SAETS- Design of Semi-Autonomous Electric Taxi System for Commercial Airports

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Category: Airport Management & Planning

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1. Executive Summary

This report aims to solve three of the challenges of the ACRP Design Competition *Airport Management and Planning* category. These challenges include: (1) Innovative strategies for reducing airline fuel consumption, such as new ways to reduce gate-to-gate time or revise procedures, (2) effective alternatives to current ramp and gate controls, and (3) improved aircraft and airport design factors affecting aircraft compatibility to decrease the risk of aircraft wing tip collisions in the non-movement apron areas. The project aims to provide a means to innovate strategies for reducing airliner fuel consumption by eliminating engine-run time during taxi for transport category aircraft at commercial airports.

The Semi-Autonomous Electric Taxi System (SAETS) designed by the project team utilizes existing electronic taxi hardware implemented in a semi-autonomous way that would allow for control to remain with pilots when coupled with aircraft, and autonomous operation when detached.

In pursuit of the overarching goal of the Airport Cooperative Research Program of addressing and innovating sustainability issues among airports, our project has provided the logistical and operational framework for the implementation of an electric taxi system at a busy, commercial single-runway airport. The system is based upon semiautonomous electric tugs that will safely and efficiently move aircraft along the airports surfaces, eliminating the need for aircraft engine power during taxi.

The semi-autonomous electric system described in this design project aims to address airport financial, environmental, and social sustainability by the overall reduction of fuel consumption from the elimination of aircraft engine-run during taxi. As well, the design submission aims to provide and operational platform for the future implementation and improvement of electric taxi systems for airports worldwide.

2. Problem Statement

Carbon emissions are a major environmental concern for airports. For example, aircraft taxi at large commercial airports such as Dallas-Fort Worth International can consumes over 44,000 gallons of fuel each day leading to a release of over 22,000lbs of carbon monoxide (CO) into the atmosphere (Nikoleris, 2011). The financial, environmental, and social implications of this excess fuel consumption could significantly affect commercial air carriers bottom line as well the public health of residents residing near airports.

The implementation of the Semi-Autonomous Electric Taxi System (SAETS) would dramatically reduce the amount of fuel consumption and emissions that result from aircraft taxi.

3. Background

The current method for jet powered aircraft to travel on the ground is via the use of their main engines to provide propulsion. These engines are specifically designed for efficiency in flight and typically perform inefficiently on the ground relative to other methods of propulsion available on the ground such as electric motors. The application of electric propulsion to aircraft taxi poses an opportunity to reduce fuel consumption at airports a significant amount and have an overall positive impact on airport sustainability.

Previous research and development on the hardware to facilitate electric taxi has been conducted and documented in the literature review in this project. These electric taxi systems are capable of providing electric taxi power for aircraft and could possibly be utilized by the system described in this design.

4. Literature Review

a. Financial Factors

Modern jet aircraft are extremely complex machines that are the result of years of meticulous engineering. Every new generation of turbofan or turbojet engines contain improvements in efficiency and performance from the previous generation. With the recent volatility in the cost of aviation fuel, efficiency improvement has become a vital factor in cost reduction. Large jet engine manufacturers such as GE, Rolls Royce, and Pratt and Whitney devote billions in funding efficiency research. "GE's R&D operations last year cost $5.5 billion—twice what it spent a decade ago and more than 487 companies in the Standard & Poor's 500-stock index" (Brustein, 2014, p.1). The current generation of engines being developed by Pratt and Whitney aim to be 15% more fuel efficient than the previous generation (Coy, 2015, p.1).

By examining the triple bottom line for fuel efficiency in jet engines, it can be observed that the research and development in this area is due to the financial, environmental, and social motivations. The environmental and financial impact of a reduced fuel burn are the two factors that driving development throughout the industry.

Excess fuel burn is a costly expense for any large aircraft operators. Any delays that lead to longer engine-run time causes excess fuel expenses. A study conducted at the University of Pennsylvania found that, "the average potential airborne fuel consumption reduction from eliminating various forms of delay – airborne delay, excess planned flight time, and departure delay – to be 1.1–1.5% ; for some operations, this reduction is up to 20%" (Ryerson, 2014 p.1). This shows that there is a clear, quantifiable relationship between delays on the ground and in the air and total operating cost. By reducing unplanned delays, there will be a decrease in overall expenses.

Delays on the ground are extremely common due to reasons such as crossing aircraft, clearance delays, and runway crossings. Each stop an aircraft makes not only increases the total taxi time, but leads to increased thrust usage in order to bring the aircraft back to speed. Both factors lead to increased fuel consumption and have room for improvement. A study conducted at Dallas-Fort Worth International Airport found that stop-and-go during taxi accounts for "about $15,000 a day. Eliminating such stop-and-go situations would probably reduce the daily and annual fuel consumption as well as emissions" (Nikoleris, 2014, p.1).

Fuel burn is an expense that is incurred at all times engines or auxiliary power units are operated. Large advances in technology have allowed for a dramatic increase of in-flight fuel efficiency of jet main engines, but on the ground, these main engines burn a large amount of fuel for the amount of thrust they are producing. Jet engines are not the ideal source of taxi propulsion; their design is optimized for in-flight efficiency performance, not ground performance. In an effort to reduce fuel consumption, many commercial jet operators implement single engine taxi procedures. This allows the aircraft to taxi using only one engine operated at a slightly higher RPM. These procedures do save a marginal amount of fuel, but not nearly enough as other technologies currently available. An ideal taxi power source would provide high levels of torque with limited fuel or electricity used. Electric motors provide this torque at a lower operational cost.

Auxiliary power units are a major source of fuel consumption during the taxi process. It is standard for many models of aircraft to operate the APU during taxi to provide power for various systems within the plane. Aircraft APUs are small jet engines that consume fuel from the same tanks as the main engines. Although, unlike the aircraft engines, APUs operate at a constant RPM, regardless of the power demanded from them. "The disadvantage of the known auxiliary power units is their relatively poor efficiency, particularly with respect to generating electricity. Their operation is also connected with high exhaust gas and noise emissions" (Konrad, 2000). APU are a necessity to power systems on the ground. Because of the limited fuel sources available, they are designed to utilize Jet A through a jet engine. This is not the most efficient application for a jet, although it is one of the only solutions that is viable enough to operate onboard the aircraft. Electric taxi systems that are also capable of providing ground power and pneumatics could provide an increased level of efficiency by eliminating the need for an APU, aside from the auxiliary systems of the aircraft.

Overall, the prospect for fuel expense mitigation by the use of electric taxi systems is substantial. A recent study found that, "the savings for one aircraft may reach up to one hundred thousand Euros per year (Hospoka, 2014 p.1). If these savings are scaled to the operations of an entire international airport, the savings could reach tens of millions of US dollars.

b. Environmental Factors

Along with being financially inefficient, excess jet fuel consumption during taxi and delays is detrimental environmentally due to the increased levels of emissions. A reduction on overall fuel consumption by the implementation of an electrically powered taxi system definitely poses an opportunity to reduce emissions by a significant amount.

One of the most harmful types of emissions found commonly among modern engines in general is nitrogen oxides or NOx. It is released during the combustion process of fossil fuels such as diesel, coal, or kerosene. NOx has the potential to cause serious health problems in high concentrations with animals and has been shown that, "at concentrations encountered in the home environment, can potentiate the specific airway response of patients with mild asthma" (Tunnicliff, 1994 p.1).

The combustion of jet fuel is a large component of the global NOx emissions. In a study conducted by the US Environmental Protection Agency they found that, "Commercial aircraft comprise almost 70 percent of oxides of nitrogen (NOx) emissions from the total aircraft sector" (EPA, 1999). That is an extremely significant section of the total NOx pollution. Jet aircraft make up well over half of the NOx pollution and are a large target for emissions reduction.

Jet engines have few pollution suppression systems. Other vehicles burning fuels that release NOx are mandated to contain systems that limit the total NOx output. In diesel land vehicles, urea injection systems are used to neutralize NOx emission and lower them to an acceptable level (Eddy, 2015, p.1). No such implementation of similar systems have been applied to aircraft engines and accordingly, their levels of NOx emissions remain extremely high.

The implementation of an electric taxi system has shown prospect in reducing the overall levels of NOx emissions by aircraft by simply reducing the engine-run time. Independent from the actual engines and APU, an electric taxi system would eliminate the need for engine operation on the ground and allow for a reduction in emissions as a result.

c. Existing Technology

As the aviation industry expands, we are faced with an ever existing crisis of how to resolve shortage of supplies within the infrastructure. In order to accurately measure the need for supplies, labor, or other resources, the industry must first measure what is being used and forecast future demand. According to the CEO of Airports Council International – North America (ACI-NA, 2015), Kevin M. Burke in a press release from earlier this year,

> *As the U.S. Economy continues to gain strength and air travel rebounds, we must guarantee to passengers and cargo shippers that we can continue to meet increases in demand with safe, secure, and efficient facilities that keep pace with our global competition.*

As CEO Kevin M. Burke suggests, the airport infrastructure must continue to grow accordingly to meet demands to ensure the economy continues to thrive. From the same press release from ACI-NA, the outline several areas in their Five-Year Plan, a common technique for the airline industry to incorporate detailed forecasts for the future of the industry, where it is expected of the majority of the aviation industry to include their percentages of needs across the board. The ACI-NA estimates that within the commercial-airport segment:

- Large Airports account for $40.1 billion (52.9%)
- Medium airports account for $9.1 billion (12%)
- Smaller airports account for $7.7 billion (10.1%)
- Non-hubs account for $5.3 billion (7.1%)

Also noted within this plan, there are airports that have projects that are essential to the plan to respond to increased demand within the infrastructure of aviation. According to ACI-NA, they have noted that commercial airports accredit 82.1 percent, meaning that non-commercial airports host the other 17.9 percent of the total $75.7 billion figure plan of growth (Airports Council International, 2016, p.1).

So with all these figures, and the already introduced topic of expected and essential plans to improve and expand the aviation industry, there is only predictions of what will really happen in the next few years, with only expected plans of what the airports and the companies involved will be demanding. It can be said that we do not know the route to be taken in the next 5 years, nor do we know exactly what plans will be put into place as we near 2020. Among these growing concerns and the ever eluding future, the need to reduce both carbon emissions and fuel usage will be essential in the transformation.

In 2008, US patent number 7445178 B2 (2008) was published and given credit to William R. McCoskey, Richard N. Johnson, and Matthew J. Berden. It outlines a detailed analysis and a complete briefing on how a “powered nose aircraft wheel system” could come into fruition . A brief description of the system is noted in the abstract, stating that the implementation is based off of the landing phase of flight, where the aircraft will land, allowing free rotation of the nose wheel, while transferring the power of the rotation to a separate power unit from the Auxiliary Power Unit, or APU (McCorskey, 2008).

An initial problem that arose during the investigation into the development of this patent is that the initial fundamental powering source of the system is the APU. If the system is powered by the APU, it is possible that the system could be even less fuel efficient, due to the APU being a crude version of fuel transfer system, engineered very inefficiently. However, the APU is not the main power source after the landing phase, and it is assumed that the APU will be shut down along with the engines and generators aboard the aircraft to allow the wheel motor to be the singular source of power for the nose wheel.

Inside the patent, there are at least two separate means of control for the nose wheel gear system. The first, is a direct connection, possibly on board of the aircraft inside of the cockpit, which would be the most logical means of control for the nose wheel. This would allow each pilot to be in control of their aircraft directly from the cockpit, allowing for nearly no change of control away from the standard nose wheel tiller that is in place today to direct the nose wheel by thrust power from the engines.

The second is a separate, isolated source, possibly remote within the airport itself to give a separate controller access to the aircraft and control over all aircraft with the powered nose wheel system capability. This second means would allow better coordination due to only one or a very small number of people being in control over the whole system rather than each pilot being in control of their own aircraft, possibly reducing or eliminating taxiway incursions or ground accidents.

A more overlooked aspect of this change would be the complete elimination of nose wheel tow systems, as the aircraft would have the ability to now push itself back from the gate as well as bring itself back up to the terminal. While the towing vehicles would be eliminated, there is also the factor of another system being added onto the aircraft, making it not only heavier, but more than likely needing more maintenance with a system that would be used every time the aircraft moves along the ground apart from being on the runway itself.

d. Existing Electric Taxi Hardware

As our society looks to more efficient and environmentally-friendly options to solve our societal problems, the airline industry is trying to find ways that will help improve the process of aircraft taxiing in a well-rounded way. Engine-Off taxiing has been a highly debated topic within the aviation industry. The primary reasons for implementing this idea is to help reduce taxi times, save fuel, and limit the amount of carbon emissions in our environment. Currently, there are three companies looking into finding solutions for aircrafts to taxi with the engines shut off. The overall goal between the three companies is to create on-board or external systems that allow the aircraft to be able to be autonomous while driving on the runways. By developing these systems, these companies hope to achieve and discover a new fuel-saving format for success. Each company is competing against each other in order to offer a more efficient solution, and each is implementing their solution in a different location of the aircraft or a different vehicle entirely.

The three existing system for electric taxiing are: (1) Gibraltar, a UK-based WheelTug is installing its system on the nosewheel, (2) Safran, an aircraft engine-based company, and Honeywell, an engineering company, are currently in a 50/50 joint venture to develop an electric green taxi system (EGTS), and (3) Israel Aerospace Industries (IAI), partnering with global ground support equipment manufacturer, to develop an autonomous vehicle that can tow the aircraft from the gate to the runway threshold and back (Dubois, 2014).

Gilbraltar's WheelTug electric taxi system is a nose wheel-mounted motor and drive powered by the aircraft's auxiliary power unit. This allows the aircraft to move around the runways without using their main engine. This creates an opportunity to save time, fuel and money. According to Thierry Dubois, a report from AIN Online, states that the WheelTug system does involve some modification. The Wheeltug are currently targeting short to medium haul aircrafts. In addition, implementing the system may be applying extra weight to the aircraft. However, the CEO Isaiah Cox, mentioned that this technology is rather cheap to produce, which can help airlines maximize their revenues. The Wheeltug will allow speed going up to 7-10 knots in Boeing 737 and Airbus A320s. However, on occasions like slippery or frosty runways, the system will be not be able operate correctly. The CEO Isaiah furthermore emphasizes the point that installing this business model “will cost airlines nothing to install, with the airline keeping 50% of all proven savings...”(Dubois 2014 p.1). One of the most significant benefits of the WheelTug is its ability to reduce the turnaround time. Cox claimed that “by allowing the aircraft to park sideways and thus use two jetways for passenger boarding/deplaning”, will help reduce up to 20-30 minutes per flight. This will save airlines a significant amount of money per minute.

Both Safran and Honeywell Aerospace are looking to further their electric green taxi system (EGTS). This is a device that enables aircraft to taxi from the gate to the runway autonomously without turning on the auxiliary power unit generator to power electric motors (Bill Carey, 2013 p.1). The EGTS claim maximum speeds of 20 knots, targeting short to medium-haul aircraft. As of 2013, Safran and Honeywell have installed this system on an Airbus A320, partnering with Air France, looking to develop and analyze “potential technical, operational, and financial benefits”(Carey, 2013). Recently, they have announced that the EGTS will help improve airline operating efficiency during taxi and cut fuel consumption by up to four percent per flight cycle net of any weight penalty (Carey, 2013 p.1).

(3) Israel Aerospace Industries is taking a more external route in terms of developing a fuel-saving solution to the current problem. In the airline industry, often times, other vehicles are used in the process of moving and relocating an aircraft. According to Charles Alcock, a reporter from AINonline, “The European Aviation Safety Agency and the Civil Aviation Authority of Israel have issued a supplementary type certificate (STC) for the TaxiBot© aircraft towing system developed by Israel Aerospace Industries (IAI) in partnership with France’s TLD and

Lufthansa LEOS” (Alcock, 2014). There have been multiple test runs and trials of the TaxiBot© system Alcock later states that, “Trials of TaxiBot© have proven its ability to taxi a fully loaded 737 at 23 knots, which IAI claims is the fastest speed achieved by a taxiing system to date.“ The final base price for the TaxiBot© was not released around this time, however, IAI is confident in their system. They believe that in a time period less than 18 months, their clientele, the airlines, will gain back their capital, ultimately leading towards a successful fuel-saving taxiing system (Alcock, 2014 p.1).

The TaxiBot itself is viable for all ranges of operations, whether it be short or long-haul. While this is true, there are a few safety precautions that must be taken when acquiring this system. While this system is being used, there must be a safety driver inside. According to Ron Braier, the Taxibot© program director, this is for a number of reasons, “first, to have rear vision during the pushback and, second, “because the authorities are still conservative and don’t allow autonomous return without a driver...”. After this has been completed, the power will be passed to the pilot while inside the cockpit.

The implementation of these new taxi system creates challenges. Engine wear may be reduced, but ground operations may be more prone to more damages. Furthermore, it may over-complicate ground control. Some taxi systems may add extra weight onto the aircraft, while electric motors and hot brakes may not work well together. These are questions that are still being debated today.

5. Sustainability Measurement Method

This design project aims to not only provide an implementation model for electric taxi system but also to measure the impact on sustainability these systems could have in a quantitative and qualitative way.

The three major areas of sustainability are outlined in the *Triple Bottom Line Model;* financial, environmental, and social sustainability (Elkington, 1987). In this project, sustainability will be measured using various techniques. The sustainability data addressed in this report span between the ratio and nominal levels of data and will require different measurement and analysis methods.

a. Financial

Financial sustainability will be a quantitative measure. In order to accurately gauge the project's impact on financial sustainability, analysis will be conducted on the differences in the operational cost of airports and airlines utilizing the electric taxi system as compared to the cost for current operations. Long-term cost analysis will also be conducted to give accurate measures on the financial implications of long term use of an electric taxi systems.

Electric taxi systems are an emerging technology have not been implemented realistically as of yet. Because of this, there is no reference for actual costs of various aspects of implementation and operations of these systems. In order to provide the most accurate measures and analysis possible this design project will utilize information from similar industries and technologies in conjunction with informed inferences.

b. Environmental

Environmental sustainability will also be a metric that can be measured and analyzed in a quantitative way. The environmental impact on sustainability to be measured in this project is the consumption of fuel and the emissions that result.

In order to accurate measure this aspect of sustainability, the calculated current taxi fuel burn and emissions using existing technology will be compared to emissions and fuel burn of an airport using the electric taxi system described in this project. Environmental factors that also translate into financial factors such as carbon credits and government subsidies will also be analyzed.

c. Social

Social sustainability will be an inherently qualitative value. It cannot easily be measured in a numerical way. In order to assess the social implications of the implementation of an electric taxi system, interviews will be conducted with stake-holders in the industry. Personnel such as airline pilots, dispatchers, and airport management will be interviewed. Their opinion and outlook on the project will aid in making inferences and measuring the impact on social sustainability that may result.

6. Safety Risk Assessment

The implementation of a semi-autonomous electronic taxi system would have a significant impact on the operations at a commercial airport. The system would introduce new risk factors to the overall operation of an airport, as well as augment the frequency and severity of exiting risk factors. Because of this change in risk factors, risk analysis must be conducted on risks that pose a high frequency or severity potential.

Safety Management Systems (SMS) can be implemented to mitigate and prevent risks within a system. The SAET System will be implemented to conform to the Federal Aviation Administration's current SMS model. The FAA's SMS model consists of four major components: safety policy, safety assurance, safety risk management, and safety promotion. SMS for the SAET will take into account each component (Advisory Circular 120-92B, 2015, p. 8).

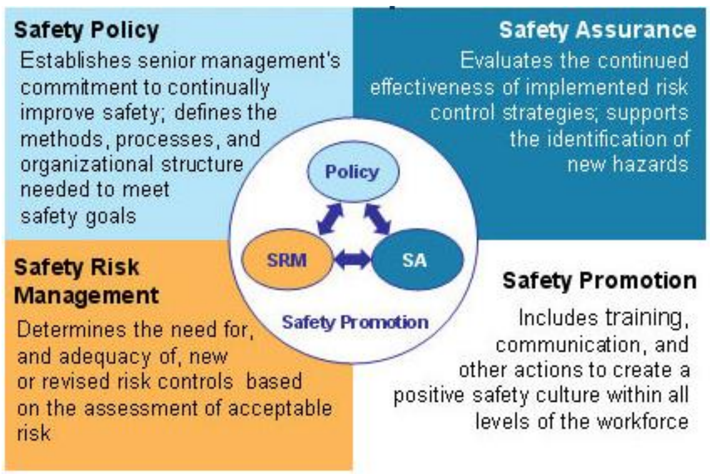

Figure 1 FAA SMS Model, FAA. *The Four SMS Components.* 2015.

- **Safety Policy:** The SAET System will have clear operational policy and objectives focused on continuous safety improvement. The policy will focus on reaching and exceeding safety goals as well as encouraging data-sharing amongst other systems for the purpose of improved operational safety.
- **Safety Risk Management:** The SAET System will also implement automated and manual safety reporting in order to gather operational data and improve overall

operational safety. Analysis of safety reports will allow for risk identification and mitigation.

- **Safety Assurance:** The initial implementation of the SAET System will be under the supervision and consultation of an Aviation Safety Organization in order to confirm the policies implemented as well as aid in evaluating and improving overall safety.
- **Safety Promotion:** All personnel who will be dealing with the SAET system, directly or indirectly, will be trained on its operations and the SMS designed for the system.

The SAET System will significantly affect how ground operations at an airport are conducted. There are numerous new risks that will be introduced, as well as changes in the frequency and severity of existing risks. Risk analysis for every single new factor is not feasible for the scope of this report.

Specific risks identified by the project team have been selected for risk assessment and analysis below.

- **Aircraft collisions during taxi:** The risk of aircraft colliding with each other would be increased by the added workload to pilots and controllers of learning and operating a new taxi system. The increased frequency of collisions on the ground could result from the implementation of the SAET System. The severity of the risk may remain unchanged.
- **Damage to aircraft from tug:** The use of heavy equipment to pull aircraft poses a risk of damage to the aircraft. The severity of the risk may be low due to the slow speed in which a tug approaches an aircraft, while the frequency may be high.
- **Injury to personnel on the ground:** The SAET Systems poses a risk of injuring personnel when under autonomous control as well as when coupled with an aircraft. The

severity of contact between humans and the SAET tugs may be high due to the size and power of the equipment. The frequency of injuries should be low due to the SMS and training that will be put in place.

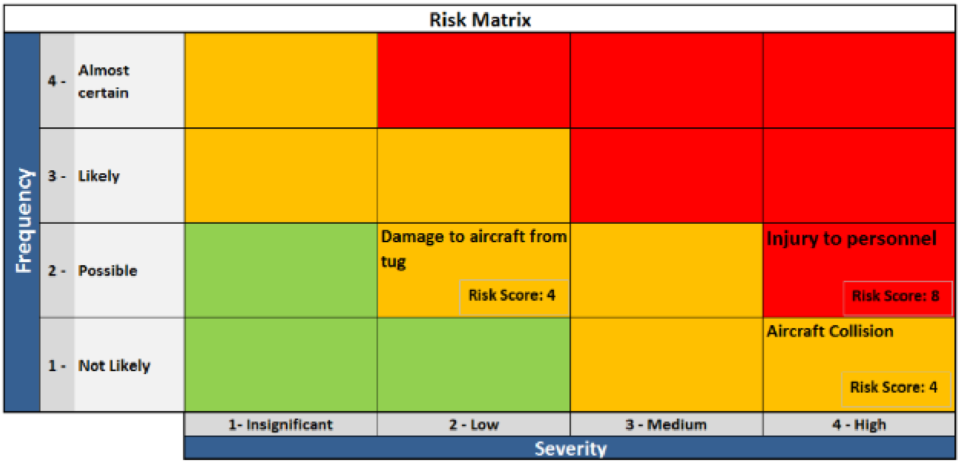

Figure 2 Risk Matrix

7. Technical Aspects

a. Hardware Features

There are many of opportunities for improvements when it comes to aircraft taxi methods. The SAETS is a revolutionary tool that will bridge the current pilot-based technology, with the engine propelled taxi and the fully automated taxi system.

Developing an improved system where taxiing becomes autonomous will ultimately help increase the efficiency and coordination of the airport and air traffic control operations.

The idea of a semi-autonomous electric taxi system will consist of two parts: towing taxi vehicle and the pilot of the aircraft. In order to maximize efficiency of the taxiways in an airport, the pilot is designed to control the towing taxi vehicle. The pilot will follow ground control and air traffic control to search for the most efficient route. The towing vehicle is designed to autonomously attach and detach from the aircraft, locating aircrafts in their correct destination, with the assistance from the pilot.

b. Software Features

The main software feature will most likely be the Airport Surface Detection Equipment, or ASDE-X. The automatic nature of the tugs require a unique perspective of interactive materials, which in transportation is almost always connected to GPS. The system itself, as described by SAAB, a technology innovator and manufacturer, "ASDE-X is a traffic management system for the airport surface that provides seamless coverage and aircraft identification to air traffic controllers" (SAAB, 2016, p.1).

The airports that already use the ASDE-X system have a radar design similar to the following figure, which represents the innovation of the system and its already wide use across the United States in the 35 busiest airports across the country.

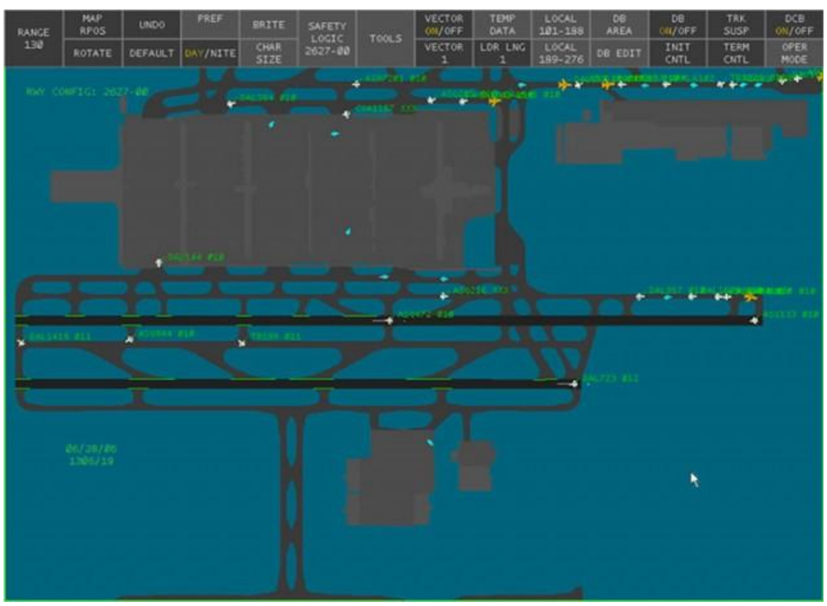

Figure 3 ASDE-X Model. Federal Aviation Administration. (2014) ASDE-X model. Washington DC.

According to SAAB (SAAB, 2016, p.1), the technical aspect of the ASDE-X system is complex as it is revolutionary for traffic guidance and communication. There are five main components of the system: Multilateration, Surface Movement Radar, Automatic Dependent Surveillance – Broadcast (ADS-B), Multi-Sensor Data Processing, and Tower Displays.

Multilateration, a secondary surveillance of all aircraft or equipment with an installed ADS-B device, helps controllers with their radar detection, to determine the best possible location with the multiple data sources (SAAB, 2016, p.1).

*c. Airport Procedure*s

The SAETS is a system that will need extra space within an airport. The method of implementation will be shown in the figures below, of where and how the SAETS will station in an airport.

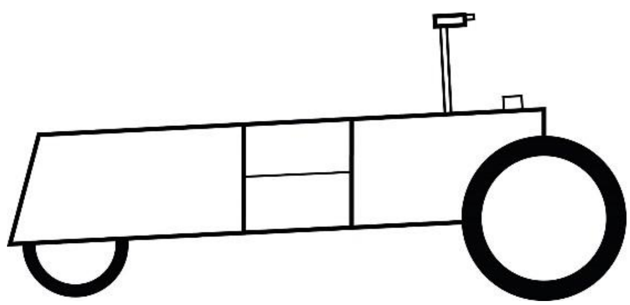

Figure 4 Sketch of SAETS tug

Figure 5 Sketch of connected SAETS tug

Design Requirements

For SAETS to fulfill its role of transporting aircrafts in a more efficient manner, it must meet the needs of its product design specification. The design requirements for the semi-autonomous electric taxi system will be broken down into two main categories: storage and positioning. These aspects of the SAETS will outline its competitiveness to the airline industry, as well as showcase it's necessities in order to maintain a successful and fully-functioning design.

d. Storage

In order to implement the SAETS into a standard airport, we are looking at using a single runway commercial airport; for example, San Diego International Airport. Near the terminal gate, there will be an appointed place for the SAETS to be stored, referred to as the *holding dock*. The holding dock will be explicitly used for maintenance, and as a charging station for the SAETS. The storage of the SAETS will be easily accessible yet not impairing the current setup/layout of the airport. These locations will be the primary focal point for the detachment and reattachment of the SAETS. **Figure 2** below depicts where exactly the loading dock will locate at San Diego International Airport.

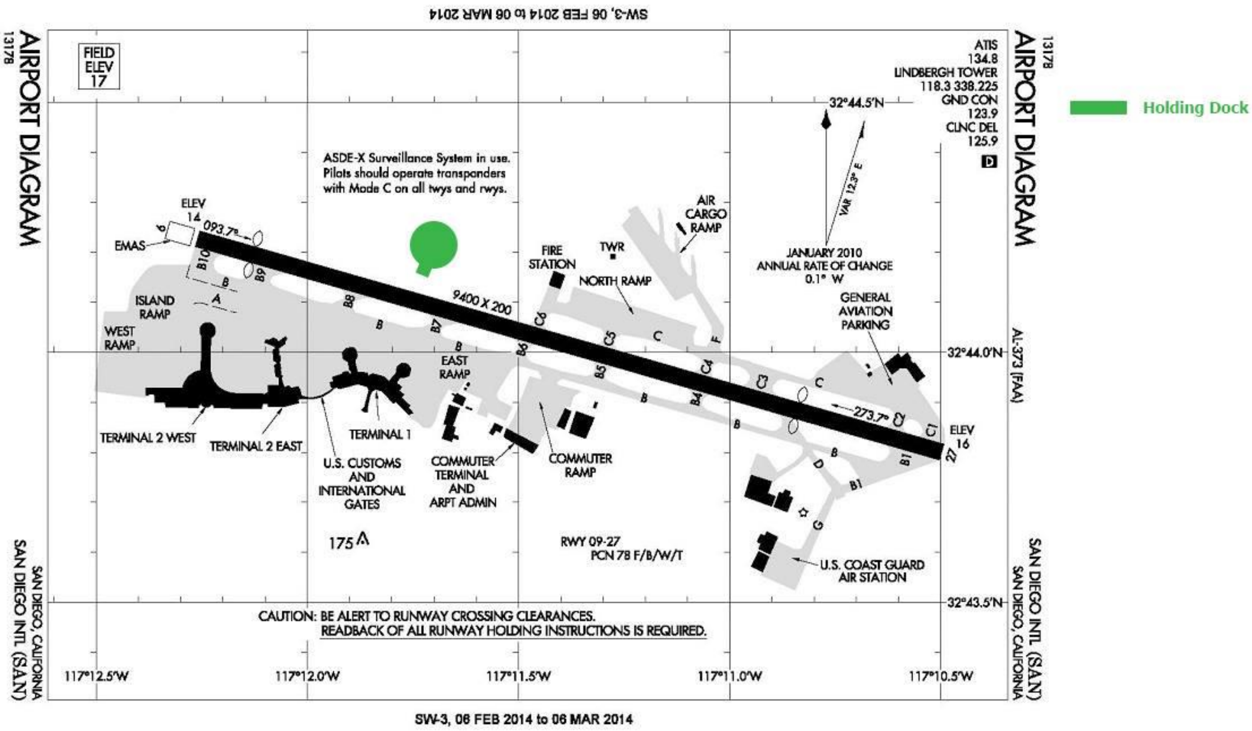

Figure 6 Holding Dock   Federal Aviation Administration. (2016) KSFO Airport Diagram. Washington DC

e. Positioning/Travel Route

Within the airport, there will be designated taxiways for the SAETS to operate, called *vehicular routes*. These routes will be specific for SAETS to travel through ground operations. It is imperative that this machine does not have a negative impact on the current process of aircraft taxiing, therefore, the vehicular routes will be built into the airport reducing the potential traffic problem. **Figure 7** below depicts where exactly the vehicular route is located at San Diego International Airport.

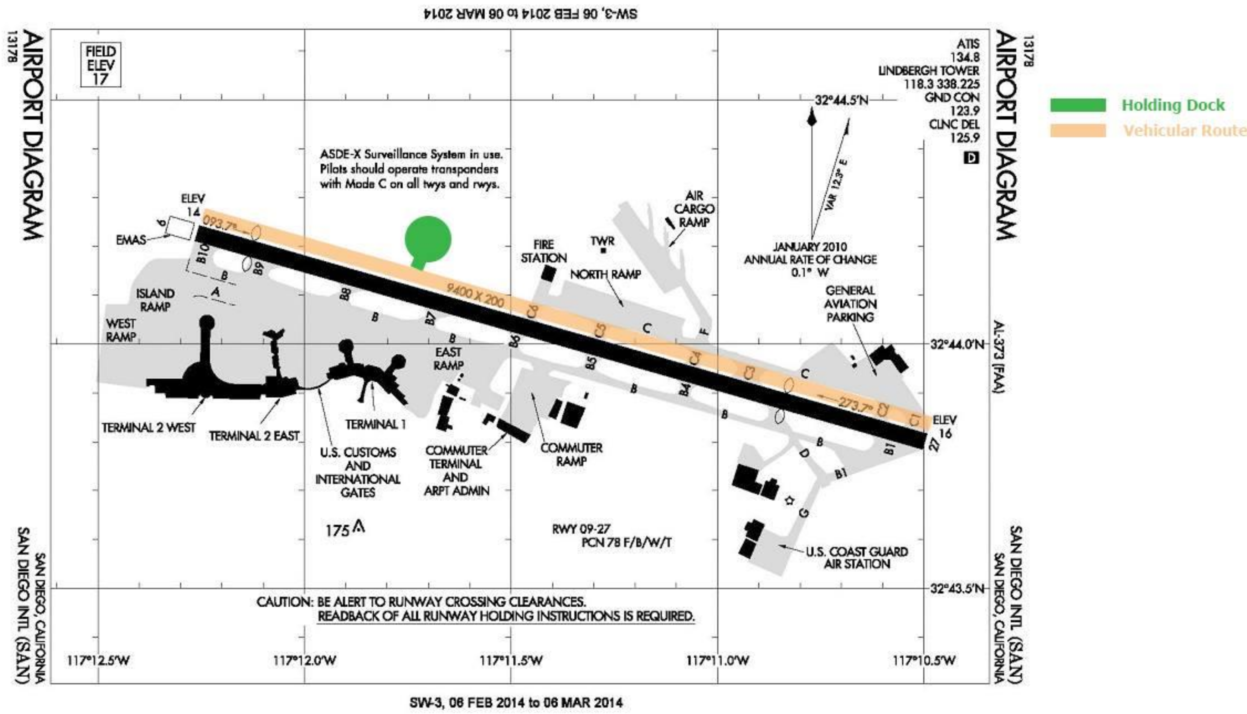

Figure 7 Vehicular RoutesFederal Aviation Administration. (2016) KSFO Airport Diagram. Washington DC

Vehicular routes are specifically designed for SAETS tugs. This will allow the routes to be significantly narrower than other taxiways and roads on the airport surface. The routes width will be sufficient to fit two-way SAETS tug traffic. The vehicular routes will guide the tug via a single rail. The SAETS tugs will travel the routes with the rail between their wheelbase. This will physically prevent possible deviations from planned route when in the vicinity of active runways.

The *vehicular routes* will also intersect taxiways. These intersections pose the most significant risk for collisions with aircraft and ground equipment. The routes rail will be laid into the concrete of a taxiway, similar to a railroad crossing, to avoid conflict.

f. Departure Procedure

SAETS tugs will provide transport of aircraft from their gate to the departure end of the active runway. The SAETS tug will autonomously depart from the *loading dock* when required for a departure. The tug will leave the *loading dock* for the departure gate when signaled by the pilot in the aircraft.

The pilot will then taxi the aircraft via remote. The taxi routing and communications will remain the same as engine powered taxi. This will allow for smoother integration of the electric taxi system because flight crews will not be required to learn new procedures besides the operation of the SAETS tug.

Upon reaching the active runway, the pilot will signal the SAETS tug to disconnect from the aircraft. Once disconnected, the tug operates autonomously and relocates to a station via the *vehicular routes.*

Engine start can be accomplished during the taxi process. The SAETS tug will be located in front of the aircrafts nose wheel. This will allow sufficient distance from the aircraft engines to not impede on engine start. Engine start during taxi will also minimize the additional time that the implementation of an electronic taxi system adds.

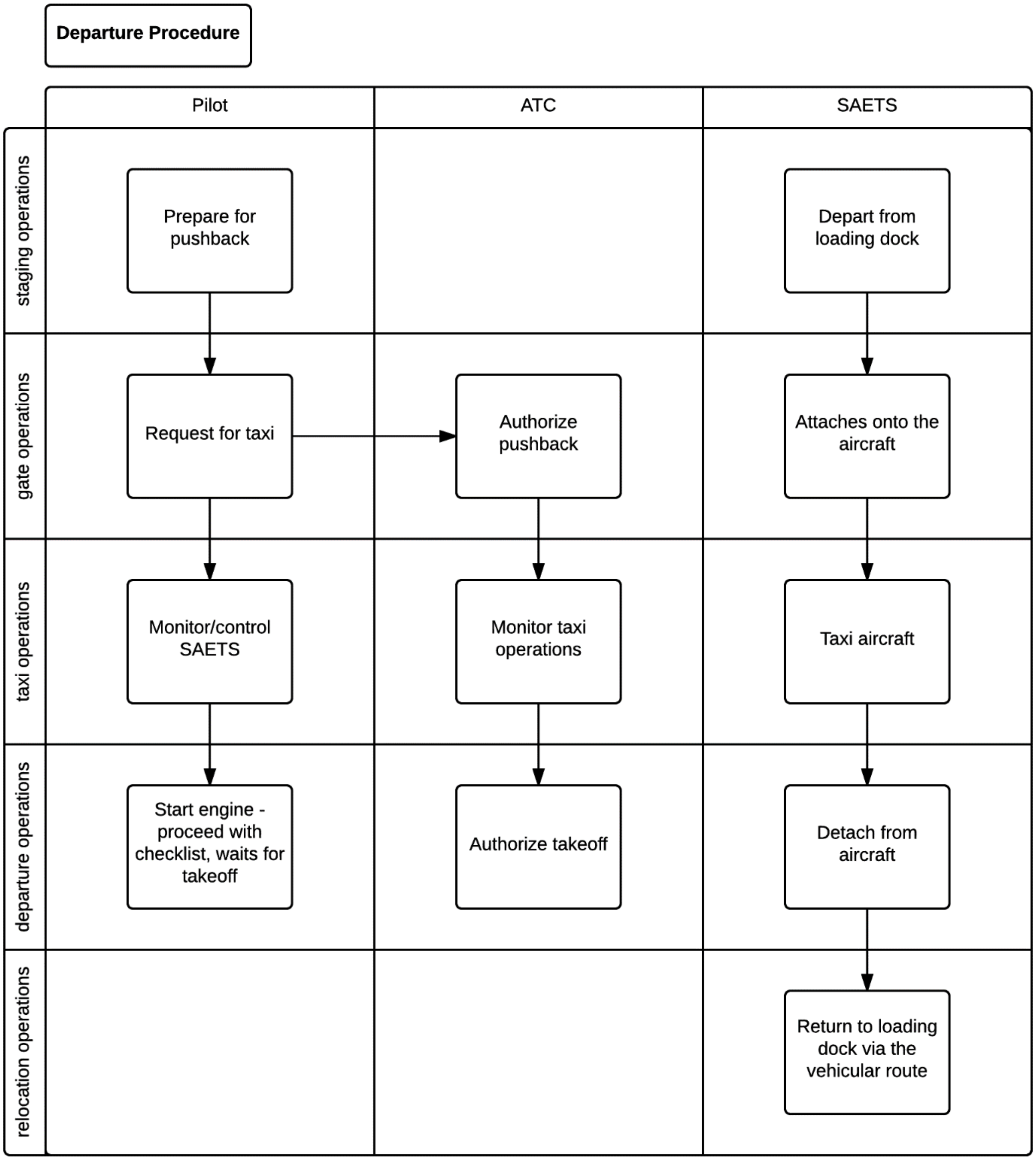

Figure 8 Departure Procedure

g. Arrival Procedure

The arrival procedure is similar to the departure procedure. SAETS tugs will remain on position in a holding area at the departure end of runways. The tugs will then proceed to the aircraft at the appropriate taxiway via *vehicular routes* once the aircraft has cleared the runway and signaled for the tug. The tug will then link with the aircraft autonomously. Once linked, the flight crew will control the tug via remote, and taxi the aircraft to the arrival gate utilizing standard taxi procedures.

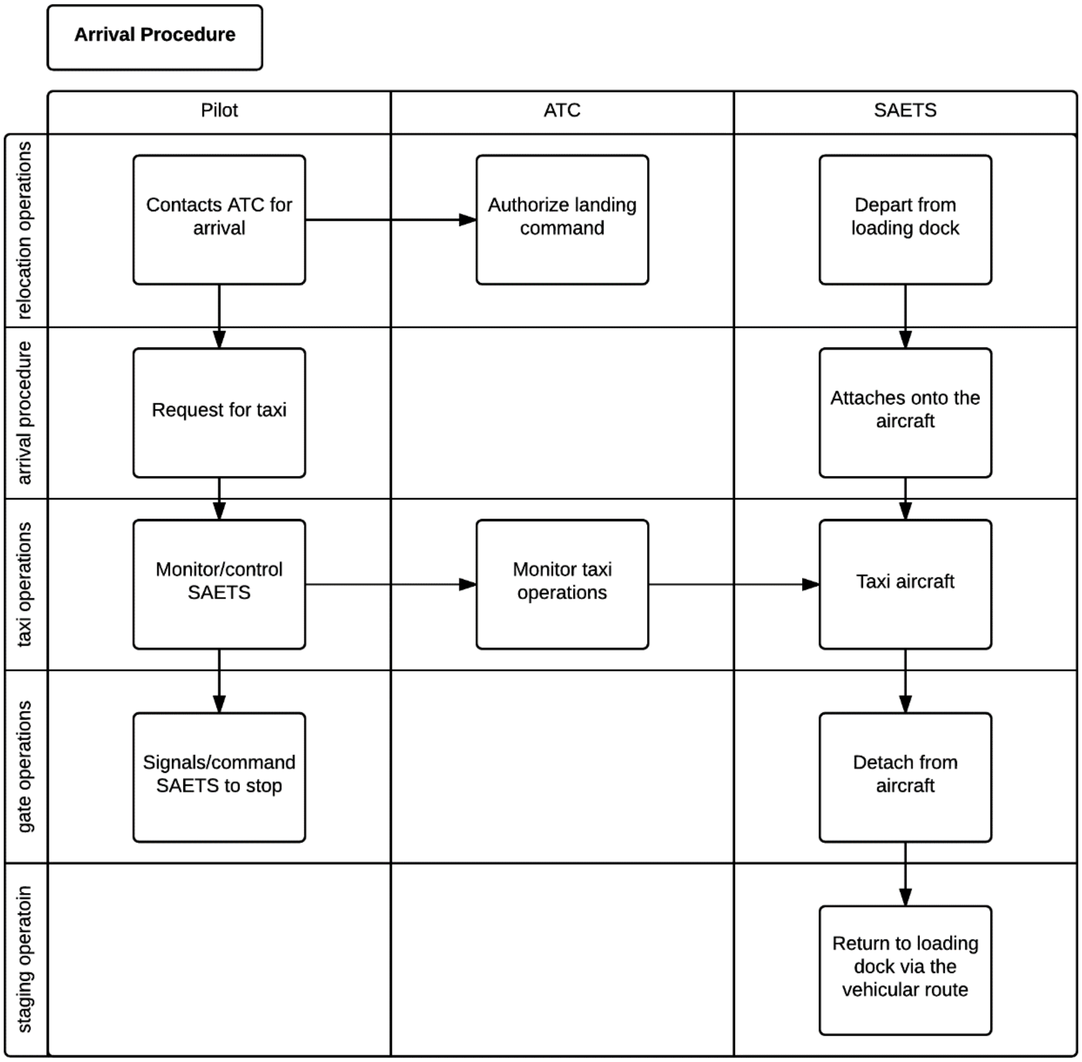

Figure 9 Arrival Procedure

8. Interactions

The mechanisms of a well-structured airport can be difficult to piece together, however with the right planning it can become a very efficient model for the whole of the aviation industry. The implementation of an enhanced electrical taxi system into an airport operations systems can be a tricky business when considering practicality and restrictions that can be caused by adding a new factor into the works. Many questions arise when considering the possibilities, such as: who would control the system, where would the resources come from, what possible emergency procedures would be involved, how would the system operate for each specific airport, would emissions actually lower since the airplanes are not being used to taxi but other devices are, would this help or hinder turn-around times for airlines, and similar questions along the route of practicality.

In order to address the questions that arise when forming a new change in the industry, a common perspective is needed among the people who work in the industry. Therefore, interviews were taken and recorded with the permission of those within the industry that would be directly affected with this new system. The interviews were conducted at the Purdue University Airport, with several faculty and staff that are veterans of the aviation industry.

The first interview was conducted with the Chief CFI of the Purdue University program, Dr. Ronda Cassens. She was asked various questions about efficiency and productivity from the pilot perspective, as well as what she thinks the airline perspective would be of the introduction of a separate taxiing system for the airplanes. As a pilot herself, she has a unique addition to the process because she has had first-hand experience with the current system, and although not familiar with how the implementation of the electrical taxi system has worked in practicality thus far, she has a valid opinion on what the system would look like at both a relatively smaller operation such as Purdue, as compared to how effective or ineffective it may be to be used for an airline at a larger operation airport such as Chicago O'Hare International.

An interview was conducted with Dr. Cassens (personal communication, March 10th, 2016) on the issues with smaller airports implementing the capabilities of this system, and she seemed to believe that it would be illogical for smaller airports, such as Lafayette or an uncontrolled airport, to implement this device within the operation. However, she also admitted that when thinking about a larger scale airport implementing the device, it seemed a bit radical to her.

> *When I think of an electric taxi system, I think of the device that Honeywell made, but I don't think that's very efficient since it runs off an APU. Maybe if they made something compact and was able to be charged easily, I'd buy into that. They would basically be making an automated version of a tug, and that would be pretty cool.*

Dr. Cassens mentioned that she would want to see the way the controllers would react to the same questions that she was asked about the system, as her opinion was that they would take it rather poorly having to be charged with another potential system underneath their charge, with already so many operations being supervised by them. She felt that they would have to add new people, which could create new jobs, but simultaneously make the whole operation more convoluted and crowded.

The second interview was conducted with the Purdue University assistant professor, Dr. Sarah Hubbard. She was asked questions about both the controller and management perspective, to see if the controllers would be on board with a separate system being added into the mix at both larger and smaller operation airports. In addition, if a controller was to be put in charge of an emergency backup system, or even the initial system that controls these devices. Dr. Hubbard has a unique perspective of airport management and gave input from the eyes of controller and their possible outcries, to be able to identify the workload management and overall flow of the Purdue University airport, as well as flows at other airports that she is familiar with.

Dr. Hubbard (personal communication, March 10th) mentioned a few key ideas about how the system could operate, as well as the input from controllers and the Operations branch of the airports, in the interview she added,

> *I think that if the system will have a tremendous amount of logistical planning, just based off of the scale of what you are dealing with. It could be viable if the ASDE (airport surface detection equipment) type guidance was used, which is comparable to a transponder for ground operations.*

The operations of a large scale airport will be a tremendous hurdle, as well as the support from the controllers of approach, tower, ground, and the other separate angles of the sky. Dr. Hubbard was asked if she could see the controllers being on board with the implementation of the system, and promptly said that there is little that the controllers and operations management can agree on, and this does not seem to be one of those topics that they can come together with.

The third interview was conducted separately from the Purdue University airport, with UPS Captain Mike Aven, who has been flying for several decades as a cargo pilot among various countries and airports around the world, and has one of the better perspectives of how the electric taxi system could be implemented globally, as well as with a larger scale operation such as UPS. Mike has been a part of the aviation industry for years, and has perfected the art of efficiency and using his talents as a very veteran pilot to make himself and others around him into better and more proficient pilots as well as people as a whole.

Mike (personal communication, March 8th, 2016) decidedly was optimistic of the system, explaining that it would help reduce the workload of the pilots, and while they would still need to pay attention during the taxi procedure in case the system were to fail, they would be able to drastically improve their after landing efficiency, and simultaneously save fuel as well as time by changing the flows to help better prepare the airplane during shutdown, possibly increasing after landing time to the gate.

> *I think it would be wonderful. The system provides a way for airplanes to move without their engines, and I love the fact that I can just sit back and let the tug pull me in, I love the flying part, I love hand flying the airplane as you know, but I have things to do on the ground! I can't be worrying about if my [First Officer] is about to run me off the taxiway, but I also want to be able to make last minute changes, and that all depends on if I have control of the system and where it goes. I would hope I have control.*

Mike Aven is a veteran pilot, and rarely uses an autopilot to help him fly unless he absolutely needs it. This personality trait makes him reluctant to trust a system similar to an autopilot on the ground, however his optimism that it could help reduce workload and overall efficient improvement helped him become more attuned to the system.

The overall reaction was a bit of a mix, with some optimism from the pilot side who benefit from the reduction in workload, and negativity from the controllers who would appear to be in the deep end for the responsibility of the system. The tendency for the system to be less efficient with an APU was a common hindrance to implementation and acceptance, yet the gate-to-gate time was also a worrying factor.

The implementation of an enhanced electrical taxi system into an airport operations systems is fundamentally questionable when considering practicality and restrictions that can be caused by adding a new factor into the works, and based off the interviews conducted in the research, the acceptance of the system is just as questionable. Overall the system has just as much promise as it does potential for failure, just like any system and machine, it will need to be perfected over time in the practicality, but the idea of a system that can be used to taxi, regardless of the flaws inherent, seems to be an inspiring idea.

9. Impacts on Sustainability

This section discusses the potential impacts on the three pillars of sustainability.

a. Financial Sustainability

SAETS should have a positive impact on financial sustainability. The ability to move aircraft across airport surfaces without fuel burn significantly reduce operating costs of aircraft operators. The system has the potential for significant cost saving by reducing fuel consumption during taxi and exemplifies goals of the ACRP.

A study conducted at Dallas-Fort Worth International airport found that on average, the combined taxi fuel-burn for one day’s flight operations totaled to 44,500 gallons of jet fuel (Nikoleris, 2011, p.1). Based on the fuel price derived in the study for the region of $2.20/gallon, the total cost of taxi fuel for a day would be $97,900. Over the course of a year of flight operations at the airport, there could be a theoretical savings of over 35 million dollars. These savings would be passed down directly to aircraft operators who opt to utilize SAETS.

Although there is significant cost savings due to a decrease in fuel consumption, SAETS is a comprehensive system of hardware and structures that would require substantial initial investment. The cost of implementation could be offset over time by the use of fees on aircraft operators that utilize the system. The fees would be minimal enough to still allow cost savings for aircraft operators while at the same time fund the operational costs, maintenance, and initial investment of SAETS.

Airports that implement the SAETS system may also be qualified for local and federal subsidies. These subsides could aid in funding the initial costs of installation.

b. Environmental Sustainability

SAETS should significantly reduce fuel consumption during taxi. Based on the study conduct at Dallas-Fort Worth International airport, aircraft taxi accounts for approximately 10,100kg of Carbon Monoxide (CO) emissions daily (Nikoleris, 2011, p.1). The SAETS system removes almost all engine-run time from the taxi process and also stands to remove a substantial amount of the related emissions.

SAETS should dramatically reduce the total emissions from commercial airports. Excessive concentrations of carbon pollutants in a specific area can be highly detrimental to human health. An airport emissions study in Zurich, Switzerland found that, "CO concentrations in the vicinity of the terminals were found to be highly dependent on aircraft movement" (Schurmann, 2006, p.1).

The SAETS system has the potential to significantly reduce the emissions related to aircraft surface movement at a commercial airport and in turn have a positive impact on the public health of the surrounding areas. This correlates directly with the goals set by the ACRP.

c. Social Sustainability

The Environmental Protective Agency, or EPA, has developed a "Sustainability Primer" (2015) that covers the three respective pillars that provide us the key definition basis for sustainability. Beginning with the social aspect of the definition, it is important to grasp that, based on other definitions, it is more of a centerpiece to the structure of the system. The social pillar, also known as "people", has a variety of subjects underneath its breadth, such as

Environmental Justice, Human Health, Participation, Education, Resource Security, and Sustainable Communities (United States Environmental Protection Agency (EPA, 2015, p.1).

During the research of this topic, sources from different angles of aviation were interviewed to see their ideas and opinions of the semi-autonomous electric taxi system, and what concerns and praises they had. The interviews were conducted based on the branches of the pilots, controllers, airport management and operators. Overall the general consensus was that it would be a huge logistical project that not all parties involved would agree with, and the implementation would have to be a well thought out and highly intricate system.

In the ACRP guidelines document, the overall goals for the project have to do mainly with improving operations and economic stability, however social sustainability is a primary target for managing the logistics of the system, because without the support of the controllers or operators, the system cannot be implemented. The pilot category was the most optimistic of the implementation, however even from them they expressed a disdain toward the APU being a main operating center point of the power supply. It was noted that unless the APU was replaced by a more sustainable resource such as a hydrogen or electric powered device, the system would effectively just be getting in the way of operations that are doing the equivalent of the work without the extra device.

10. Conclusion

The continued sustainability improvement of commercial flight operations is essential for growth of the aviation industry. The SAETS system, when implemented as outlined in the project, poses significant potential in improving the environmental, financial, and social sustainability of commercial aviation. The SAETS can utilize existing hardware technologies implemented in a simplistic manner that should minimize required infrastructure and operational augmentations and integrate easily amongst operators. By reducing the jet engine run-time during taxi, the SAETS system can save fuel, decreasing airline's operating cost, while also decreasing emissions.

The implementation of the SAETS system at a large commercial airport such as Dallas-Fort Worth International and San Diego International could eliminate a great deal of the estimated 44,000 gallons of fuel consumed each day for aircraft taxi (Nikoleris, 2011). In addition, figures were included to show the visual implementation of the vehicular roadways and holding docks. This decrease in fuel consumption lowers operating costs for air carriers while also decreasing overall emissions and strengthening the future sustainability of the aviation industry.

Appendix A

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Appendix B

Purdue University is a land, sea grant public university and a member of the Big 10. The aviation program is over 75 years old, part of the Polytechnic Institute, and has undergraduate and graduate degrees programs. The Purdue Polytechnic Institute, previously named the College of Technology, is one of 10 colleges at Purdue University offering undergraduate and graduate degrees. The following statements are from the www.purdue.edu website.

As one of the Purdue Moves initiatives, the college is undergoing a major transformation that affects all facets of the college, the scope of which is so profound that a name change was warranted. The Polytechnic name best embodies the characteristics, elements, and philosophy of the transformed college and readily represents a distinctive brand that highlights the unique nature of the learning experience.

The academic programs combine theory-based applied learning, team-based projects, integrated humanities studies, competency-based credentialing, and a series of experiential components such as industry-sponsored senior capstone projects, internships, global immersions, and certification-earning activities. The Polytechnic learning experience is designed to produce graduates who not only have deep technical knowledge and applied skills in their chosen discipline, but also possess problem-solving, critical thinking, communications, and leadership skills sought by industries and communities.

Appendix C

No non-university partners were involved in this project.

Appendix E

a. Student Team

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?

There was a meaningful learning process during the design competition, mainly in gathering the research information about the software and the connection to the GPS system. I learned quite a bit about the technology that goes into an electrical taxi system, and how they operate in real-world application. I found the information from various airports around the country, and how they emphasized that they are in a prototype phase, but they are working exceptionally well. The only downside to the system that I had found during my sections of the report is the fact that the controllers do not want to deal with the taxi system as an addition to already hectic airport operations.

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

We encountered time constraints, to be certain. During the beginning of the research process we found little time to be able to gather the information and be ready by our personal due dates, however we stuck to them and were able to begin coasting at the end of the projects data gathering and formation, with time to be able to make several edits in the information.

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

We determined that there was an issue with taxi time and pilots having to create various ways to get around using so much fuel during the initial taxi out, and subsequently the taxi back in. We then determined that to get around this, we would have to use a system separate from the engines themselves, so as to avoid using fuel as a whole, while still maintaining the time constraints that are put on the airlines and the pilots. Using a taxi system seemed fitting, by using tugs you can avoid using the aircraft systems in a safe and effective way.

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

Participation from the industry was absolutely important and meaningful, because their opinions and concerns about the diversity and the vagueness of the project helped us better define our goals and what we wanted to accomplish with the completion of our taxi system project.

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?

We learned that the tugs are a better, but still not exactly an acceptable replacement to things such as “single-engine taxiing” or idling on the ramp. While they reduce emissions and fuel costs, it is not by much, and they are still being run off a source equivalent to an APU, or an APU itself. To correctly address this issue, we would need to replace the source and the ability to be able to taxi in a reasonable time could not be compromised.

b. Faculty Advisor

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

The educational value for the students is immeasurable. The process of reading the guidelines for the design challenges, generating ideas, developing the ideas into a design, and preparing the technical report helped the students take a vague idea of a problem existing at airports into a designed solution. The student team completed this project as their required course project for an aviation sustainability graduate class that I teach. The team is comprised of three graduate students. Two of the graduate students are from the Purdue BS in Professional Flight Technology and are Certified Flight Instructors; and the third is a “3+2” student pursuing her BS in Aviation Management at Purdue and is a first semester graduate student. The team members are all students in our MS in Aviation and Aerospace Management program. They learned each other’s’ strengths and worked as a team to develop the design solution. Taking an idea from a general notion to a design in three months is a difficult process. The team selected their design challenge area and their specific problem to address. They learned to see airports differently when they got a chance to suggest changes that affect airport operations such as electric taxi. There were details to consider for connecting and disconnecting the taxi system to aircraft and for airport operations, and they used their backgrounds in flight and aviation management to develop a solution.

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

Yes, this learning experience was appropriate for the course level. This is a one semester graduate course that starts in January. The team had to decide the challenge and their approach very early. This means that the team put this together in less than 3 months.

3. What challenges did the students face and overcome?

Doing this project in one semester is a challenge. The team had to settle on an idea quickly to get this design package completed in three months. The team learned a great deal about electric taxi for commercial aircraft, both the advantages and disadvantages. The additional challenge for the team was to address aviation sustainability specifically in the design and report. This is not a requirement of the ACRP competition, but it is a requirement for the course. Each student developed their own definition of aviation sustainability based on extensive reading and study. The ACRP, ICAO, FAA and IATA reports on aviation sustainability were used in addition to company websites and academic texts and articles. They had to overcome the lack of a unified definition in the literature and develop their own definition that had meaning to them. Then, as a project team, they developed a consensus definition of aviation sustainability for this project and used it in their analysis.

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

In the future, I do plan to use this competition as an educational vehicle. In most of my graduate classes, the students prepare an extensive technical report or paper. The difference in this competition is that the fact that there is a competition, that there are numerous design challenges and project ideas, and that the submission will be judged by aviation experts. This is very inspiring to the team. I think that it pushes the students to do more when they know that there is a competition.

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

Please keep doing this competition. I realize that it must take countless hours of dedication from dozens of people to read and judge these entries. I do not have any changes at this time.

Appendix F

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