3.3 Model:

In this section, the formulation of taxiing operations with the gate-to-runways/runways-to-gates towing option is introduced. First, the objective is defined. Next, routing and timing constrains are introduced. In the 3rd sub-section, we provide the set of constraints to handle collision and conflict. Finally, in the 4th sub-section, necessary constraints to provide gate-to-runways/runways-to-gates towing option are introduced.

a. 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 an on-time arrival and departure service for all customers. Therefore, in the formulation of objective function, deviations from the scheduled arrival and departure times are also penalized.

$$\min \sum_{f \in F} COST_{FUEL} * TOTAL\_FUEL^f + \sum_{f \in F} COST_{DELAYS}{}^f * DELAY^f \tag{1}$$

b. Routing constraints

In this section, the set of constraints that is required to navigate aircraft between gates and runways through taxiways is introduced.

$$\sum_{l \in L(ORG^f)^-} x_l^f = \sum_{l \in L(DEST^f)^+} x_l^f = 1 \qquad \forall f \in F \tag{2}$$

$$\sum_{l \in L(n)^+} x_l^f = \sum_{k \in L(n)^-} x_k^f \qquad \forall f \in F;\ \forall n \in N \backslash \{ORG^f, DEST^f\} \tag{3}$$

$$\sum_{l \in L(ORG^f)^-} a_l^f \geq t_{EARLY\_LEAVE}^f \qquad \forall f \in F \tag{4}$$

$$\sum_{l \in L(DEST^f)^+} d_l^f \geq t_{EARLY\_ARRIVE}^f \qquad \forall f \in F \tag{5}$$

$$d_l^f \geq a_l^f + t_l^{SELF}\left(x_l^f - \sum_{v \in V} y_v^f\right) + t_l^{TOW}\left(\sum_{v \in V} y_v^f\right) \qquad \forall f \in F;\ \forall l \in L \tag{6}$$

$$\sum_{l \in L(n)^-} a_l^f \geq \sum_{l \in L(n)^+} d_l^f \qquad \forall f \in F;\ \forall n \in N \backslash \{ORG^f, DEST^f\} \qquad (7)$$

$$x_l^f * M \leq a_l^f \leq d_l^f \qquad \forall f \in F;\ \forall l \in L \qquad (8)$$

In Constraint 2, it is ensured that the aircraft leaves the origin and reaches its destination. Aircraft arriving to a transition node is forced to leave the node in Constraint 3. Constraints 4 and 5 coordinates the arrivals and departures according to given schedules. Travelling time on a link change depending on the nature of taxiing (self-powered vs tow-truck assigned navigation). Constraint 6 sets the bound for the earlies departure from a link. Arrival time at a consecutive link depends on the departure from the previous link (Constraint 7). Finally in Constraint 8, it is ensured that arrival and departure times at a link is only possible if the aircraft visits the link.

c. Collision and conflict avoidance constraints

The foremost important consideration in aviation is safety. Both in the air and on the ground, air traffic controllers (ATCs) spend most of their time and energy separating aircraft from one another to ensure the safety of the public and the environment. Hence, in order for a decision support system to be a viable option to manage the air/ground traffic, the collision and conflict avoidance must be well incorporated. In our case, we modeled the collision and conflict avoidance to handle three important conditions during taxiing:

i) Two aircraft must sustain a separation distance when they travel on the same link at the same time
ii) Aircraft must sustain sufficient separation distances when they pass through intersections.
iii) Two aircraft cannot travel on the same link at the same time from opposite directions

If an aircraft enters a link earlier than another aircraft, than they should sustain a desirable separation distance ($\Delta^{ff'}$) from each other both at the time of their entrance to a link $\left(a_l^{f'} - a_l^f \geq \Delta^{ff'}\right)$ and at the time of their exit from the link $\left(d_l^{f'} - d_l^f \geq \Delta^{ff'}\right)$. Constraints 9-12 ensures the separation of aircrafts using the same link at the same direction.

The following set of constraints are considered for $\forall f, f' \in F: f \neq f', \forall l \in L$

$$a_l^{f'} \geq a_l^f + \Delta^{ff'} - \left(1 - \varphi_l^{ff'}\right) M - \left(2 - x_l^f - x_l^{f'}\right) M \qquad (9)$$

$$a_l^f \geq a_l^{f'} + \Delta^{ff'} - \varphi_l^{ff'} M - \left(2 - x_l^f - x_l^{f'}\right) M \qquad (10)$$

$$d_l^{f'} \geq d_l^f + \Delta^{ff'} - \left(1 - \varphi_l^{ff'}\right) M - \left(2 - x_l^f - x_l^{f'}\right) M \qquad (11)$$

$$d_l^f \geq d_l^{f'} + \Delta^{ff'} - \varphi_l^{ff'} M - \left(2 - x_l^f - x_l^{f'}\right) M \tag{12}$$

When an aircraft reaches the same node from different links, possible collision is avoided by separating them from each other by $\Delta^{ff'}$ amount of time by using the following set of constraints. In this paper, the arrival time at a node is equal to the departure from a link where the end-node of this link is the node in consideration.

The following set of constraints are considered for $\forall f, f' \in F: f \neq f', \forall n \in N$

$$\sum_{l \in L(n)^+} d_l^{f'} \geq \sum_{l \in L(n)^+} d_l^f + \Delta^{ff'} - \left(1 - \tau_l^{ff'}\right) M - \left(2 - \sum_{l \in L(n)^+} x_l^f - \sum_{l \in L(n)^+} x_l^{f'}\right) M \tag{13}$$

$$\sum_{l \in L(n)^+} d_l^f \geq \sum_{l \in L(n)^+} d_l^{f'} + \Delta^{ff'} - \tau_l^{ff'} M - \left(2 - \sum_{l \in L(n)^+} x_l^f - \sum_{l \in L(n)^+} x_l^{f'}\right) M \tag{14}$$

Finally, the collision and conflict free taxiing operation is ensured by introducing the following set of constraints. Constraints 15 and 16 eliminate the possibility of traveling from opposite directions on the same link at the same time. The decision variable $\pi_l^{ff'} = 1$ if the aircraft f leaves the link l from node j before aircraft f' enters the link from node j.

The following set of constraints are considered for $\forall f, f' \in F: f \neq f', \forall l \in L$

$$a_{l(ji)}^{f'} \geq d_{l(ij)}^f + \Delta^{ff'} - \left(1 - \pi_l^{ff'}\right) M - \left(2 - x_l^f - x_l^{f'}\right) M \tag{15}$$

$$d_{l(ji)}^f \geq a_{l(ij)}^{f'} + \Delta^{ff'} - \pi_l^{ff'} M - \left(2 - x_l^f - x_l^{f'}\right) M \tag{16}$$

d. Towing option

The main objective of the work presented in this paper is to design a collision and conflict free taxiing operation with an objective to minimize the contribution of airports towards GGE. Once collisions and conflict avoidance is guaranteed, the operations research solutions to taxiing operations would significantly improve the traffic flow which ultimately helps airports to reduce their GGE. However, further GGE reduction is possible through electrification of airport operations. In recent years, alternative technologies have been proposed to reduce or eliminate aircraft engine usage during taxiing: electric powered towing vehicles (TaxiBot, Lukic et al., 2018) and onboard aircraft electric drive systems (WheelTug, Postorino, 2017).

Today, towing vehicles only assist aircraft during push-back from gates. On the other hand, systems such as TaxiBot considers 100% coupling with the aircraft during the entire taxiing process between gates and runways. Such a system clearly requires a considerable number of additional towing vehicles in the system. On the other hand, systems such as WheelTug, require modification on current aircraft designs. Furthermore, fuel carried by the aircraft may be increased in order to offset the impact of additional weight of the WheelTug system which consequently causes more fuel usage during flight. In this paper, we evaluate the utilization of electric-driven towing vehicles during taxiing. The following set of constraints is introduced to handle the assignments of available towing vehicles on aircraft. Once a towing vehicle is assigned to an aircraft, the entire taxiing operation is completed as a pair. Once the towing vehicle is decoupled from aircraft, it is available for the next assignment.

Let us assume that there are V towing vehicles available in the system. All towing vehicles are introduced to airport operations from a dummy ENTRANCE node (N_{ENT}). At the end of the day, all towing vehicles are removed from the airport operations through a SINK node (N_{SINK}). In order to minimize delays due to lack of available towing vehicles, the model enables some aircraft to self-taxi. As shown in the objective function, the mathematical model aims at minimizing the cost associated with delays and fuel consumption. Consequently, when the delay cost offsets the fuel consumption cost, aircraft select the self-taxiing option. Given that smaller aircraft burn less fuel, when there is a competition for a towing vehicle, the mathematical model assigns the towing vehicle to a large (less fuel efficient) aircraft.

$$y_v^f \leq \sum_{f' \in F: f \neq f'} z_v^{f'f} + z_v^{N_{ENT}f} \qquad \forall f \in F;\ \forall v \in V \qquad (17)$$

$$y_v^f \leq \sum_{f' \in F: f \neq f'} z_v^{ff'} + z_v^{fN_{SINK}} \qquad \forall f \in F;\ \forall v \in V \qquad (18)$$

$$\sum_{f \in F} z_v^{N_{ENT}f} = \sum_{f \in F} z_v^{fN_{SINK}} \leq 1 \qquad \forall v \in V \qquad (19)$$

The constrain (20) is valid for $\forall f, f' \in F: f \neq f';\ \forall v \in V$

$$\sum_{l \in L(ORG^f)^-} a_l^f \geq \sum_{l \in L\left(DEST^{f'}\right)^+} d_l^{f'} + \left(z_v^{ff'} t^{SP}_{DEST^{f'}ORG^f}\right) - \left(1 - z_v^{ff'}\right) M \qquad (20)$$

Constraints (17) and (18) are formulated for managing the towing vehicle assignments. A towing vehicle can be assigned to an aircraft $\left(y_v^f = 1\right)$ either after completing the towing operation of another aircraft $\left(z_v^{f'f} = 1\right)$ or entering the system directly from the dummy node $\left(z_v^{N_{ENT}f} = 1\right)$. After serving to an aircraft, the towing vehicle is either assigned to another aircraft $\left(z_v^{ff'} = 1\right)$ or leaves the system through the SINK node $\left(z_v^{fN_{SINK}} = 1\right)$. In Constraint (19), those towing vehicles used for taxiing operations are forced to enter the system through serving an aircraft and leave the system after serving an aircraft.

In order for an aircraft to leave its origin (a gate or a runway node) with a towing vehicle, the assigned towing vehicle first must complete the previous task $\left(y_v^{f'}\right)$ and travel from the destination of f' $\left(DEST^{f'}\right)$ to the origin of f $\left(ORG^{f}\right)$. The travelling time from $DEST^{f'}$ to ORG^{f} $\left(t^{SP}_{DEST^{f'}ORG^{f}}\right)$ is estimated by the shortest path between these two nodes and it is assumed that towing vehicles do not cause collision and conflict with aircrafts while they travel alone. Consequently, the Constraint (20) is formulated.

e. Fuel consumption

The following set of constraints determines the fuel consumption and delay cost:

The fuel usage occurs when aircraft is self-taxiing ($Y_v^f = 0, \forall v \in V$). Constraint 21 determines the total amount of fuel used during taxiing by an aircraft.

$$TOTAL\_FUEL^f \geq \sum_{l \in L} FEUL^f * LENGTH_l * X_l^f - \left(1 - \sum_{v \in V} y_v^f\right) M \qquad \forall f \in F \qquad (21)$$

If an aircraft leaves the gate or the runway after its scheduled departure/arrival time, it is subject to a delay penalty. The following constraints determines the duration of delays if it occurs.

$$\sum_{l \in L(ORG^f)^-} a_l^f - t^f_{LATE\_LEAVE} \leq DELAY\_ORIGIN^f \qquad \forall f \in F \qquad (22)$$

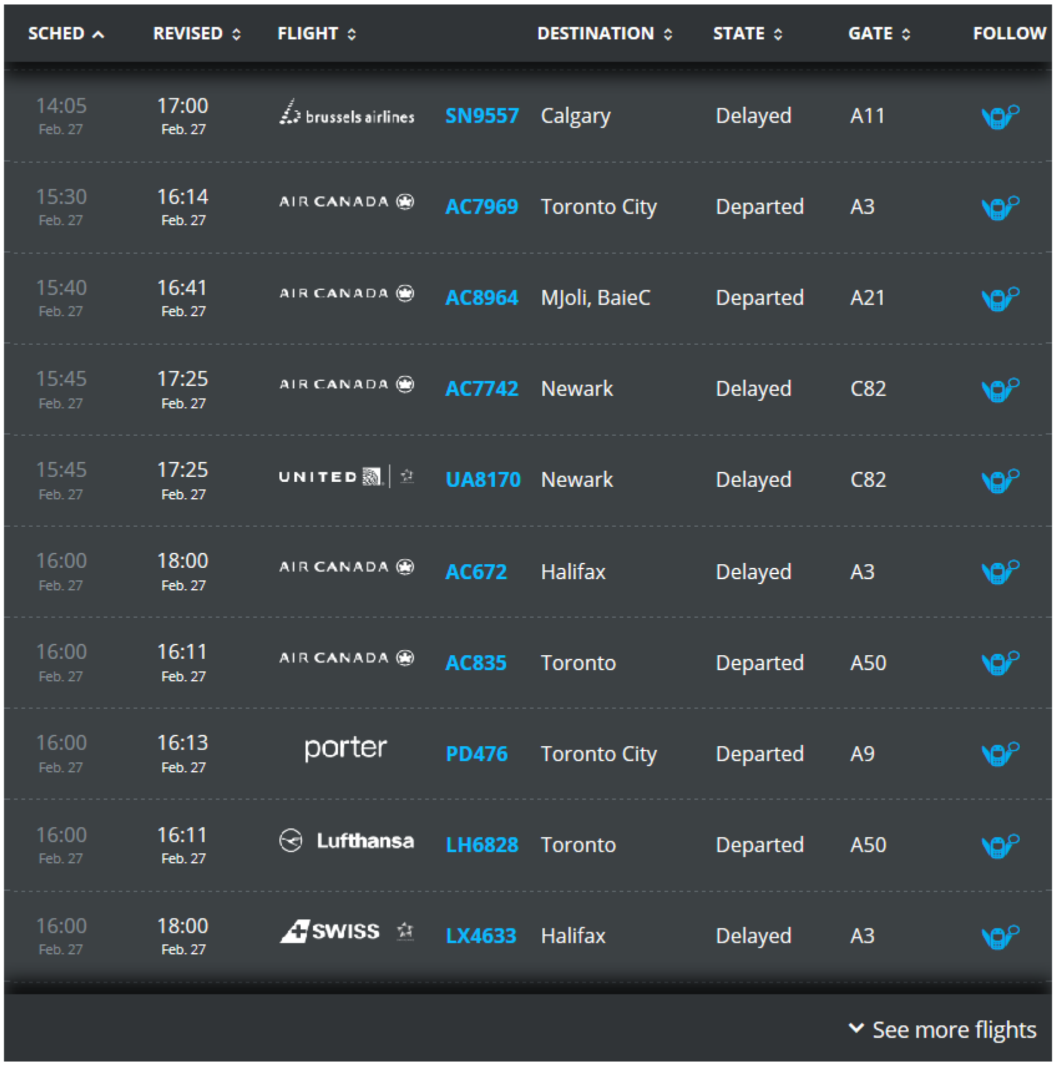
$$\sum_{l \in L(DEST^f)^+} d_l^f - t^f_{LATE\_ARRIVE} \leq DELAY\_DEST^f \qquad \forall f \in F \qquad (23)$$

$$DELAY\_ORIGIN^f + DELAY\_DEST^f \leq DELAYS^f \qquad \forall f \in F \qquad (24)$$

Consequently, the total cost, incurred due to fuel usage and delays, is formulated in the objective function (Constraint 1) with an objective to minimize the total cost of taxiing operations.

4. Results and Discussions

In order to test the capabilities of the proposed mathematical model, a network model, based on Montreal's Pierre Elliott Trudeau International Airport (YUL) is designed. A total of 52 gates were considered in the model. In order to provide access to 3 runways at the airport, 7 entrance locations are selected. Finally, 79 nodes were identified from the satellite image (Figure 1) of the airport to determine the taxiing network. Arrival and departure times of flights for a given day is pulled from the airport webpages (see Figure 2 for sample data).



SCHED	REVISED	FLIGHT		DESTINATION	STATE	GATE	FOLLOW
14:05 Feb. 27	17:00 Feb. 27	brussels airlines	SN9557	Calgary	Delayed	A11	
15:30 Feb. 27	16:14 Feb. 27	AIR CANADA	AC7969	Toronto City	Departed	A3	
15:40 Feb. 27	16:41 Feb. 27	AIR CANADA	AC8964	MJoli, BaieC	Departed	A21	
15:45 Feb. 27	17:25 Feb. 27	AIR CANADA	AC7742	Newark	Delayed	C82	
15:45 Feb. 27	17:25 Feb. 27	UNITED	UA8170	Newark	Delayed	C82	
16:00 Feb. 27	18:00 Feb. 27	AIR CANADA	AC672	Halifax	Delayed	A3	
16:00 Feb. 27	16:11 Feb. 27	AIR CANADA	AC835	Toronto	Departed	A50	
16:00 Feb. 27	16:13 Feb. 27	porter	PD476	Toronto City	Departed	A9	
16:00 Feb. 27	16:11 Feb. 27	Lufthansa	LH6828	Toronto	Departed	A50	
16:00 Feb. 27	18:00 Feb. 27	SWISS	LX4633	Halifax	Delayed	A3	

See more flights

Figure 2: Arrival and departure status with gate numbers: Sample extracted from Pierre Elliott Trudeau International Airport

Based on ICAO data concerning Montreal's YUL airport, 68% of aircraft are small size with less than 45,000 kg weight, and 32% are heavier aircraft. Below are the fuel consumption and emission statistics during taxiing operations for different types of aircraft (Table 1).

Table 1: Emission and fuel burn during taxiing statistics for different airplanes (ICAO, 2011)

		Emission(kg) during landing/takeoff			
Aircraft type	**Fuel burn (kg/min)**	**CO_2**	**NOx**	**CO**	**HC**
Boeing 767-300	23.33 (7.72 Gallon)	5610	28.19	14.47	1.19
Boeing 737-800	15 (4.96 Gallon)	2780	12.3	7.07	0.72
Airbus A320-200	12 (3.97 Gallon)	2440	9.01	6.19	0.57

ARJ85/100	4.8 (1.6 Gallon)	970	3.6	2.48	0.25

While all aircraft types differ from one another in terms of their fuel consumption patterns, based on the available data from Chati (2014), we categorised aircraft into three different groups and assumed that aircraft in the same group emit similar amounts of CO2. Accordingly, the information for 205 flights was extracted from Montreal's Pierre Elliott Trudeau International Airport webpages.

4.1 Complexity Analysis

The MILP model introduced in Section 3 is known to be an NP-Hard mathematical model. The proposed model is a synthesis of the well-known economic lot-size scheduling problem (Drexl, 1997; Raza, 2006) and vehicle routing problem with time-window (Solomon, 1987; Braekers, 2016). Moreover, the collision and conflict avoidance constraints further increase the computational complexity. For a taxiing operations planning problem that consists of 52 gates, 79 transitional nodes (taxiway intersections), two (2) runways and 205 flights, no feasible solution could be obtained by IBM ILOG CPLEX Optimization Studio 12.5.1.0 on a personnel computer with 64 bit operating system, 3.40 GHz Intel Core i7-2600 CPU and 16.0 GB RAM. Consequently, alternative solution techniques have been explored.

4.2 Sequential Taxiing Operations Planning

Airlines determines their flight schedules based on a number of factors. The most important criterion is the 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). Air-corridors which correspond to the flight-rights, must be acquired by airline companies in order to schedule a flight between two markets at the specified time according to the acquired air-corridors. Finally the availability of resources such as the aircraft, pilots and flight attendances determines the scheduling of a flight between two markets. Once these conditions are satisfied, airlines prepare a flight schedule which follows a sequential order throughout a day. In this paper, flight schedules, as determined by the airlines, are considered as inputs to the model. While bottlenecks in the air or on the ground may impact the execution of these predetermined schedules, the excess capacity in the system would not change the predetermined schedules. This paper does not focus on the improvement of flight schedules. Consequently, a solution technique based on the sequential nature of the flight schedules is developed.

Let the flight set F be $F = \{f_1, f_2, \dots, f_F\}$ where arrivals and departures to/from an airport is indexed according to their scheduled arrival or departure times: $t^{f_i}_{EARLY_{LEAVE}(or\ DEPARTURE)} \leq t^{f_{i+1}}_{EARLY_{LEAVE}(or\ DEPARTURE)}$. Given that arrivals and departures are realized during the day sequentially according to their original schedules, flights are allocated in N groups according to their arrival and departure times as $F = \{F_1, F_2, \dots, F_N\}$ where F_j includes a subset of flights from F as $\left(F_j = \left\{f_i, f_{i+1}, \dots, f_{i+n_j}\right\}\right)$, and earliest flights in set F_{j+1} expected to enter the system later than the last flight in set F_j. Subsets of flights (n_j flights in each groups) are extracted from F based on the average arrivals observed within 10 minutes intervals. The first departure is realized in the morning at 6 AM. Since all resources (taxiways, towing vehicles and runways) are free at 6 AM, earlier aircraft do not need to compete for resources. Later flights slowly start being affected by the limitations on resources. Finally at some point during the day, the airport reaches a steady state operation level and all arriving and departing aircraft start competing for limited resources (gates, runways, taxiways and towing vehicles). 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 $\left(a_l^f \text{ and } d_l^f\right)$, towing vehicle assignment $\left(y_v^f\right)$ and next assignment for the towing vehicle $\left(z_v^{ff'}\right)$. Hence $s^f = \left\{x_l^f, a_l^f, d_l^f\ \forall l \in L: x_l^f = 1;\ y_v^f\ \ \forall v \in V;\ z_v^{ff'}\ \ \forall v \in V, f' \in F\right\}$. The outcome of the first solution is included in set $S_1 = \left\{s_1^1, s_1^2, \dots, s_1^{n_1}\right\}$ and is generated for $\forall f \in F_1$. In the consecutive step, flights in F_2 are included in the problem set 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 aircraft in F_1. Therefore, the information available in S_1 is introduced in the second problem as constraints for flights in F_2. The flowchart below depicts the overall strategy implemented for the sequential solution method (Figure 3).

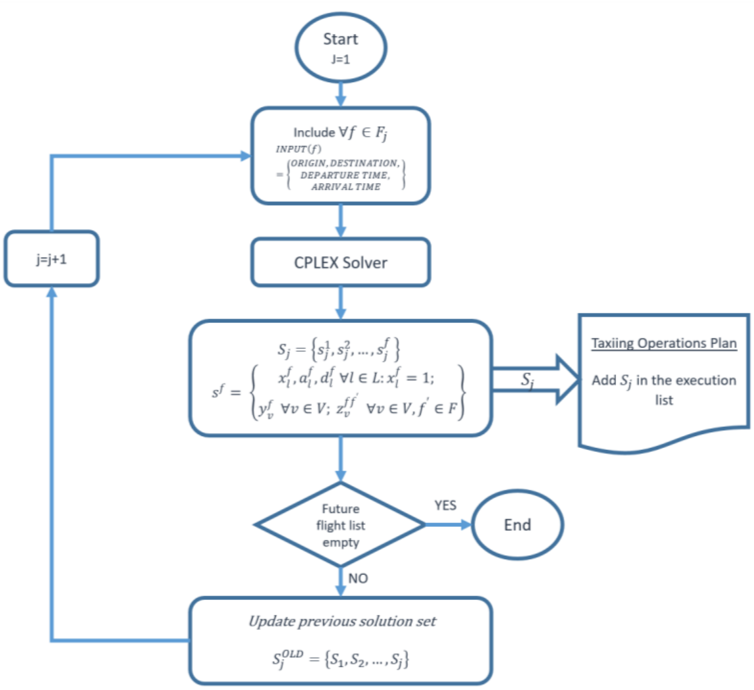


Figure 3: Sequential solution method

4.3 Results: Alternative scenarios and analysis

The main objective of the electrification of taxiing operations is to provide an environmentally friendly alternative to the current air-transportation practices without jeopardising flight safety and continue ensuring on-time arrival and departure performance. Our objective function is the minimization of cost that includes: i) towing vehicle operating cost; ii) fuel consumption cost; and iii) delay cost.

Towing vehicle operating cost: According to alibaba.com, the TK-QY400 aircraft towing vehicle with 450-ton towing capacity is priced at USD $355,000 and TK-QY200 with 200-ton towing capacity is sold for USD $120,000. Both vehicles are powered by diesel engines. Given that the electric powered cars are on average 20-30% higher than gas-powered options, we estimate an electric powered aircraft-towing vehicle to be marketed at $150,000 (QY200) and $400,000 (QY400). In recent years, self-driving options for passenger vehicles have gained enormous attention. Similarly, self-driving options for aircraft-towing vehicles will be a possibility in the near future. 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 4 for airport activities during a day); hence we anticipate towing vehicles to be operational for 2 shifts per day. According to available information concerning the operation of these vehicles, we conclude that two operators (each costing $50,000/year salary + 50% benefits) are required to operate a single towing vehicle. Given that airports operate 365 days, the average number of people required to operate a single towing vehicle is four (4). Moreover, according to Hooper (2017), towing vehicles require $6.65/hr for maintenance and repairs and $3 for insurance ($154.40/day). Consequently, the operating cost for a single towing vehicle is estimated to be $356,000/year. Assuming a 7-year depreciation period, the cost of operating a TK-QY200 is $378,000/year and a TK-QY400 is $414,000/year.

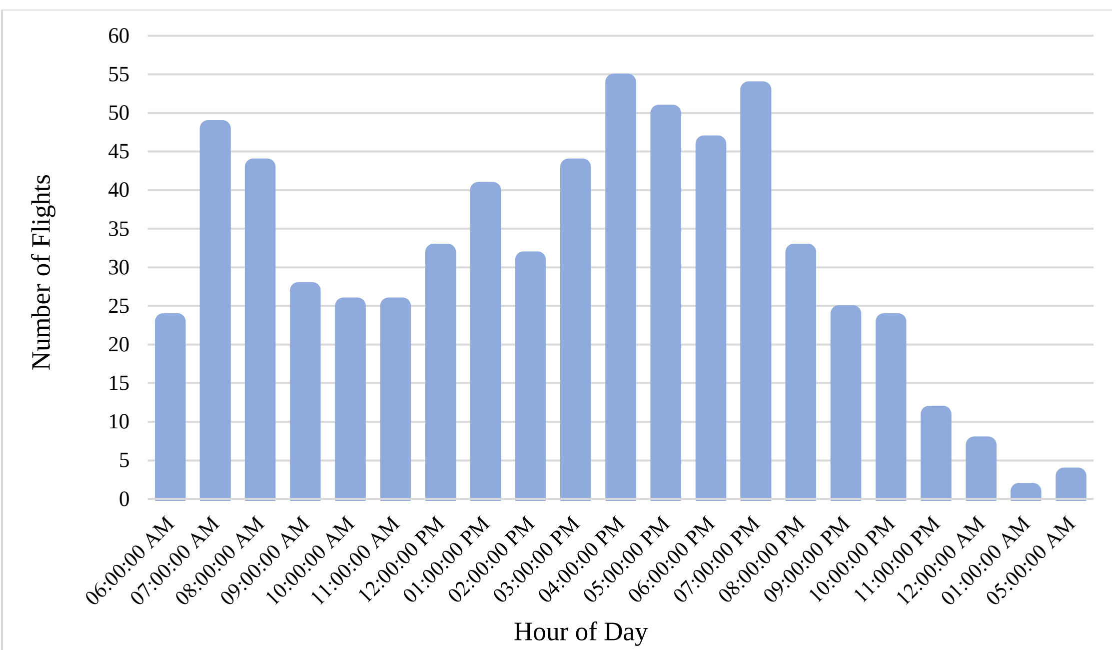


Figure 4: Frequency of arrivals and departures based on hourly intervals

Fuel cost during taxiing: In the mathematical model, it is assumed that an airplane does not consume any fuel during taxiing if the towing vehicle is coupled. On the other hand, aircraft that complete their taxiing by using their engines would consume up to 8 pounds (large aircraft), 5 pounds (medium aircraft) and 2 pounds (small aircraft) for per minute taxiing. In 2018, the average jet fuel cost was $2.50 in the US. The fuel consumption amount is calculate based on the speed and the distance travelled during taxiing. As mentioned earlier, we categorized aircraft based on their fuel consumption patterns in three groups: wide-body aircrafts (WB); narrow-body (NB) aircraft; and regional jets (RJ). We estimate WB, NB and RJ aircraft to burn $27, $17 and $10 worth of fuel per minute respectively during taxiing. The impacts of stops and starts on fuel consumption are not considered. The proposed mathematical model eliminates the need for full stops at intersections, hence the impact of stops and starts on fuel consumption is minimal.

Cost of earliness and delays: According to Airlines for America, the per minute direct aircraft delay cost was $74.20 in 2018. In addition to the direct costs, delays also cause significant productivity losses for the airlines. Furthermore, various forms of congestion occur due to access delays throughout the network; consequently this leads to over $28 billion US losses for the industry in the US (Airlines for America, 2018)

4.3.1 Case 1: All airplanes towed by a truck

We solved the aforementioned airport operations planning problem with an objective to tow all aircraft from gates to runways (or from runways to gates). First, we run the model for five (5) towing vehicles in the system. As seen in Figure 5, as the new flights enter the system, their waiting times (delays) considerably increase. Figure 5 clearly demonstrates that the system is not steady with five towing vehicles. Hence, we gradually increased the number of available towing vehicles in the system. As seen in Table 2, as the number of available trucks is increased, the number of delayed flights, delay time and consequently the total cost of delays are significantly reduced.

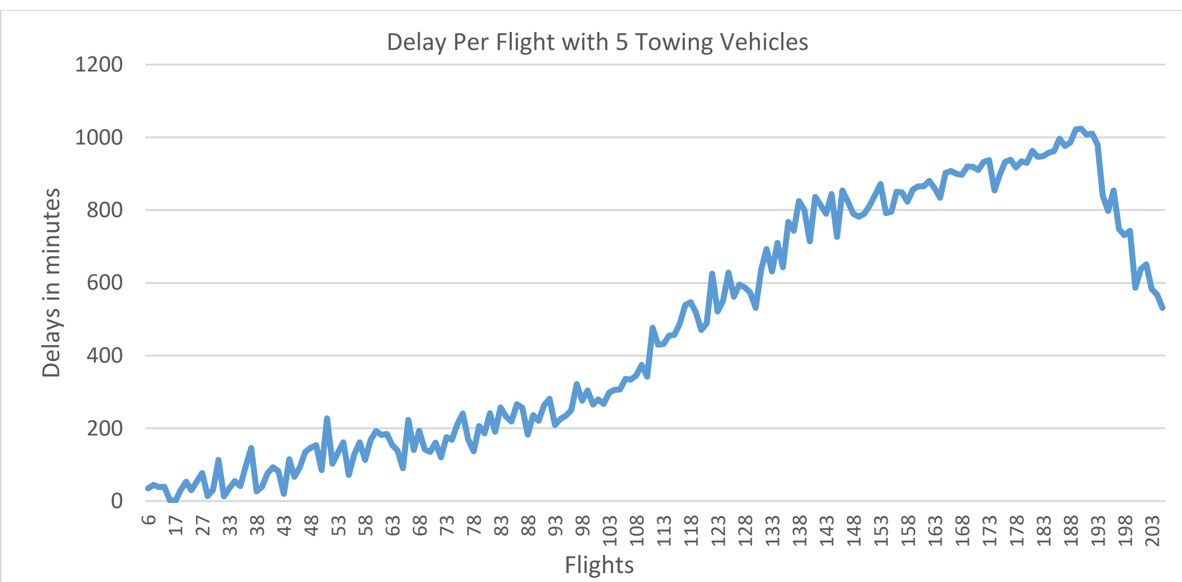


Figure 5: Delays for individual aircraft with five towing vehicles in the system

Table 2: Impact of the number of towing vehicle in the system performance and the yearly cost

Number of Tugs	Number of workers	Purchase cost (7 years amortization)	Yearly Energy Cost ($0.12/kWh, 33 KWh/hr)	Yearly labor cost	Yearly Maintenance Cost	Total Delays per Day (in minutes)	Yearly delay cost (74$/min)	Total cost
5	20	$321,429	$112,128	$2,000,000	$282,875	88,174	$2,445,938,993	$2,448,655,424
6	24	$385,714	$134,554	$2,400,000	$339,450	45,857	$1,272,066,522	$1,275,326,240
7	28	$450,000	$156,979	$2,800,000	$396,025	24,079	$667,939,254	$671,742,259
8	32	$514,286	$179,405	$3,200,000	$452,600	12,139	$336,740,021	$341,086,312
9	36	$578,571	$201,830	$3,600,000	$509,175	9,273	$257,224,421	$262,113,997
10	40	$642,857	$224,256	$4,000,000	$565,750	5,170	$143,402,485	$148,835,348
12	48	$771,429	$269,107	$4,800,000	$678,900	1,507	$41,798,632	$48,318,068
15	60	$964,286	$336,384	$6,000,000	$848,625	477	$13,232,812	$21,382,107
18	72	$1,157,143	$403,661	$7,200,000	$1,018,350	145	$4,022,023	$13,801,176
20	80	$1,285,714	$448,512	$8,000,000	$1,131,500	87	$2,413,380	$13,279,106
21	84	$1,350,000	$470,938	$8,400,000	$1,188,075	35	$965,352	$12,374,365
22	88	$1,414,286	$493,363	$8,800,000	$1,244,650	30	$289,606	$12,241,905
24	96	$1,542,857	$538,214	$9,600,000	$1,357,800	18	$72,401	$13,111,273
26	104	$1,671,429	$583,066	$10,400,000	$1,470,950	7	$28,961	$14,154,405
30	120	$1,928,571	$672,768	$12,000,000	$1,697,250	3	$5,792	$16,304,382

While increasing the number of towing vehicles in the system decreases the delay costs and improves the airport operations performance, each additional towing vehicle increases the operating costs. As seen in Table 2, the least expensive solution is obtained with 22 towing vehicles ($12,241,905/year).

4.3.2 Case 2: Hybrid option – Self towing option when tow truck is not available

In the second case, aircraft are given the self-towing option when towing vehicles are not available within a desirable time frame. When the model is tested with six towing vehicles out of 205 aircraft, 60 aircraft are selected to complete taxiing using their engines and the remaining 145 aircrafts are towed by towing vehicles. Similar to Case 1 results, the cost of handling taxiing operations is decreased as the number of towing vehicles is increased; however, the impact of towing vehicles' increase on total cost became negative once 12 vehicles in the system is reached (Table 3). In Table 3, the cost of operating towing vehicles is calculated based on purchasing cost (7 years amortized), labour cost, energy consumption (electricity) and maintenance cost. Accordingly, it can be concluded that, for the problem described in this paper, taxiing operations of 205 airplanes can be optimally managed with 12 towing vehicles. While the proposed MILP model for the airport taxiing operation problem enables decision-makers to select the optimum number of towing vehicles to minimize the cost, it also gives an opportunity to study the impact of taxiing operations on the environment. Figure 7 summarizes the fuel usage information for all aircraft which were not assigned to a towing vehicle. Moreover, with 12 towing vehicles in operations, for the described problem, the fuel consumption during taxiing is reduced by more than 80% in comparison to 6 towing vehicles in the system and over 95% when no towing vehicles is used.

Table 3: Impact of number of towing vehicles on yearly fuel consumption, delay and operating cost

Number of Towing Vehicles	Number of workers	Cost of operating towing vehicles	Travelling Time by Aircraft Engine (min)	Fuel consumption (gallons)	Fuel cost ($2.7/gallons)	Delays (min)	Yearly delay cost (74$/min)	Total Operating Cost
0	0	**$-**	2,520,322	12,223,564	**$33,003,623**	43,040	**$3,184,936**	**$36,188,559**
6	24	**$3,259,718**	639,743	3,102,753	**$8,377,432**	43,041	**$3,185,010**	**$ 14,822,160**
8	32	**$4,346,291**	455,795	2,210,606	**$5,968,635**	38,719	**$2,865,172**	**$13,180,098**
10	40	**$5,432,863**	264,990	1,285,202	**$3,470,044**	27,315	**$2,021,292**	**$10,924,200**
12	48	**$6,519,436**	123,005	596,574	**$1,610,750**	11,687	**$864,850**	**$8,995,036**
15	60	**$8,149,295**	36,526	177,149	**$478,302**	10,106	**$747,846**	**$9,375,443**
18	72	**$9,779,154**	31,532	152,932	**$412,916**	4,204	**$311,061**	**$10,503,131**
20	80	**$10,865,726**	23,886	115,845	**$312,782**	142	**$10,510**	**$11,189,019**

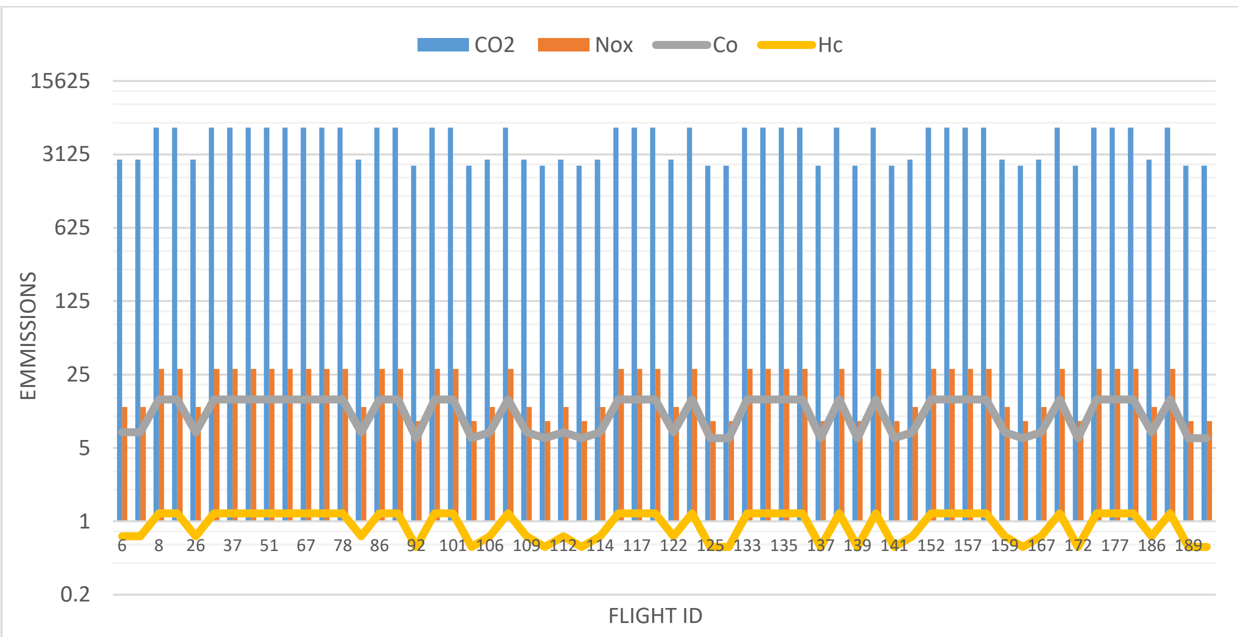


Figure 7: Emission amounts and the composition of emissions for aircrafts elected to self-taxiing

5. Conclusions

This paper introduces a MILP model to optimally control taxiing operations in an airport with an emphasis on collision and conflict and GGE problems. The major contributions of the paper are: first, the modeling of collision and conflict avoidance in a unified airline operations management model; second, the evaluation of towing truck usage to minimize fuel consumption; and finally the analysis of different strategies which may bring further insights to the airline and airport operations problem.

The developed mathematical models to tackle this problem are computationally complex and requires unique solution strategies in order to handle real-life-size problems. Hence we developed a sequential solution method which takes advantage of airlines' business practices.

Consequently, we were able to handle a large airport's daily traffic. We tested towing options (no-towing, 100% towing and optional towing). Hybrid solutions which gives an option to the aircraft to complete taxiing with its own engine power performed better in comparisons to no-towing or 100% towing options. While the hybrid option provides the most economical solution, it also help airlines to reduce their GGE during taxiing drastically (average 95% CO_2 reduction in comparisons to no-towing option).

While the mathematical models described in this paper provide an extensive analysis of airport operations with electric-powered towing vehicle options, only the deterministic cases are covered. Hence, further research is needed to better capture the impact of towing vehicle based taxiing operations management under stochastic airport operation conditions.

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