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DESIGN COMPETITION

Design the Allocation of External Alternative Aircraft

Taxiing System at Airports

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TABLE OF CONTENTS

1. EXCUTIVE SUMMARY

To further improve the economics and reduce the environmental impact of aviation operations, a new concept using external tugs to replace engine-powered taxiing has been proposed and adopted at some airports. We built a mathematical model and used it to explore the feasibility of such an external/alternative aircraft taxi system for Tampa International Airport. The taxiway structure and operations data of Tampa International are used as inputs, and several tug allocation strategy are designed to explore the feasibility and efficacy of the green taxiing operation. Efficiency and operational cost are used as indicators to determine the required number of tugs and the tug allocation strategy to satisfy the departure taxiing demand. The operational benefits and cost analysis show that the alternative aircraft taxiing system could reduce jet fuel consumption and associated emissions with only a modest impact on taxi times.

2. PROBLEM STATEMENT AND BACKGROUND

Jet fuel consumption is one of the key operating costs that airlines must consider. Most jet fuel is consumed during the cruise phase of flight, which has been optimized given forecasted weather and operational conditions and is hard for airlines to further reduce with tactical operation strategies. However, airlines have more flexibility of reducing fuel usage and corresponding air pollutant emissions in other flight phases, such as while taxiing, by using an alternative aircraft taxiing system (AATS) instead of the aircraft's main engines (Fordham et al., 2016). In conventional taxiing, the aircraft is pushed back from the gate to the apron by a pushback tractor, then some or all main engines are turned on and used to power the aircraft from the apron to the departure runway. However, these engines are designed for operation at high speed and power. Using the engines for much lower speed taxiing leads to unnecessary consumption of jet fuel and corresponding air pollutant emissions.

The AATS developed in recent years fall into two categories, external or on-board. External systems include dispatch and semi-robotic dispatch AATS. On-board systems include nose-wheel and main-landing-gear-mounted AATS, and on-board taxi jet engines. The two categories and five types of AATS are shown in Figure 1.

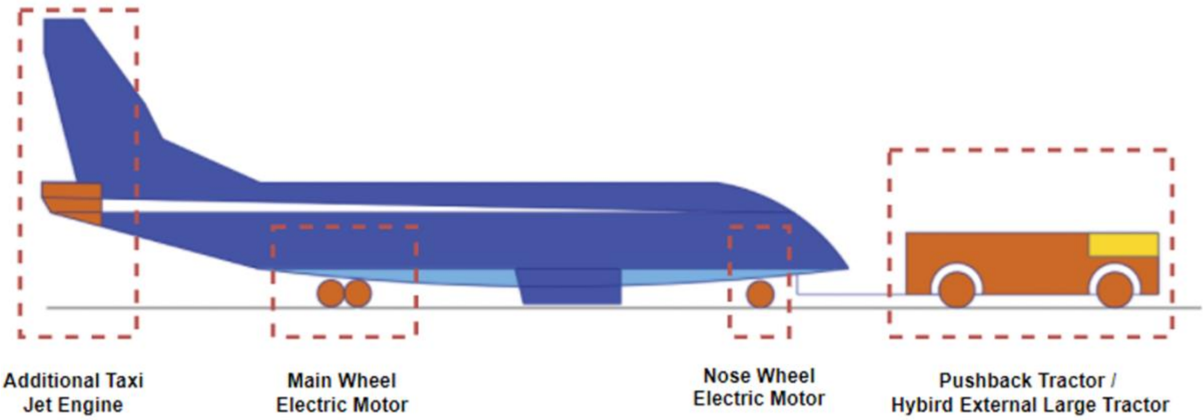

Figure1 Five types of alternative aircraft-taxiing systems

Dispatch or semi-robotic dispatch AATS are tractors designed with high horsepower that can tow the aircraft from the gate to the departure runway. They are different from conventional pushback tugs, which are only used for aircraft backward movement from gates to hand-off points. The dispatch and semi-robotic dispatch AATS has automated features built-in so that they can easily to be hooked up with the aircraft and follow a designated taxiing path (Re, 2012b; Deonandan and Balakrishnan, 2010). While aircraft engines can use sustainable jet fuel, such fuel is of limited availability. The tractors in external systems can be powered by many kinds of renewable energy. On-board systems use the onboard Auxiliary Power Unit (APU) to power motors in the aircraft wheels or add an additional jet engine that is specifically designed for taxiing purposes. On-board systems must still rely on jet fuel but benefit from increased fuel efficiency.

Whether to install an on-board system is obviously the decision of the airline. Given that this is a low profit margin industry, such an investment may not come easily. On the other hand, external systems can be purchased by airports and airlines collaboratively. This may also be attractive for airports with more severe air pollution and noise issues. However, airports have different layouts and flight operation features. At some airports, terminal buildings may be designated for specific airlines, e.g., JetBlue has one designated terminal at Newark Liberty International Airport. Furthermore, according to the agreement between airports and airlines, some of the terminal gates are exclusively used by certain airlines. Thus, careful attention must be given to design when considering external AATS at an airport. This is the objective of this design project, and we will use Tampa International Airport to demonstrate our design concept, approach, and outcomes.

3. SUMMARY OF LITERATURE REVIEW

Several studies have shown that the electric taxiing system is more fuel-efficient, emission-reduced, and cost-effective than the traditional (diesel tug) taxiing system. Dzikus et al. (2011) analyzed the fuel-savings of an on-board taxiing system. He emphasized that potential fuel savings are determined by plane types, total taxiing time, and flight distance. For example, a short-haul aircraft (like an A320) that carries people or cargo on a flight of 1,000 nautical miles can save 3% in block fuel. Total estimated savings on US domestic flights performed by A320s and B737s in 2007 range from 1.1 to 3.9%, based on the weight of the system. Roling et al. (2015) studied the electric tug taxiing speed limit and subsequent delays. The results showed that an average speed of 10 meters per second for electric tugs should not cause major flight delays. Hospodka (2014) found in the worst-case scenario, with the lowest possible savings and the highest cost, an estimated cost savings of 250 euros per cycle using the electric taxiing system. Considering that an aircraft performs approximately 1,000 cycles per year, air operators can save up to 250,000 euros per aircraft per year. The fuel-saving and emission reduction of various electric taxi systems have been studied by Guo et al. (2014). They found that compared with the traditional taxiing method, the on-board electric taxiing system can achieve the greatest CO emissions reduction, while the external electric taxiing system can achieve the greatest fuel savings, but with an increase in NOx emissions.

Lukic et al. (2019) summarized the characteristics of different electric taxing systems (ETS) and conducted an overall review of ETS, including external and on-board ETSs. A comprehensive comparative challenges analysis was carried out. Research showed that based on the current development of ETS, it could be foreseen that although there is no significant taxiing time saved in total, some apparent advantages can be summarized: 1) Depending on the flight distance and the weight of the airborne ETS, the amount of fuel burned will be reduced by 14 %. 2) Each aircraft can save 50,000 to 500,000 U.S. dollars per year by using ETS. 3) According to the capabilities of the fleet and the characteristics of the airport, by alternately employing external and on-board ETS, the advantages of adopting ETS can be maximized.

The Smart Urban Mobility Laboratory (SUM Lab) at the University of South Florida (USF) compared various emerging AATS and presented a comprehensive review on the merits and challenges of each system, along with the local environmental impacts of these systems (Guo et al. 2014). Using operational data for the 10 busiest U.S. airports, a comparison of conventional, single engine-on, external, and on-board systems show that there are tradeoffs in fuel and emissions among AATS. On-board systems exhibit the best performance in emission reduction, while external systems show the least fuel burn. Compared to a single-engine scenario, external AATS shows a reduction of HC and CO emissions but an increase of NOx emission. When a general indicator is considered, on-board AGPS shows the best potential of reducing local environmental impacts. The benefit-cost analysis shows that both external and on-board systems are worth being implemented and the on-board system appears to be more beneficial.

The advisor of this design project, Dr. Yu Zhang, also participated in one TRB ACRP project and contributed to ACRP Report 158: Deriving Benefits from Alternative Aircraft-Taxi Systems. This research project explored how AATS could provide net benefit for both the airport and aircraft operator. Besides the benefits of the AATS, the research also investigated potential challenges to aircraft operators and air traffic control, as well as needs of expanding airport infrastructure to accommodate the operations of AATS, especially the external AATS. One of the products of the project is the Alternative Taxiing Assessment

Matrix (ATAM) tool, a spreadsheet tool that allows the user to enter different aircraft fleet mixes and taxiing times to assess potential overall fuel and emissions changes of AATS.

It was emphasized in the ACRP report that airlines and airports, while considering implementing AATS, are aware that the external systems can be used for different aircraft types and different airlines whereas the on-board system will be installed on particular aircraft. Also, the investment of the external AATS could be supported by both airports and airlines (through agreement between them on capital improvement projects).

The aircraft towing process was studied by Du et al. (2014), who proposed a MIP-mixed-integer-programming model based on the vehicle routing problem (VRP). The model assigned different types of towing tugs combining multiple stops, mixed fleets, and multiple trips. In the case of meeting certain operating conditions (such as the technical compatibility of the tug type and the aircraft type), an optimization model with the minimum operating cost as the objective function is proposed, which solves the scheduling problem of the airport towing process.

To reach the maximal economic and environment benefits of external AATS, the tugs should be powered by electricity rather than diesel fuel. Relevant studies have shown that electrically powered external AATS not only affect the taxiing phase but also the apron and pushback procedures. They can improve the efficiency of apron operations, reduce delays and increase gate capacity. In a study analyzed by Sopnel et al. (2017), the pit stops expansion analysis model showed that when the turnaround time of a pit stop candidate reaches at least 170 minutes, a maximum of 25% of the added flights can be scheduled. In addition, the qualitative evaluation of the value model shows that electrically powered external AATS can improve the safety, capacity, and efficiency of the airport apron environment while reducing cost and environmental impact.

Program integration is an important aspect of the air transportation system, which mainly focuses on interoperability, safety, and security. A semi-automatic vehicle called TaxiBot (Taxiing Robot) was used as a prototype to analyze the integration of loading and unloading vehicles and aircraft during taxiing (Postorino et al., 2016). This study verified how to better integrate vehicles and aircraft using the usual airport procedures (especially for the taxiing procedure), thus benefiting the local communities and air transport participants. Results show that the introduction of this system and the improved integration of tugs and aircraft during taxiing have brought environmental benefits to local communities and economic benefits to airlines.

4. PROBLEM SOLVING APPROACH TO THE DESIGN CHALLENGE

Based on the literature review, this design project focuses on the implementation of external AATS, using TaxiBot as the possible external AATS, which is powered by a hybrid combination of electric and diesel engines. The objective of the design is to optimize tug allocation, considering two system performance metrics: the time the aircraft is waiting for the tug and the total aircraft taxi time. Our design approach includes developing a simulation tool that can be used to evaluate the performance of different AATS allocation strategies, analyzing the trade-off between the two performance metrics (if any), and determining the optimal strategies. The simulation modules and data processing procedures are shown in Figure 2. The detailed steps are elaborated in the next several subsections.

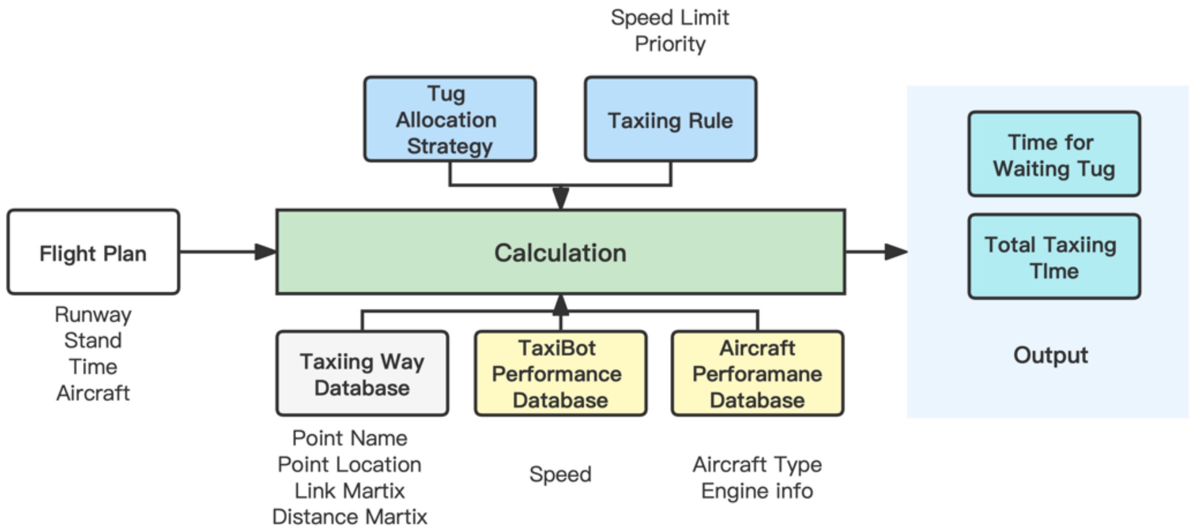

Figure 2. Simulation tool for evaluating performance of external AATS allocation strategies

4.1 Data Collection and Process

Data used in the simulation includes the airfield geometry, airport operational data, and external AATS operating parameters. Airfield geometry data is collected from Google Earth and an airport GIS map. The operational data describing the number of scheduled arrivals and departures is obtained from the FAA Aviation System Performance Metrics (ASPM) data store. In this study, TaxiBot is chosen to represent the external AATS and its operating parameters are obtained from publicly accessible online resources.

4.1.1 Airfield Network

The study airport airfield map is digitalized into a node-edge network by discretizing the taxiways, marking nodes at the junctions of the runways and taxiways, the intersections of taxiways, and the junctions between the taxiways and aprons, using google earth to estimate the distance between the nodes (see Figure 3).

Figure 3. Digitalized study airport airfield network

4.1.2 Airport Operational Data

The FAA ASPM database contains airport quarterly or hourly operational data as well as detailed flight-specific operational data. Nine elements from the database (as shown in Table 1) were collected to define the departure process for departing aircraft.

Table 1. Data Elements and Example from ASPM

No.	Data Elements	Example
1	Date	2020-02-02
2	Flight ID	AAL541
3	Aircraft Type	A319
4	Departure Airport	TPA
5	Arrival Airport	DCA
6	Actual push out time	66720
7	Actual departure time	67500
8	Stand	F78
9	Runway in use	1L

The flight ID is used as the unique identifier of the aircraft, the departure and arrival airports are used to identify the flight as an arrival or departure for the study airport, and the parking position information and runway in use information are used to obtain the corresponding taxi route and distance. The actual push-out time is used as the estimated push-out time of the aircraft in the simulation, and the actual take-off time is used as a key parameter for evaluating the operating efficiency of taxiing.

Statistical information about the total number of departures and the detailed departure plan for the different terminals and runways can be found in Appendix A.

4.1.3 Operating Parameters of TaxiBot

Following the suggestions of the ACRP report on AATS, only departure aircraft falling into the light to medium wake turbulence categories will be towed by external AATS from the gate to the runway. Heavy departure aircraft and all arrival aircraft will use the conventional taxiing mode powered by aircraft main engine(s). For this case study of Tampa International Airport, Table 2 shows the counts and percentage of arrival and departure aircraft in different wake turbulence categories. We can see that heavy departure aircraft comprise less than 6% of total departures.

Table 2. Wake Turbulence Categories at Tampa International Airport in 2019

			Wake Turbulence Category (WTC)			Total
			Light (L)	Medium (M)	Heavy (H)	
Flight category	Departure	Count	38	1,716	105	1,859
		% in departure	**2.04%**	**92.31%**	5.65%	100.00%
	Arrival	Count	39	1,713	106	1,858
		% in arrival	2.10%	92.20%	5.71%	100.00%
Total		Count	77	3,429	211	3,717
		% in total	2.07%	92.25%	5.68%	100.00%

Therefore, we refer to the operating parameters of the Narrow Body (NB) TaxiBot (TaxiBot., n.d.) and set the unloaded taxiing speed of the tug to 8.33m/s, and the loaded taxiing speed of the tug to 5.56m/s.

4.2 Understanding the Current Taxiing Process at TPA

The taxiing process of the aircraft on the surface can be divided into two types: departure taxiing starting from the terminal gate and ending at the waiting point of the departure runway, and arrival taxiing beginning at the exit of the arrival runway and ending at the target stand. For departing aircraft, the taxiing process can be further divided into two parts: pushing out and taxiing to the runway.

Figure 4 Sample taxiing routes of arrival and departure aircraft

When the aircraft is ready to go, the pilot will apply for clearance to push-out. A push-out tractor will be attached to the aircraft and push the aircraft away from the parking stand. During this process, the aircraft does not turn on the main engines, and the power required for the movement of the aircraft is completely provided by the tractor. At a certain location of the apron area, the tractor will be detached from the aircraft, pilots will turn the main engines on and, after about 5 minutes warm-up, the aircraft will taxi into the active movement area, follow the assigned taxi path, and arrive at the waiting point close to the end of runway. When the aircraft gets permission from the air traffic controller, it will enter the runway to perform the takeoff steps.

For arrival aircraft, after exiting from the runway, the aircraft will taxi to the designated terminal or remote stand following the path designated by the tower air traffic controller. This process is powered by the main engines.

4.3 Simulation of the Taxiing Phase with External AATS

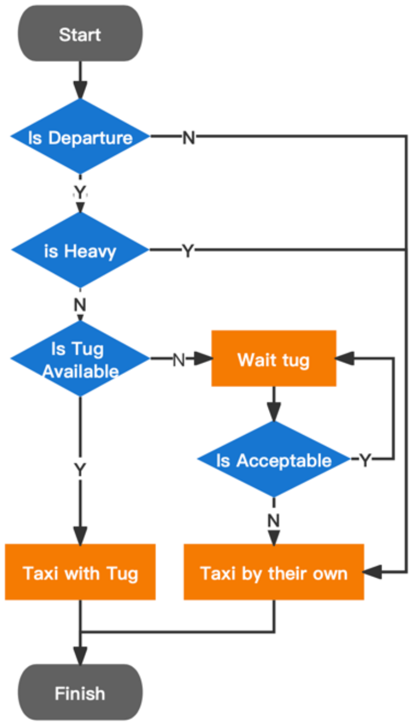

Figure 5. Module of simulating taxiing phase

As discussed earlier, departure aircraft falling into light and medium wake turbulence categories can be towed by external AATS. A maximum wait time threshold is used for eligible departure aircraft waiting for the next available external AATS; if this wait time is reached the aircraft will taxi out following the conventional push-back, main engine on, and taxiing procedure. When the aircraft moves to the waiting point at the end of the runway, the aircraft will be separated from the external AATS, the external AATS will return to the terminal building, and the aircraft will enter the runway and take off after getting permission from the air traffic controller. All arrival flights will taxi in without using external AATS. This taxi logic is depicted in Figure 5.

4.3.1 Assumptions for Simulating the Implementation of External AATS

While developing the simulation tool, the following assumptions were made:

a) The tug moves at a constant velocity without considering acceleration and deceleration during movement. In addition, the tugs will move at the full loaded speed when towing an aircraft, and move at the unloaded speed when not towing.

b) If there is a potential conflict between arrival aircraft, departure aircraft (towed by tug or not), and repositioning tugs during surface movement, the arrival aircraft gets the highest priority, followed by the departure aircraft, and then the tug.

c) No auxiliary taxiway is added to the taxiway-runway network at the study airport.

4.3.2 Variables and Notations

Based on the above assumptions, the operation of the AATS and aircraft movement in taxiway network is simulated. The following variables are used in the simulation:

F: $Set\ of\ Aircraft$

G: $Set\ of\ Terminal\ Gate$

R: $Set\ of\ Runway$

E: $Set\ of\ Tugs$

I: $Set\ of\ Nodes\ on\ Taxiing\ way$

RT_f: $Ready\ time\ for\ aircraft\ f$

$POT_f: Push\ out\ time\ for\ aircraft\ f$

$AT_{f,i}: Arrival\ Time\ on\ Node\ i\ for\ aircraft\ f$

$PT_{f,i}: Passed\ time\ on\ Node\ i\ for\ aircraft\ f$

$DT_f: Departure\ time\ for\ aircraft\ f$

$RT_e: Ready\ Time\ for\ Tug\ e$

$BT_e: Go\ back\ Time\ for\ Tug\ e$

$CT_e: Charging\ Time\ for\ Tug\ e$

$T_i: Last\ passedby\ time\ on\ Node\ i$

$Sep_i: Seperation\ time\ for\ the\ Node\ i$

$TT_{g,g'}: Transferring\ Time\ between\ Terminal\ g\ and\ Terminal\ g'.$

4.3.3 Simulation Modules

The simulation tool includes three modules: 1) Assigning the tug to the ready-to-push-back aircraft; 2) Modeling taxiing of aircraft; 3) Modeling the idle tug going back to the terminal.

Module 1: Tugs will be assigned to eligible departure aircraft following first-ready-first-serve rule. Note that the heavy aircraft will not be towed by the tug. Given the time of aircraft ready for being pushed back, the module will search available tugs, if the answer is “Yes”, the tug will be assigned to the aircraft. The push-back time of the aircraft will be the later time of aircraft ready time and tug ready time.

$$POT_f = \max(RT_{f_i}, RT_{E_i}) \qquad (1)$$

A waiting time threshold is set up in the module. If the ready departure aircraft cannot be assigned with a tug after the thresholder time, the aircraft will be pushed back with conventional tractor and turns the main engines on for taxiing to the end of runway.

Module 2: According to the information of the stand where the aircraft is located and the runway it plans to go, this module assigns a taxiing path to the aircraft by looking up the path table. Potential conflicts between aircraft or aircraft and idle tug at the intersection of taxiing paths is resolved in this module by following a first-come-first-serve rule. Thus, the time for the aircraft (towed by tug) to reach the end of the runway can be obtained.

$$PT_{f_i,N_i} = max\left(AT_{f_i,N_i}, T_{Ni} + Sep_{N_i}\right) \qquad (2)$$

Module 3: When the aircraft and tug reach the end of the runway, the aircraft and tug will be detached. This module simulates the return of tug to the terminal. For case study, Tampa International Airport, it is assumed that no auxiliary taxiways are added to the existing taxiway network. If there are any potential conflicts between idle tug and aircraft, the idle tug will wait for the aircraft to pass before it can keep on moving. Once the idle tug returns to the terminal, it will appear in Module 1 as an available tug.

Note that in this simulation, we assumed the tug is powered by a hybrid combination of electric and diesel engines and there is no range limit. The simulation tool can be further expanded for electric tugs considering the charging needs by monitoring the level of charge of the electric tug and adding a rule of allowable low level of charge. The tug will be charged if the level of charge is lower than the threshold. The charging time will be calculated and thus the tug ready time.

4.3.4 Tug Allocation Modes

Where and how many tugs allocated to airfield concourses will affect the taxiing performance. Based on the understanding of flight operations at study airport, Tampa International Airport, we tested four allocation strategies, Decentralized, C-Exclusive, Part-Decentralized, and Centralized. The main differences of these strategies are the operation coverage and affiliation of the tugs. In the Decentralized mode, each terminal owns its tugs and the tugs only service the departure aircraft from that terminal. Knowing the Terminal C at Tampa International Airport is exclusively used by Southwest Airlines, we also set up a C-Exclusive mode assuming that tugs at terminal C will exclusively serve the departure aircraft from the terminal C. For other terminals, they share a fleet of tugs. Part-decentralized mode let two terminals close to each other use the same fleet of tugs. As shown in the figure below, Terminal E and F will share the fleet, and Terminal C and A will share the fleet. The Centralize mode let all terminals share the same fleet of tugs.

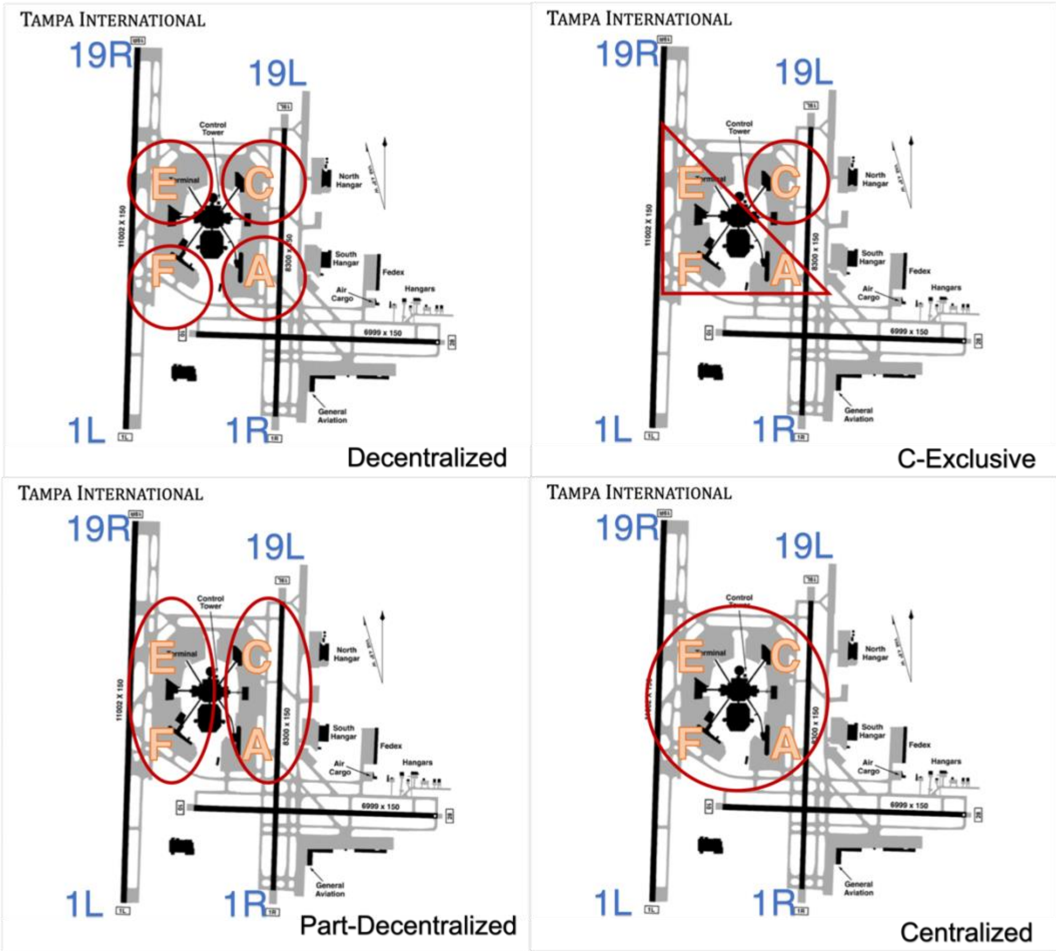

Figure 6. Four tug operation modes

Table 3. Tug Allocation Strategies

Mode	**Operation range**
Decentralized	(A) (C) (E) (F)
C-Exclusive	(A, E, F) (C)
Part-centralized	(A, C) (E, F)
Centralized	(A, C, E, F)

4.3.5 Metrics for Evaluating the Efficiency of Taxiing Phase

To apply the external AATS to Tampa International Airport, it is necessary to consider both the operating cost of the tugs and taxiing efficiency of the departing aircraft.

Thus, post-simulation analysis is performed to calculate and compare the two performance metrics for different allocation strategies.

4.4 Experimental Design of Simulation

In the simulation design, the four tug allocation strategies were applied to the operation of the alternative taxi system. For each strategy, we set the tug number from 2 to 4 for each terminal. The total combination of the tug numbers is 2*2*2*2 for four terminals, and in total there are 81 scenarios (see Appendix H for details). For each scenario, we used one day's operation data as the input to simulate aircraft taxiing and calculated the taxiing time and time for aircraft waiting for tugs.

The simulation was coded in MATLAB and runs on a 2.0 GHz Mac computer with 16 GB RAM under a 64-bit macOS 10.15 operating environment.

4.5 Experiment Result Analysis

4.5.1 The impact of operation mode and total tug number on average departure taxiing time

Figure 7 shows the impact of operation mode and total tug number on average departure taxiing time. Each node in the figure denotes one tug allocation scenario (mode and combinations of numbers of tugs) and the red line is the frontier of the results, which shows the allocation scenario leading to lowest average departure taxiing time. The black arrow points to the results with minimal average taxiing time.

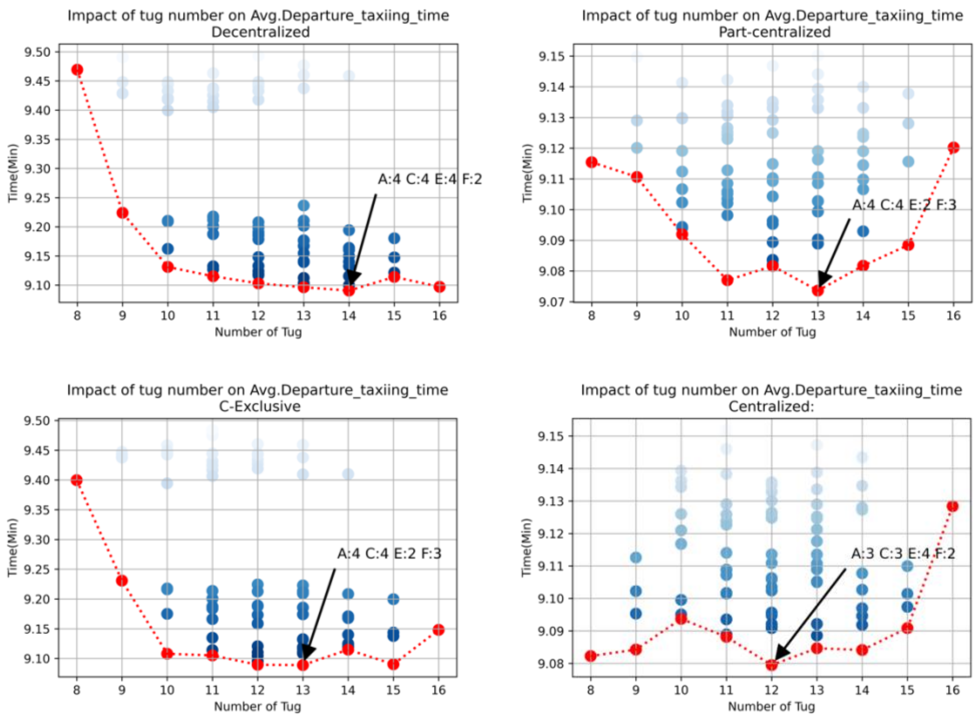

Figure 7. The impact of operation mode and tug number on average taxiing-out time

We can see from the figure that the Decentralized mode is the least efficient in terms of average departure taxiing time, unless the total number of tugs exceeds 15. It shows that Part-Centralized mode with a total of 13 tugs leads to the lowest average departure taxiing time. The allocation of the 13 tugs is [A:4; C:4; E:2; F:3]. However, for slightly higher average departure taxiing time, Centralized mode can save one tug, from 13 to 12, with the allocation of [A:3; C:3; E:4; F:2].

4.5.2 The impact of operation mode and total tug number on average waiting time for tug

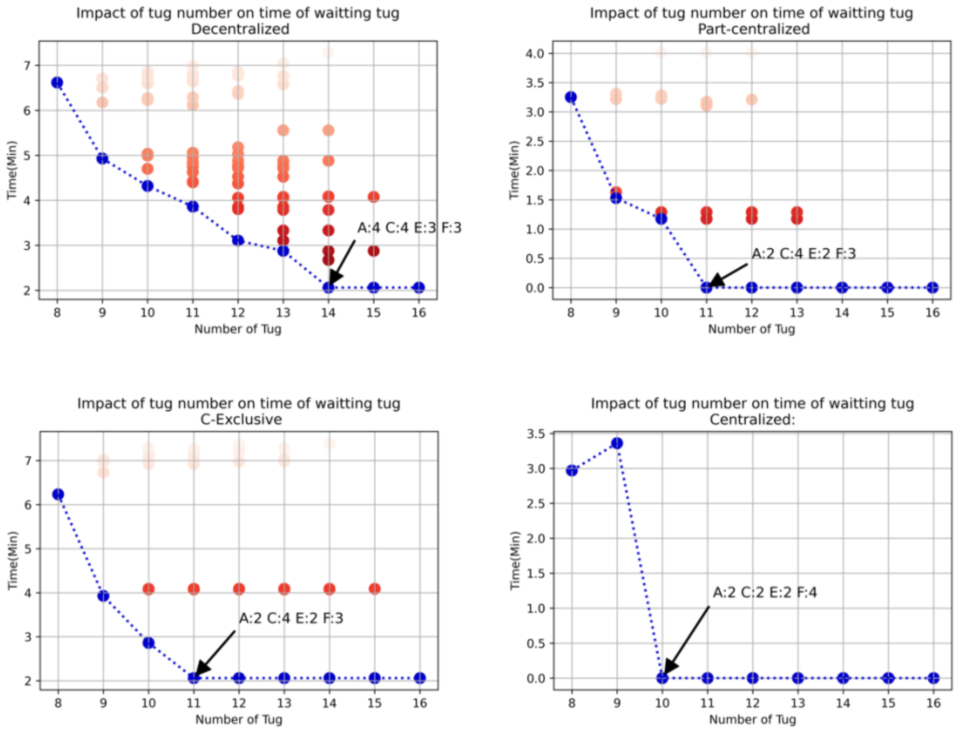

Figure 8. The impact of operation mode and tug number on average time of waiting for tugs

For time of waiting for tugs, Decentralized mode demonstrated the worst performance. Even with large number of tugs, (14, 15, or 16), there still be waiting time for tugs. Part-Centralized and Centralized modes work much better. For Part-Centralized mode, if there is a total of 11 tugs being allocated as [A:2; C:4; E:2; F:3], tugs could be readily available for departing aircraft. For Centralized mode, the total number of tugs could be reduced to 10 with the allocation of [A:2; C:2; E:2; F:4] for serving the departing aircraft without letting them waiting for tugs.

4.5.3 Summary of Experiment Result Analysis

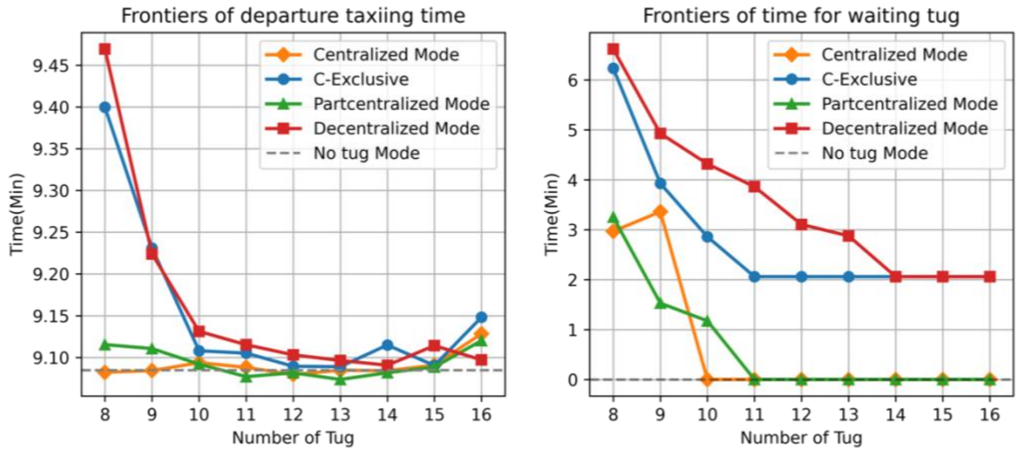

Figure 9. The frontiers of average taxiing out time and time for waiting for tugs

Figure 9 shows the frontiers of different allocation scenarios for two performance metrics. Table 4 lists the tug allocation leading to minimal average taxiing out time and waiting time for tugs. The main findings of the experiments are listed below.

1) For both performance metrics, at Tampa International Airport, Part-Centralized mode and Centralized mode work better than Decentralized and C-Exclusive mode. While taking average taxi-out time as performance metric, when the total number of tugs exceeds 15, e.g., 16, the Decentralized mode performs better than three other modes.

2) The difference of performance metrics is negligible for Part-Centralized and Centralized mode; however, Centralized mode requires one less tug, which could reduce the capital investment of implementing the external AATS at Tampa International Airport.

Table 4. The impact of tug number on departure time and time for waiting tug

	Sharing Index	Total Number of Tugs with Minimal Avg. Taxiing Out Time	Minimal Avg. Taxiing Out Time	Total Number of Tugs with Minimal Avg. Waiting Time for Tugs	Minimal Avg. Waiting Time
Centralized	1	12	9.079	10	0
C-Exclusive Mode	0.75	13	9.088	11	2.060
Part-centralized	0.5	13	9.074	11	0
Decentralized	0	14	9.091	14	2.060

3) The trade-off between the two performance metrics need to be taken into consideration because the detailed allocations of tugs are different at the dominant points.

4.6 Conclusions of the Design Project

Existing literature has proved the economic and environmental benefits of alternative aircraft taxiing systems (AATS). Compared to on-board systems, external tugs, towing departing aircraft from terminal stand to the end of runways, have some appealing advantages. However, to implement such systems, airports need to determine the appropriate number of tugs and allocations of tugs given the layout of terminal buildings and airside taxiway network, as well as aircraft operational patterns. This design project tackled the challenges by developing a simulation tool and using that to evaluate the performance of different allocation scenarios and determine the optimal allocation scenario.

Taking Tampa International Airport as the case study, the research team proposed four allocation modes, Decentralized, Terminal C Exclusive, Part-Centralized, Centralized and created 81 allocation scenarios. Simulation results show that Part-Centralized and

Centralized mode with a total of 11, 12 or 13 tugs outperform other scenarios. If average taxiing out time is considered as the critical performance metric, Part-Centralized mode with the allocation of [A:4; C:4; E2; F3] is the best. If average time of waiting for tug is considered as the critical performance metric, Centralized mode with the allocation of [A:2; C:2; E:2; F:4] is the best.

Given that the optimal allocation scenarios could be different while considering two performance metrics, decision makers can select the optimal allocation scenario based on the needs of a particular airport.

This design project fills in the gap of potential implementation of external AATS and contributes to making airport greener. The simulation tool can be used at other airports by updating the inputs, e.g., airport layout and taxiway network, suitable allocation modes for the airport, aircraft operation data, and for testing different allocation scenarios.

5. SAFETY RISK ANALYSIS

Compared to conventional taxiing procedures, implementing external AATS at airport increases the volume of moving objects (idle tugs) in taxiway system if no auxiliary taxiways are added in the network. In this section, we conduct a safety risk analysis based on the safety risk management (SRM) process outlined in the Safety Management System (SMS) manual (FAA, 2017).

According to FAA SRM requirements, the evaluation process is divided into five stages: (1) describing the system, (2) identifying hazards, (3) analyzing the risk in terms of likelihood and severity, (4) assessing the risk, and (5) controlling the risk. FAA SRM also uses a forecasted risk matrix as shown in Table 5).

Table 5 FAA Risk Classifications

Severity / Likelihood	No Safety Effect (1)	Minor (2)	Major (3)	Hazardous (4)	Catastrophic (5)
Frequency (5)	5	10	15	20	25
Probable (4)	4	8	12	16	20
Remote (3)	3	6	9	12	15
Extremely (2)	2	4	6	8	10
Extremely Improbable (1)	1	2	3	4	5

Note: Red indicates high risk, yellow medium risk, and green low risk.

Table 6 summarizes the analysis results. We can see that the likelihood of listed events at different function spaces are remote or extremely remote. Also, additional countermeasures could be applied to further reduce the likelihood of hazards occurance.

Table 6 Safety Assessment Analysis of Additional Idle Tugs in Airfield

Function Space (Event)	Hazards	Likelihood	Severity	Additional Countermeasures
Runway (Tug runs into runway)	Runway incursion; Affect aircraft take-off and landing	Remote	Hazardous	Connected vehicle technologies can be applied to monitor the conformity of taxiing path.
Taxiway (Incident involving tug)	Tugs collide with aircraft and other tugs.	Remote	Major	1. Improve taxiing route selection and conflict resolution. 2. Reduce tug's speed limit.
	Tugs break down in the middle of taxiway; Affect the movement of aircraft.	Remote	Minor	1. Notify AOC urgently and coordinate aircrafts to bypass. 2. Apply proactive maintenance.
	Tugs collide with ground support equipment (refueling vehicles, luggage carriage, shuttle bus, etc.)	Remote	Minor	1. Improve the signs and marking 2. Educate drivers
Apron area (Incident involving tug)	Tugs collide with staff	Extremely Remote	Minor	Operators must wear reflective vest.
	Tugs collide with passengers (especially passengers waiting for	Extremely Remote	Minor	1. Remind passengers to pay attention to surroundings. 2. Improve the dispatch of

	shuttle bus)			shuttle bus to reduce passengers' exposure in the apron area.
	Tugs collide with aircrafts parked on apron (especially for night or when the line of sight is not good)	Extremely Remote	Minor	Improve lighting。

6. COST AND BENEFIT ANALYSIS

6.1 Cost Analysis

The cost of implementing external AATS contains purchase cost, operating cost, maintenance cost, and labor cost. According to previous analysis, 10 tugs could meet the taxiing demand of the Tampa International Airport. Thus, we suggest ten tugs being purchased and assume the life span of tugs is 15 years. So the annual purchase fee is set as the total purchase fee divided by 15. (*Celebi Aviation to Invest Rs 354 Crore Towards Taxibots for Indian Airports*, n.d.)

For the energy consumption of hybrid tugs, each TaxiBot has a 600L tank that can support one day's operation. Thus, we assume that each tug will consume 600L diesel per day. The average price of diesel is $5.37 per gallon ((Byron Hurd, n.d.)(accessed by May 03, 2022), which is equal to $1.18 per liter.

The Maintenance fee containing the inspection fee and parts purchase fee. We assume that tugs need to be fully checked twice a year. The parts purchase costs $2,000 per tug per year.

The labor fee containing the salary for hiring tug operators and tug dispatchers. We assume the average annual salary of the operators and dispatchers is $60,000. For operational hours from 6:00am to 11:00pm, three operators are needed to support one tug. For the same operation time, the airport needs at least three dispatchers.

Table 7 Operation cost of External Alternative Aircraft Taxiing System

Item	Price	Quantity	Annual Cost	Additional Annual Cost*
Purchase of TaxiBot	$1,580,000 per tug	10 tugs (life span of 15 years)	$1,053,333	$948,000
Diesel Consumption	$1.18 per Liter	600L per tug per day	$2,584,200	$2,067,360
Maintenance Check Fee	$100 per check	2 per year per tug	$2,000	0
Maintenance Parts Fee	$2000 per tug	10 tugs	$20,000	0
Labor Fee of tug operators	$60,000 annual salary	3 operators per tug	$1,800,000	$600,000
Labor fee of dispatcher	$60,000 annual salary	3 dispatchers	$180,000	0
Total Annual Cost			$6,166,200	$3,615,360

*Compared with conventional taxiing system.

To summary the discussion, Table 7 lists the estimated costs. Note that for comparing with the benefits of implementing external AATS elaborated in next section, we need to obtain additional cost of external AATS compared to conventional taxiing system. The convectional tractors will be replaced by external AATS. About 10 percent of the purchase cost could be covered by the liquidation of existing equipment. The diesel consumption of AATS, towing aircraft from terminal stand to the end of runway, is much higher than conventional tractors that only perform push-back of aircraft in apron area. Maintenance cost of a feet of tugs versus conventional tractor is about the same. Consider the operating time of AATS is longer than conventional tractors, about 10 more tug operators are needed for implementing external AATS. However, no additional dispatchers are needed. Thus, as shown in the last column of Table 7, the total additional annual cost of implementing external AATS is estimated as $3,615,360.

6.2 Benefit analysis

The advantages of applying external AATS are reflected in jet fuel saving, emission reduction, prolonging the service life of aircraft, and improving airport operation efficiency.

The fuel saving effect include the fuel saving during the taxiing phase without turning main engines on and the fuel saving during the cruising phase by carrying less fuel on board. For example, with conventional operation, the average taxi out time at Tampa International is about 13 minutes. After the implementation of external AATS, most aircraft are towed from the gate to the end of runway. The pilot only needs to ensure that the engine becomes available before entering the runway. It takes 5 minutes for engine from start to take-off power if the engine was shut down for more than 2 hours before. Thus, the AATS adoption can reduce 8 minutes, or 480 seconds, of engine usage for each eligible departing aircraft.

We use the below formula to estimate the jet fuel saving and related cost saving

$$D_{task} = Fuel\ Flow * Num\ of\ Engine * T \tag{3}$$

$$D_{year} = D_{task} * Num\ of\ task * 365 \tag{4}$$

The fuel flow rate is 0.11kg/sec/engine in average for different types of engines on narrow body aircraft. Assuming conventional taxiing out is single-engine on, we calculated the fuel saving of each task by using formula (3) and then multiply the number of tasks per day (around 270 departing flights per day) and 365 to convert it into the annual fuel consumption (see formula 4). Jet fuel price monitor of IATA shows that the jet fuel in North America is about lease note the Jet A-1 Oil is 4.81$ per gallon (Flight Deck Friend, n.d.)(accessed date: May,11,2022). So, the total annual saving is $6,507,422, which is greater than the annual cost using external AATS calculated in above section.

In addition, not using jet fuel during taxiing phase reduces the needs of reserved fuel and make the aircraft lighter. It will help save jet fuel during cruise phase.

In the convectional taxiing process, a push-out tractor is connected to the nose landing gear of the aircraft using a connecting device, and then apply thrust to move the aircraft. Such repeated operations will increase the fatigue of the nose landing gear struts of the aircraft. TaxiBot (example of external AATS) uses a hugging structure which directly lifts the tires of the trolley together without exerting force on the front landing gear struts, which can elongate the life span of nose landing gear fatigue and save the cost. Furthermore, reducing the use time of the engine during the taxiing phase can also prolong the service life of the engine, thereby reducing the operating cost.

7. EXPERT INTERACTION

When we decided to work on this topic, we directly contacted Mr. Joseph A. Post, who served as the Acting Director in National Airspace System (NAS) Systems

Engineering & Integration of Federal Aviation Administration (FAA) and is now a Visiting Professor of Practice at USF. Besides that, through the suggested resources provided on the ACRP Competition website, we also contacted Mr. Corkey Romeo through emails. He is the director of aviation for Community College of Beaver County Pennsylvania. After briefly introducing our research idea to them, we asked the following questions:

1. Parking locations of push-back tractors will highly influence taxiing efficiency. So, how they park at the airport now? Do they park at one specific area, or at each terminal?
2. How to obtain the operating features of external AATS?

Mr. Joseph provided insight on a variety of data sources and mentioned web sources/papers to us. For question1, he suggested we contact operational personnel of Tampa International Airport and obtain the information of current push-back operations. For question 2, he suggested we visiting the website of TaxiBot and contacting the staff if it is necessary.

Mr. Corkey indicated our topic is very interesting, but it is true that the existing information is insufficient. He recommended we find some answers in the literature, or we may have to propose a ConOps or alternative concepts.

Appendix A: List of Contact Information

Team Members

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Appendix B. Description of University of South Florida and Smart Urban Mobility Laboratory

University of South Florida

USF is situated in the vibrant and diverse Tampa Bay region, with campuses in Tampa, St. Petersburg, and Sarasota-Manatee. Together these campuses serve more than 50,000 students and offer undergraduate, graduate, specialist, and doctoral degrees. Over the past five years, USF has been the fastest-rising university in the nation, public or private, on the U.S. News and World Report's list of best universities. USF ranks as the 44th best public university in America. Established in 1956, USF is a leader among young universities. We are also leaders internationally, and in 2018 was the number one producer of Fulbright Scholars in the nation, for the second year in a row.

Smart Urban Mobility Laboratory at the University of South Florida

SUM Lab at USF is led by Dr. Yu Zhang. The main research areas are Transportation system modeling, analysis, and simulation; Resilient system design and operations; Air transportation and global airline industry; Multimodal transportation planning and sustainable transportation. Researchers at SUM Lab develops mathematical programming and solution algorithms, simulation tools, econometrics and statistical models, machine learning/deep learning methods for obtaining innovative solutions for more efficient, resilient, and sustainable multimodal transportation systems. SUM research projects are funded by government agencies, such as NSF, FAA, FHWA, FDOT, and local cities and industry companies. For more information of SUM Lab, please visit http://www.sum-lab.org.

Appendix C. Description of Interaction with Industry Contacts and Airport Operators

The research team contacted Adam Bouchard, Vice President of Operations at Tampa International Airport and had a video meeting with Mr. Bouchard. Dr. Zhang and Mr. Post attended the meeting as well. During the meeting, Mr. Bouchard described aircraft push-back operations at the airport. Mr. Bouchard also provided insightful comments to our design project.

Appendix E. Evaluation of the Educational Experience Provided by the Project

Students

1. Did the Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airports Needs provide a meaningful learning experience for you? Why or why not?

Yes. The ACRP University Design Competition is a meaningful and motivating event, as it provided us the precious learning experience and opportunities for teamwork. Under the supervision of Dr. Yu Zhang and Mr. Joe Post, the independent and critical thinking abilities were enhanced and improved during this journey of solving practical problems. Also, we had opportunities to communicate with representatives from Tampa International Airport to obtain a deep understanding of the current airfield operations and challenges that they are facing to make the airport greener and more sustainable. It has been a priceless experience.

2. What challenges did you and/or your team encounter in undertaking the competition? How did you overcome them?

Although external alternative aircraft taxiing system (AATS) has been developed and tested at several airports and studies on this topic have been conducted, it is still hard to get the operating parameters of external AATS products. Fortunately, Dr. Yu Zhang has participated in the ACRP project on Deriving the Benefits of Alternative Aircraft Taxiing

Systems and has contacts that who kept tracking the operating parameters. So, Dr. Zhang helped us obtain the data.

3. Describe the process you or your team used for developing your hypothesis.

In the “Air Transportation” course co-taught by Dr. Zhang and Mr. Post, we learned how different layouts of airport terminal buildings and runway configurations would affect the taxiing times of arrival and departures. We believe the different allocation strategies of external AATS will lead to different airfield ground movement performance. Dr. Zhang and her former Ph.D. student received support from ACRP Graduate Research Award to simulate the financial impact of emerging AVs on airport parking revenue. Inspired by their study, we decided to develop a simulation tool, use that tool to evaluate different allocation scenarios of a study airport, and identify the best one for that airport.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Yes. The involvement of operational personnel from Tampa International Airport is very helpful. They helped the design team to understand the current airside operations, including flight operation pattens, gate assignment, tractor dispatch, and taxiing performance. Such understanding is essential for the research team to develop the design approach and conduct simulation and analysis.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

Both team members learned a lot from participating in this design competition. I, Pengli Zhao, as the team leader, developed the simulation tool in MATLAB. It is a learning process by conquering challenges one by one. With the help of Dr. Zhang, I also learned how to plan and monitor work schedule, communicate with representatives from airport, and improve writing skills. My teammate, Huang Feng, worked on collecting data and developing allocation scenarios. The skills and knowledge that we obtained from this design project better prepare us for further graduate study and future career development.

Faculty

l. Describe the value of the educational experience for your student(s) participating in this competition submission.

Pengli and Huang got interested in the alternative aircraft taxiing system and decided to study the allocation strategies for the implementation of AATS at a study airport. It has been a productive learning process while students were pushed by the deadlines of the competition. By going through the competition submission, they applied the knowledge learned from classroom and build up skills that could be very useful for their further graduate study and career development.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

I teach “Air Transportation” annually and students are required to work in teams on term projects seeking solutions for challenge research problems in aviation field. For students who are interested in airport-related research, I encourage them considering the design competition while framing their research scope and approach. Meanwhile, the guideline of the competition gives students ideas of research problems.

3. What challenges did the students face and overcome?

Students faced challenges while collecting data. I tried to contact local airport as well as collaborators from previous ACRP project to help students obtain the data.

4. Would you use this competition as an educational vehicle in the future? Why or why not?

Yes. As I mentioned earlier, it fits well with the term project requirement in Air Transportation course that I teach annually. I will keep on encouraging students participating in this competition.

5. Are there changes to the competition that you would suggest for future years?

Not sure why a hard copy is needed. To make the competition more environmentally friendly, suggest removing this requirement.

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Appendix G: Statistic Information on Taxiing Route Plan in Operation Day

Date	Runway in Use	Terminal				Remote Stand	Grand Total
		A	C	E	F		
2020/2/2	1L	1	1	48	41	12	103
2020/2/2	1R	60	88	0	0	25	173
Grand Total		**61**	**89**	**48**	**41**	**37**	**276**

Appendix H: Tug Allocation Strategies

A	C	E	F	Total	A	C	E	F	Total
2	2	2	2	8	3	3	3	4	13
2	2	2	3	9	3	3	4	2	12
2	2	2	4	10	3	3	4	3	13
2	2	3	2	9	3	3	4	4	14
2	2	3	3	10	3	4	2	2	11
2	2	3	4	11	3	4	2	3	12
2	2	4	2	10	3	4	2	4	13
2	2	4	3	11	3	4	3	2	12
2	2	4	4	12	3	4	3	3	13
2	3	2	2	9	3	4	3	4	14
2	3	2	3	10	3	4	4	2	13
2	3	2	4	11	3	4	4	3	14
2	3	3	2	10	3	4	4	4	15
2	3	3	3	11	4	2	2	2	10
2	3	3	4	12	4	2	2	3	11
2	3	4	2	11	4	2	2	4	12
2	3	4	3	12	4	2	3	2	11
2	3	4	4	13	4	2	3	3	12
2	4	2	2	10	4	2	3	4	13
2	4	2	3	11	4	2	4	2	12
2	4	2	4	12	4	2	4	3	13
2	4	3	2	11	4	2	4	4	14
2	4	3	3	12	4	3	2	2	11
2	4	3	4	13	4	3	2	3	12
2	4	4	2	12	4	3	2	4	13
2	4	4	3	13	4	3	3	2	12
2	4	4	4	14	4	3	3	3	13
3	2	2	2	9	4	3	3	4	14
3	2	2	3	10	4	3	4	2	13

3	2	2	4	11	4	3	4	3	14
3	2	3	2	10	4	3	4	4	15
3	2	3	3	11	4	4	2	2	12
3	2	3	4	12	4	4	2	3	13
3	2	4	2	11	4	4	2	4	14
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3	2	4	4	13	4	4	3	3	14
3	3	2	2	10	4	4	3	4	15
3	3	2	3	11	4	4	4	2	14
3	3	2	4	12	4	4	4	3	15
3	3	3	2	11	4	4	4	4	16
3	3	3	3	12					