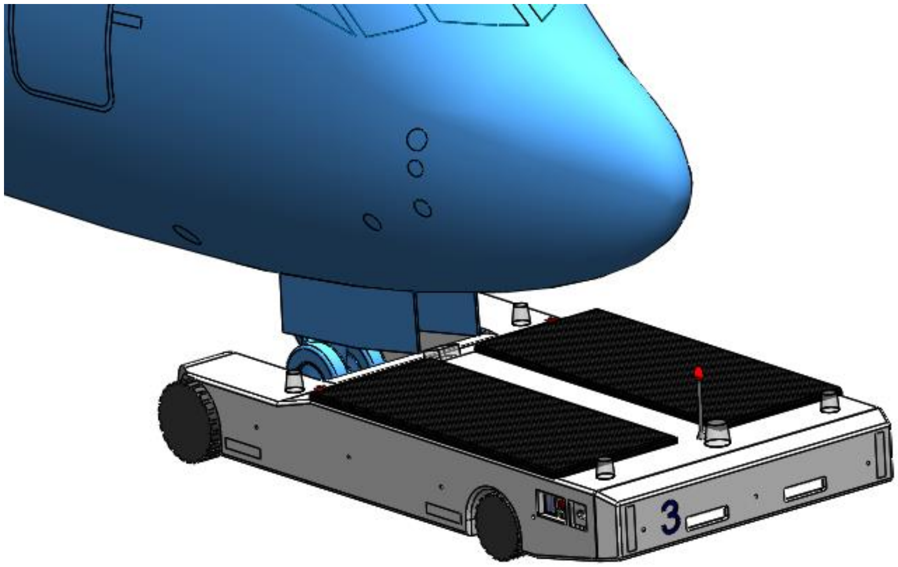
Autonomous Electric Aircraft Tug

2023-2024 ACRP Design Competition



Design Challenge: Airport Environmental Interactions Challenges: New tools and approaches to noise reduction at airports, enhanced methods for improving air quality around airports, and methods of reducing carbon emissions from ground equipment at large hub airports.

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Executive Summary

This paper addresses the **Airport Environmental Interactions Challenge**, specifically challenges D, E, and H: “New tools and approaches to noise reduction at airports, enhanced methods for improving air quality around airports, and methods of reducing carbon emissions from ground equipment at large hub airports.” Anticipated future growth in air travel amplifies the importance of reducing carbon emissions during the Landing and Takeoff Cycle (LTO).

During the design process, the team interacted with different industry experts both through interviews and from visiting the Salt Lake City International Airport. A survey was also conducted which helped narrow down different design requirements and important features to implement. Electrically powered, autonomous tugs address this challenge by providing an efficient means of taxing aircraft out to the runway without the associated carbon emissions or noise from traditional methods while minimizing changes to airport infrastructure and aircraft.

The Federal Aviation Administration’s (FAA) Aviation Environmental Design Tool (AEDT) was utilized as part of the calculations for the cost/benefit determination, including the amount of fuel that will be saved. The benefit to cost ratio was 6.56 saving an estimated $63.4 million over a period of ten years at one airport for one type of aircraft. Furthermore, as air travel continues to rise, the adoption of these eco-friendly tugs not only aligns with the industry’s commitment to environmental responsibility but also serves as a practical measure to manage the surge in demand while mitigating the environmental impact of ground operations.

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Problem Statement and Background

The problem addressed by this proposal is the emissions and noise given off by aircraft (and related ground equipment) during the LTO cycle. Accordingly, this proposal addresses the **Airport Environmental Interactions Challenges D, E, and H**: "New tools and approaches to noise reduction at airports, enhanced methods for improving air quality around airports, and methods of reducing carbon emissions from ground equipment at large hub airports."

Current Conditions

Air travel around the world is increasing every day with airlines expecting to increase global traffic 400% by the year 2050 [1]. The main source of emissions at airports is the aircraft. The combustion of jet fuel from domestic and international aviation accounts for more than 97% of U.S. aviation CO_2 emissions" [2]. While aircraft emit the majority of their pollutants during the cruise phase when flying at high altitudes, addressing emissions during the LTO cycle has gained attention due to the localized impact of ground-level pollutants and the potential for improvements in fuel efficiency. Aircraft initially maneuver away from the jet bridge with the assistance of a tug, after which they rely on their engines to taxi from the apron to the runway. This practice is suboptimal in multiple ways, including in terms of fuel consumption and emissions. Traditional jet engines, designed for optimal performance during high-altitude flight, are less efficient when operating at low speeds on the ground [3]. Over the years, the taxi-out time, encompassing time spent on the taxiway system and in runway queues, has seen an upward trend. In a report by The National Academies Press, the contributors stated that "as traffic grows, and airports approach capacity, the resulting ground congestion will mean that aircraft will be spending more time on the ground in hold short positions and waiting queues" [4]. The acceleration of fuel-heavy departing aircraft will produce more noise as they approach taxiing speed from hold short positions. The overall result of these effects will be that ground operations may, in fact, become a larger contributor to airport noise and emissions.

Because a significant portion of emissions are produced at airports during the LTO cycle, numerous strategies have been explored to address this issue. These approaches encompass various methods, including employing single-engine taxiing to the runway, incorporating onboard systems like electric motors on aircraft nose wheels, and enhancing traffic flow management at airports. Further elaboration on these technologies, along with others, are discussed in the literature review.

Purpose

The intent of this proposal is to reduce emissions at airports during the LTO cycle by towing aircraft out to the runway using electric autonomous tugs. This will allow an aircraft to keep its engines off longer than is currently common. If an engine is not started after pushback until the aircraft is in an advanced stage of the taxi-out for takeoff, then such a procedure has the potential to reduce fuel consumption and emissions [5]. Other benefits of this design will be reduced noise pollution around the airport and increased cost savings in terms of fuel consumption and engine maintenance.

Summary of Literature Review

Various methods have been attempted in the past or have been implemented to reduce emissions of aircraft and Ground Support Equipment (GSE) at airports. Different ACRP reports provided valuable information that help to solidify the design of the solution proposed. These methods are examined in detail and how the team's proposal can contribute to the decrease in emissions and noise at airports below.

ACRP Reports

ACRP studies provided valuable information regarding the objectives of this design. Table 1 provides a concise summary of the utilized reports, outlining the key insights that directly relate to the proposed design.

Table 1: ACRP reports used during the literature review and problem-solving process.

Report	Title	Summary of Findings
78	Airport Ground Support Equipment (GSE): Emission Reduction Strategies, Inventory, and Tutorial	EV operational costs, energy efficiency, performance, maintenance, conversions, and limitations with regards to electric GSE vs other alternative fuel [6].
158	Deriving Benefits from Alternative Aircraft-Taxi Systems	Discusses a list of potential benefits and concerns associated with external taxi systems while taxiing aircraft to the runway [7].
Web-Only Document 9	Enhanced Modeling of Aircraft Taxiway Noise: Volume 1	Overview of airport noise including ground operation and taxiing noise levels [4].

Different Approaches

Some companies have engineered electric tugs to be operated remotely through a control device [8].This approach offers a notable advantage in enhancing visibility around the aircraft during the pushback process, enabling better detection of obstacles or potential interferences. However, a limitation of this method lies in the range of the remote control, restricting the distance from which the controller can effectively operate the tug. The person operating the tug is also responsible for being the “eyes and ears” of the tug. The tugs themselves have no situational awareness capabilities. This constraint means that the person managing the tug via remote control must remain in close proximity, assuring that no collisions or accidents occur making it impractical for towing airplanes over longer distances, such as to the runway.

Another approach considered for minimizing emissions at airports involves utilizing fewer engines during the taxiing phase. Aircraft engines typically require a warm-up period ranging from 2 to 5 minutes prior to departure, depending on the engine type. In cases where the taxi time is less than five minutes, adopting a single-engine taxi-out scenario would not alter the surface emissions for that flight. However, if the aircraft taxis for a duration exceeding five minutes, emissions would be reduced significantly [5]. This same method is used when landing a plane. One engine can be shut down while the other is used to taxi the aircraft back to the terminal. This still presents the issue of using the engines to taxi out. Additional problems with single engine taxiing include increased difficulty steering the plane and increased jet blast from the engine being used. When using only one engine, it can be difficult to turn in the direction of the engine that is being used. More thrust per engine is also required to maneuver when using fewer engines to taxi which can create excessive jet blast and foreign object and debris (FOD) damage [5].

Some airports are already in the process of converting to emissions-free ground equipment which includes the tugs [9]. However, converting to electric GSE requires greater infrastructure at airports which can allow for a large quantity of vehicles to be charging and using electricity constantly. According to a study conducted by the Government Accountability Office, 30 airports responded to a survey regarding the future implications of electric vehicles and GSE in airport operations. Among these respondents, 13 airports emphasized that the anticipated surge in demand from electric vehicles over the next decade is positioned to significantly impact their electrical power infrastructure. Additionally, 11 airports foresee a more moderate impact. Electrical infrastructure at airports will have to be able to accommodate all the electric tugs that will be implemented in this process. Many airports are already underway in making this change [10].

A fairly recent method of towing a plane out to the runway and back involves using an Aircraft Towing System (ATS). The ATS system is fully automatic, utilizing an electric-powered pullcar/tow dolly that rides on a monorail in a below-ground channel and pulls aircraft from the runway to the gate and back" [11]. This system does have many benefits involving less fuel consumption and noise generation, and a decrease in collisions and incursions. Although this method has significant potential, it would require extensive modification of every airport in which it would be implemented.

In the ACRP report 158, different methods were explored to allow an aircraft to taxi out to the runway without turning its engines on excluding the required warmup phase which is around 5 minutes [5]. In chapter 2 of the report, an alternative taxiing assessment matrix was presented and provided various benefits and issues associated with each of the alternative aircraft-taxiing systems presented. As a comparison, a column was added into the matrix that highlights the differences with the proposed design compared to the ones already presented in report 158. There are different ways in which the design would be able to outperform other ideas presented in the matrix. Table 2 below depicts the differences between the proposed electric autonomous tug and previously proposed ideas: the pushback tractor, and a hybrid external large tractor. There were three other options in the table that were analyzed which were a nose wheel motor, main gear motor, and an additional jet engine for taxiing. They were intentionally left out due to them posing more significant problems than the other three such as adding extra weight to the airplane or not doing enough to reduce noise and emissions. However, they can be seen in the ACRP report [7].

Table 2: Different methods of towing an aircraft for taxiing.

Description	Proposed Autonomous Electric Tug	Pushback Tractors	Hybrid External Large Tractor
Energy	Potential saving	Potential saving	Potential saving
Emissions	No emissions	Potential CO_2 saving; possible increase in PM	Potential CO_2 saving; possible increase in PM and NOx
Noise	Jet engine noise eliminated, and tug noise minimized	Noise reduction of approximately 10-12 decibels likely	Noise reduction of approximately 10-12 decibels likely
Cost for alternative aircraft taxiing system	Variable	Variable	Variable
Construction costs	Variable	Variable	Variable
Other costs(e.g. fuel, staff, installation downtime)	Variable	Variable	Variable

Description	Proposed Autonomous Electric Tug	Pushback Tractors	Hybrid External Large Tractor
Safety	Variable	Variable	Variable
Nose fatigue issues	Reduced fatigue loading on the nose-wheel landing gear (compared with aircraft pushback tractors if appropriately designed)	Fatigue loading on the nose-wheel landing gear	Reduced fatigue loading on the nose-wheel landing gear (compared with aircraft pushback tractors if appropriately designed)
Airframe modifications required	No aircraft modification	No aircraft modification	No aircraft modification
Aircraft brake implications	No aircraft brake issues	No aircraft brake issues	No aircraft brake issues
APU modifications required	No aircraft auxiliary power unit (APU) modifications	No aircraft auxiliary power unit (APU) modifications	No aircraft auxiliary power unit (APU) modifications
System weight	No aircraft weight issues	No aircraft weight issues	No aircraft weight issues
Center of gravity implications	No aircraft center of gravity issues	No aircraft center of gravity issues	No aircraft center of gravity issues
Typical taxi speed (i.e. around 20 knots)	Good taxiing speed (with appropriate motor size)	Increased engine capacity for towing large distances at a reasonable speed/acceleration (or towing at a slow speed with low acceleration	Good taxiing speed (with appropriate engine size)
Pilot control	No additional driver needed (can be remotely controlled if desired)	Need for driver	Need for a driver if tractor is not controlled by aircraft; driver needs to drive back to gate area
APU load	APU operated at low load	APU operated at low load	APU operated at high load
Acceleration (e.g. to allow runway crossing from stop in 40 seconds	Good acceleration	Increased engine capacity for towing large distances at a reasonable speed/acceleration (or towing at a slow speed with low acceleration	Good acceleration
Taxi in and out	Difficult to use for taxi-in	Difficult to use for taxi-in	Difficult to use for taxi-in
Attaching and detaching time	Attaching and detaching times (compared to on-board systems)	Attaching and detaching times	Attaching and detaching times (compared to on-board systems)
Start-up/disconnection area	Possible need for aircraft start-up/disconnection area and additional roadways	Possible need for aircraft start-up/disconnection area and additional roadways	Possible need for aircraft start-up/disconnection area and additional roadways
Additional roadways	Possible need for aircraft start-up/disconnection area and additional roadways	Possible need for aircraft start-up/disconnection area and additional roadways	Possible need for aircraft start-up/disconnection area and additional roadways
Pushback tractors	No Issue	Additional number of aircraft pushback tractors and drivers needed (due to increased time used)	No Issue

Description	Proposed Autonomous Electric Tug	Pushback Tractors	Hybrid External Large Tractor
Loading of passengers	Ability to have two door loading of passengers if gate infrastructure allows (i.e. use of two gates for double loading)	No Change	Ability to have two door loading of passengers if gate infrastructure allows (i.e. use of two gates for double loading)
Engine warm-up	Appropriate aircraft engine warm-up time may be required	Appropriate aircraft engine warm-up time may be required	Appropriate aircraft engine warm-up time may be required
Foreign Object Debris (FOD) damage issues	Reduced foreign object debris (FOD) damage	Reduced foreign object debris (FOD) damage	Reduced foreign object debris (FOD) damage

Over the years, many efforts have been made to decrease the noise that aircraft engines produce [12]. Technological advancements in aircraft design and engine technologies have played a pivotal role in minimizing noise emissions. Modern aircraft engines incorporate innovative features such as high-bypass turbofan engines, which significantly reduce the noise produced during takeoff and landing. Additionally, the introduction of advanced materials, including noise-absorbing technologies and soundproofing materials, has contributed to quieter engine performance. Stringent international and national regulations, set by organizations such as the International Civil Aviation Organization (ICAO), have also compelled aircraft manufacturers to adhere to strict noise standards [13]. These combined efforts and many others have resulted in a notable reduction in aircraft noise addressing concerns related to community noise. According to Penn State's "Noise Quest" aviation noise lab, "technology has reached a point where there are few things that can be done to decrease the noise of the engine" [14]. The process of towing a plane out to the runway will then greatly reduce airport noise due to the airplane's engines being kept off until the warmup period is necessary.

Team's Problem-Solving Approach to the Design Challenge

This study employed a mixed-methods approach, integrating qualitative and quantitative components for a comprehensive analysis. The qualitative aspect involved a systematic literature review, a distributed survey, and structured interviews with industry experts to gather insights and perspectives. On the quantitative front an experiment was conducted utilizing a physical model of the autonomous tug concept, and a computer simulation was employed of selected airports to illustrate the impact of the concept, highlighting the potential cost savings and emissions reductions associated with the proposed autonomous tug. The results from these methodologies were analyzed by the design team to further develop, validate, and refine the design concept.

Expert Validation

The following industry experts were consulted during the development of the autonomous tug concept. Also listed are ways the team received other insight influencing the tug's design.

Dr. Richmond Nettey, Kent State University College of Aeronautics and Engineering

The team held an interview with Dr. Nettey and discussed many aspects of the autonomous tug concept. The discussion focused on the point at which the tug should disconnect from the aircraft, turn around and how it should return. Dr. Nettey was also highly in favor of the tug being fully autonomous, highlighting the idea that this would allow ground and pilot operations to be simplified, streamlined and safer in severe conditions. He also mentioned the tug could potentially be used for other tasks at the airport.

Dr. Felipe Rodriguez, University of Maryland - Eastern Shore

Dr. Rodriguez was interviewed about various topics including the necessity for remote operators to have comprehensive awareness, visibility, the importance of wing walkers, effective communication protocols with GMC (ground movement control), ATC (air traffic control), and the optimal functionality of a kill switch in critical scenarios.

Marc Tonnacliff, Senior Aircraft Fire Fighting Specialist with the FAA

During an interview with Mr. Tonnacliff, many topics about safety and communications were discussed, particularly how it helps Aircraft Rescue and Fire Fighting (ARFF). During the discussion of communication, the issue of knowing when and where construction is happening was highlighted. A recent technology that has helped the ARFF was also mentioned, a driver enhanced vision system that allows the drivers to operate vehicles during low visibility.

Dr. Amanda Bordelon, Utah Valley University, Associate Professor – Civil Engineering

A discussion about concrete was held with Dr. Bordelon focusing on the structure and limitations of concrete at the airport, including areas such as the apron, taxiway, and service roads.

Survey Results

A survey was conducted to influence the design considerations and operations of the tug. Respondents included pilots, air traffic controllers, airport employees, military aviation personnel, aircraft mechanics, ground crew and airport administration (Figure 1). The “other” category included baggage service personnel, an aviation lawyer, aircraft passengers, ground support technicians and management in private flight departments. A total of 63 respondents participated in this survey. Questions revolved around design specifications of the tug, airport integration factors, safety issues and other subjects that experts would have concerns or opinions about.

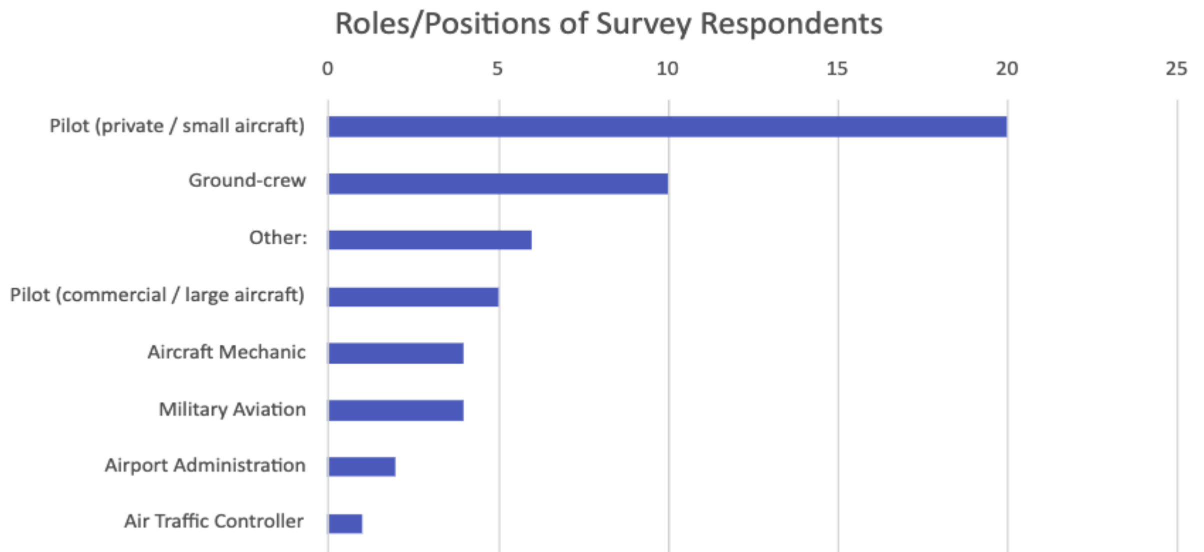


Figure 1: Roles and positions of survey respondents.

Airport Tour

The team had the opportunity to tour the Salt Lake City (SLC) International Airport. Kevin Staples, the Senior Sustainability and Environmental Coordinator for the Salt Lake City Department of Airports arranged the tour, including showing the team around the tarmac of both the commercial and general aviation areas. Many hours were spent in both areas (Figure 2). This facilitated insightful conversations with numerous airport personnel, notably members of the ground crew team. Additionally, Michael Welch, a general manager for Signature Flight Support conversed with the team about the tugs they use and the proposed tug. He also demonstrated how his tugs drive and connect to aircraft. This firsthand interaction significantly influenced the design development process, providing valuable insights into the existing procedures of tug pushback and aircraft taxiing. Furthermore, these interactions facilitated constructive feedback from ground crew members regarding the proposed autonomous tug design and the limitations of currently implemented technology. This opportunity enhanced the team's understanding and refined the envisioned concept.

Figure 2: Tour of the Salt Lake City International Airport.

How Would It All Work

The tug will be designed to minimize changes to current airport procedures and infrastructure and will require no changes to the aircraft. It will be designed to attach to an aircraft and be remotely operated to tow that aircraft out to the area just before the runway hold lines, then detach and return to the terminal either autonomously or via remote control. Figure 3 illustrates what such a tug could look like, including approximate dimensions, physical features and many instruments used for safety and general operation.

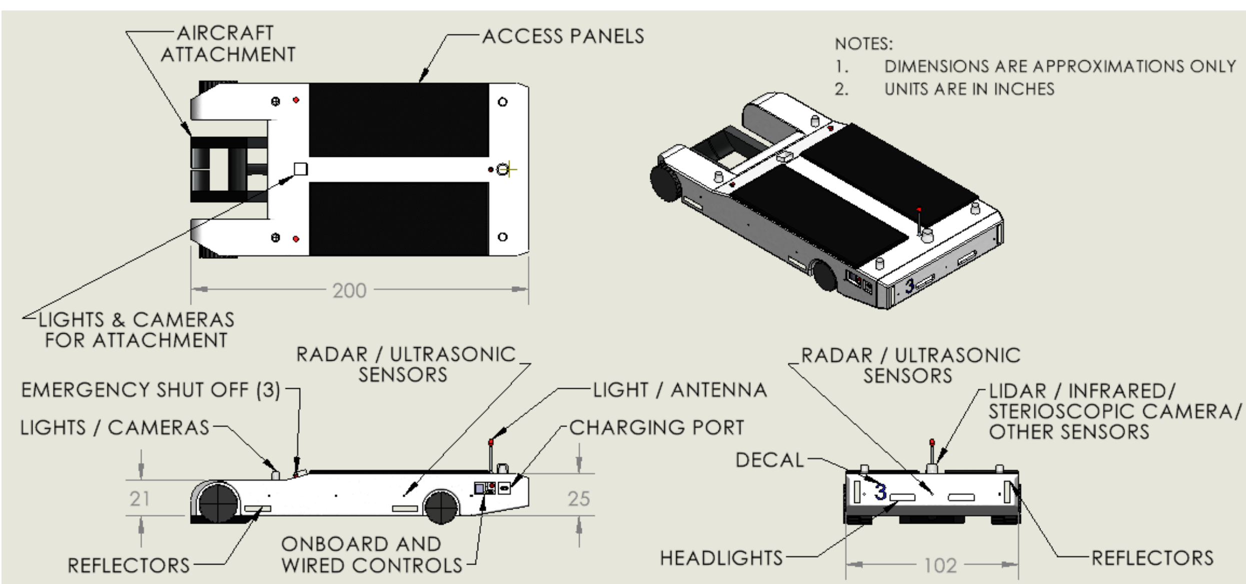


Figure 3: Approximate dimensions of electric autonomous tug.

Useful Terminology

The following definitions are useful in fully understanding the procedures to be implemented in conjunction with the autonomous tug.

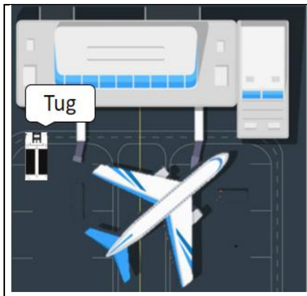
Autonomous: The tug operating without a person manually controlling it. Instead, it navigates using pre-determined routes and/or sensors. The SAE (Society of Automotive Engineers) measures self-driving autonomy on a scale from 0-5. Although this scale centers around road vehicles, it is still a useful scale for measuring autonomy of the tug. This tug fits under category 3: it can drive itself but needs human assistance in some circumstances. [15]

Tug Operations: A team of trained personnel whose assignments include monitoring the operations and whereabouts of the tugs. They have the responsibility to take control remotely as desired or if necessary. The Tug Operations center could be on-site at the airport or off, potentially being a subset of GMC.

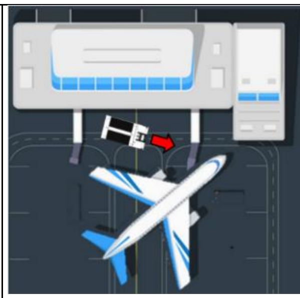
Storyboard

The following storyboard offers a visual narrative of the tug's seamless integration into airport operations, aiding in the understanding of adherence to FAA regulations, navigation strategies, and interaction with ground crew and other airport personnel. Exploring in detail these procedures reveal their potential impact on enhancing efficiency, safety, and sustainability within airport operations while minimizing operational changes for airport personnel, pilots, ground crew, and others. The storyboard starts out in Frame 1 showing a docked and fully loaded aircraft that has just completed all pre-flight safety checks and signals a tug.

Storyboard: Illustrated steps of the proposed Autonomous tug concept.



Frame 1: A loaded aircraft is docked at the terminal. Tug is docked at its charging station. [16]



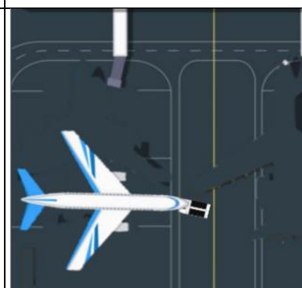
Frame 2: Tug is requested and approaches the aircraft.

Frame 3: Ground crew personnel take control of the tug. [17]

Frame 4: Ground crew personnel align the tug with the aircraft nose wheel.

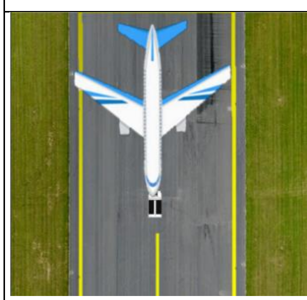
Frame 5: Ground crew personnel connect tug to the aircraft nose wheel.

Frame 6: Ground Crew personnel on the tarmac perform push back. [18]

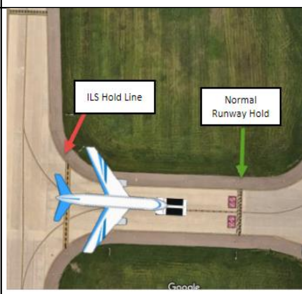


Frame 7: Pilot receives control immediately after pushback has been completed.

Frame 8: The pilot, controlling the tug via handheld controller, directs the tug away from terminal.



Frame 9: Pilot taxis the aircraft under tug power from the terminal along the taxiway. [19]

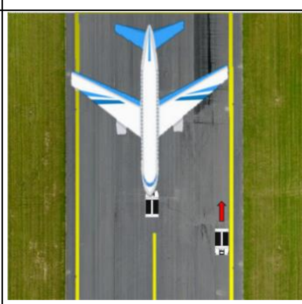


Frame 10: Pilot stops before runway hold line; pilot directs tug to detach from the plane. [20]

Frame 11: Tug turns around avoiding oncoming aircraft and returns to the terminal allowing adequate space for other traffic.

Frame 12: Aircraft engines start, pilot continues to takeoff and the tug returns autonomously or via Tug Operations Center. [21]

Frame 13: Tug returns along the taxiway, using GPS, LiDAR, and other sensors to avoid obstacles and return to terminal. [22]



Frame 14: Tug returns to the terminal giving adequate space to oncoming aircraft along the taxiway.

Frame 15: Tug continues to next task such as towing another aircraft or docking at the designated charging station.

Frame 16: Tug proceeds to the next task.

Charging

The tug starts at its charging station, as seen in Frame 1 of the story board. During the tour of the SLC airport, the team learned that many of the tugs are already electric. Additionally, it was noticed that the type of charging is similar to the charging of forklifts and other electric machinery. The proposed tug would use a uniform charging port such as the ones other tugs and machinery already use. Figure 4 shows a current tug’s 80 kW charging plug and station seen at the SLC airport.

Figure 4: Posicharge mvs800 charger for SLC airport tugs. [23]

Tug Is Brought to the Aircraft

Illustrated in Frame 2 of the story board, the tug approaches an aircraft from its previous location - in this example it is coming from its charging station, but it may also be coming from a different location such as returning from dropping off a different aircraft. When it arrives at the aircraft, the tug stops and waits for a ground crew member to control its attachment to the aircraft.

A highly desirable feature identified by 22 participants in the survey is the tug's low profile while maneuvering around terminals and aircraft (Figure 5), unlike traditional tugs like the Lektro 8900SDB or the one depicted in Figure 2. The 8900SBD is 39” at its highest point, while the proposed tug is only 25" tall. This lower profile can be partially attributed to the design not requiring a seat and controls for an onboard operator.

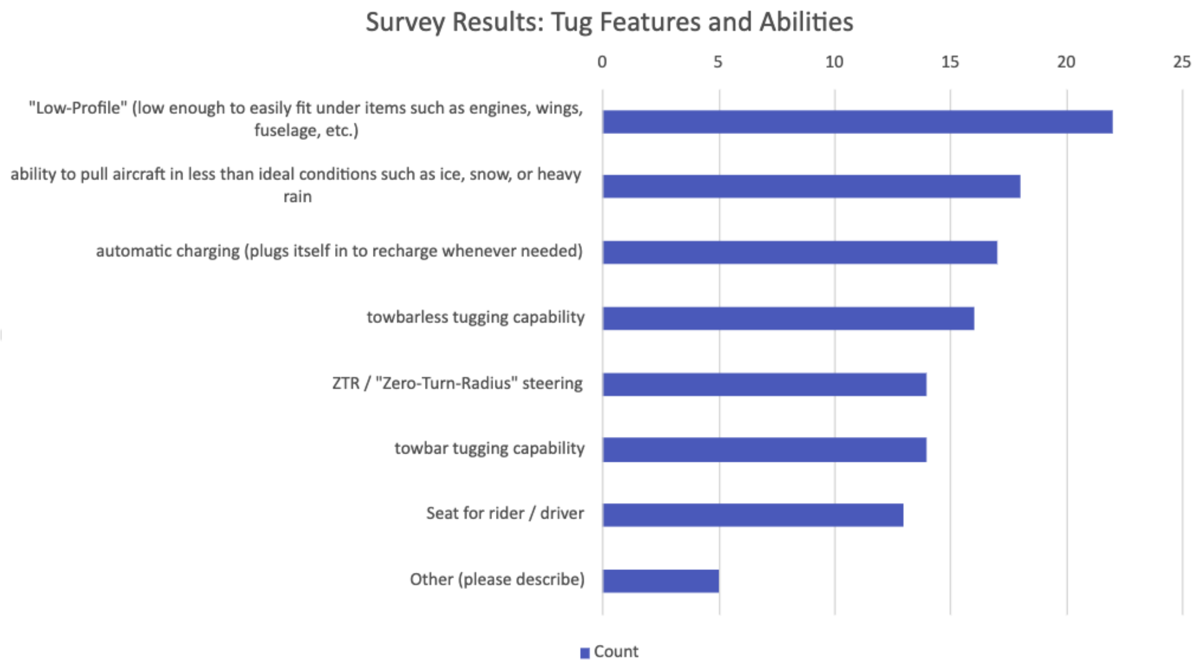


Figure 5: Desired tug features and abilities from survey of aviation experts.

Ground Crew Attaches the Tug to the Aircraft

A ground-crew member will oversee the attaching of the tug to the aircraft's nosewheel, similar to how the process is performed currently. Frame 4 and Frame 5 of the story board show this process. The ground-crew member will back the tug to the airplane using onboard controls or a remote until it is in the correct position for attachment (Figure 6). After the tug has been appropriately lined up with an aircraft, a button is pushed by the ground crew member to initiate the connecting procedure. This process will be overseen directly by a ground-crew team standing nearby and must verify that the tug is attached properly to the aircraft before continuation. The ground-crew member overseeing the attachment can also initiate a detachment of the tug if necessary.

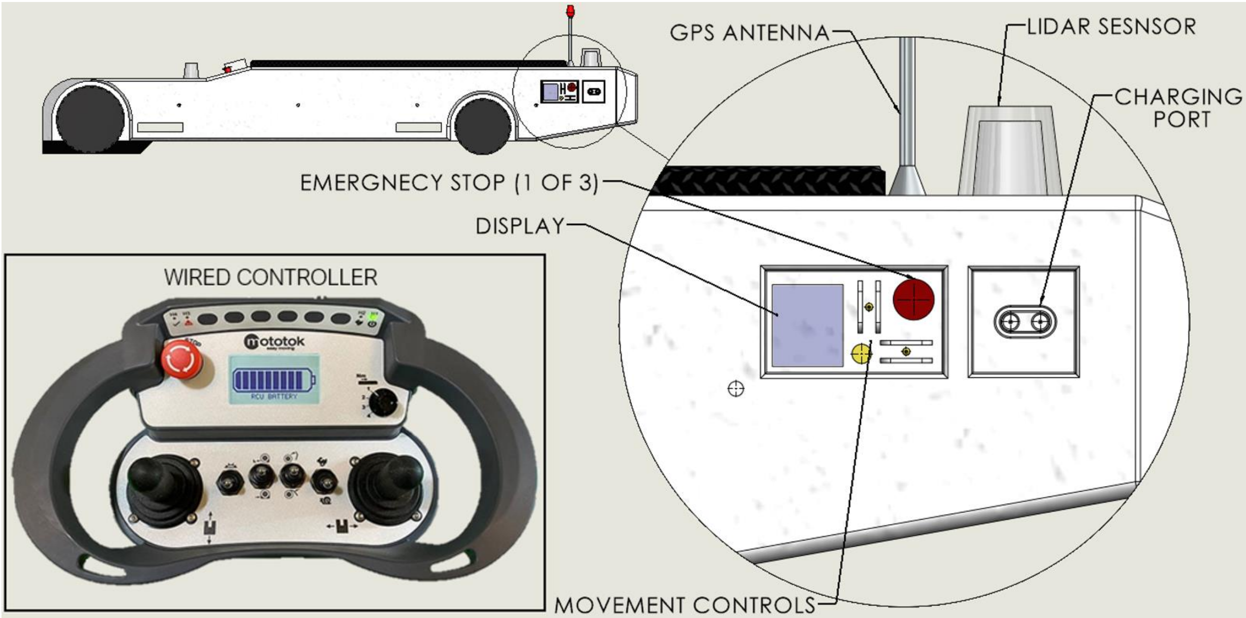


Figure 6: Autonomous tug control panel and wired controller [24].

During the tour of the SLC airport, many ground-crew members expressed annoyance with the towbar setups on tugs. A majority of survey respondents also stated a towbar-less system is advantageous over a towbar system. A towbar-less system would remove extra steps required to connect and remove a towbar, and ideally include fewer parts that could fail. One respondent – a commercial pilot – stated, "... The only 'problem' with a tug I've experienced is the breaking of a tow bar shear pin, which is an advantage of bar-less tug options."

As part of the towbar-less system for the tug, a mechanism will be included that does not require the detachment of the airplane's steering system. An example of this mechanism could be a turn table, or "lazy Susan" that can turn to a higher degree than the nosewheel gear, allowing the tug to turn sharply without relying on the turn radius of the aircraft to which it is attached. This is advantageous by making the attachment/detachment process smoother and ensuring the safety of the aircraft steering mechanisms.

Ground Crew Performs Push-Back

Similar to how it is accomplished currently, the ground crew will be in control of the tug to back the aircraft out along the pushback line, as seen in Frame 6 of the story board. This process is closely monitored by the nearby ground-crew members, this includes the pushback driver, wing walkers, tail walker, supervisor, and communications.

One crucial aspect that was emphasized through responses to the survey is the need for the tug to have exceptional traction even in poor conditions such as ice, snow, or rain (Figure 7).

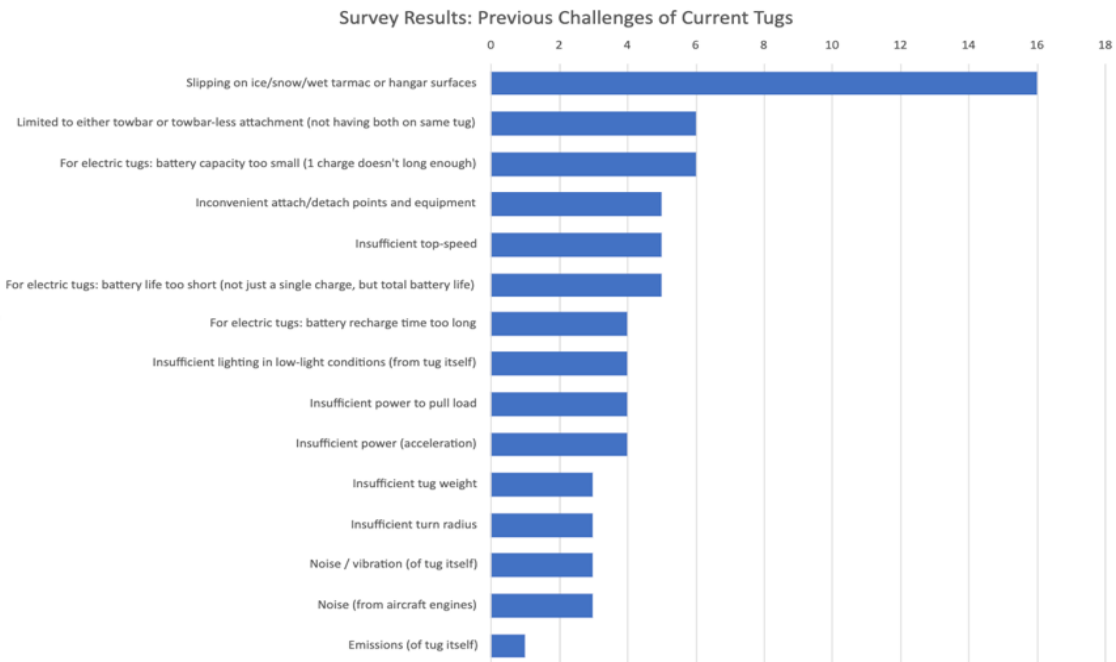


Figure 7: Challenges of current tugs experienced by survey participants.

More than any category listed, survey respondents indicated this as the biggest challenge they had faced with current tugs. In addition to using appropriate tires, one way to improve traction is to increase tug weight. This increased weight will be accomplished using extra battery capacity and larger motors which would be needed due to the longer distances and higher speeds that the tug would travel compared to current tugs. Increased weight adds an additional benefit by anchoring the aircraft to the ground even in adverse conditions, such as high wind speeds.

Control Is Switched to the Pilot

Also similar to current operations, a ground-crew member will transfer tug control to the pilot as seen in Frame 7 of the storyboard. Control is passed by using a button on the controls. The ground-crew member will physically signal the pilot that control is going to be transferred with a wave, or other signal similar to how signaling is already performed on airports at this stage. The pilot can then control the tug.

Taxiing

The pilot will taxi the aircraft to the hold line before the runway by controlling the tug, not using the aircraft's engines (see Frame 8 and Frame 9 of the story board). During the interview with Dr. Rodriguez, situational awareness was a key topic, thus it is important that the pilot has complete visibility around the tug. Cameras will be mounted on top of the tug so that the pilot or other remote operator can still see fully around the tug, including parts the pilot cannot see from the cockpit. (Figure 8). LiDAR sensors and ultrasonic sensors will also be integrated to detect obstacles; the tug will alert the pilot if obstacles are detected.

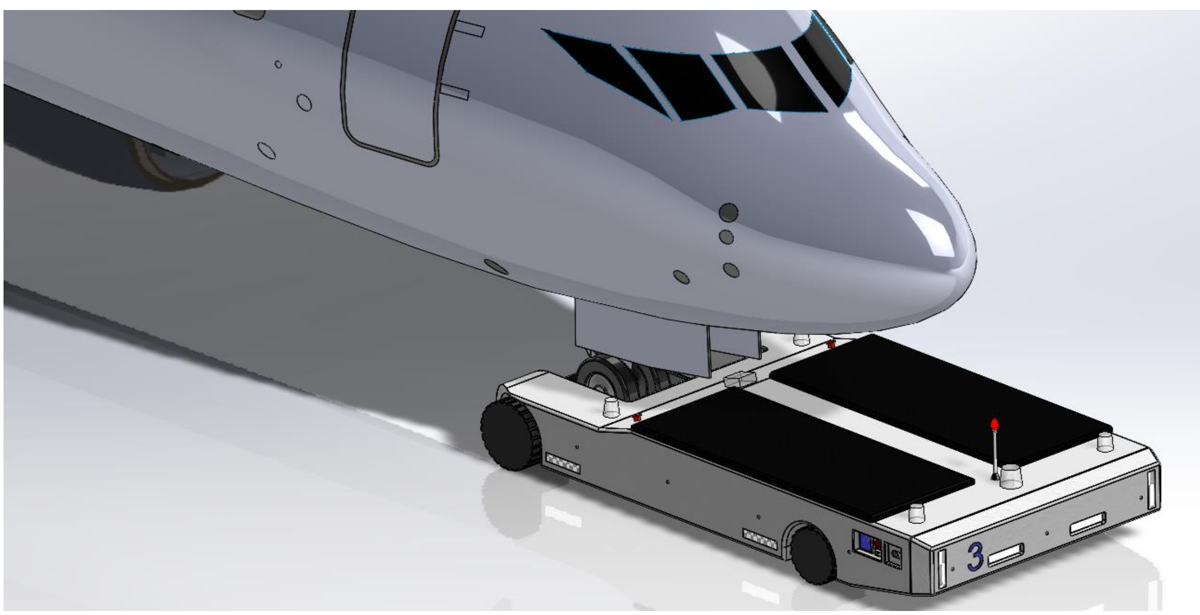


Figure 8: Electric autonomous tug with Boing 737-800

As previously mentioned in the interview with Marc Tonnaclif, a Driver Enhanced Vision System could be very useful for the pilot in taxiing with the tug in low visibility. Mr. Tonnaclif also mentioned that all FAA funded vehicles must have a forward-looking infrared system. This infrared system in addition to many others is illustrated in Figure 3.

One major consideration for towing is the speed and weight of the aircraft and tug. As stated in the Advisory Circular AC 00-65 [25] "The weight of an aircraft and its fuel load is a major consideration during towing because handling characteristics of the tow tractor changes proportionally with the change in aircraft weight. Heavier aircraft put more stress on the vehicle. After movement begins, heavy aircraft can "push" the tug with a greater force than lighter aircraft because of weight and momentum. Tow operators must recognize and understand these characteristics." The pilot should also be trained to recognize and understand these characteristics when taxiing an aircraft utilizing the proposed tug.

Aircraft Stops Before the Runway Hold Line

The pilot will stop the tow of the aircraft before the runway hold lines (Frame 10). During the interview with Dr. Nettey, it was pointed out that airport vehicles (including tugs) are not allowed past these lines. This area is highlighted in green in Figure 9 below and illustrates that plenty of space exists for tugs to detach and turn around to return to the terminal.

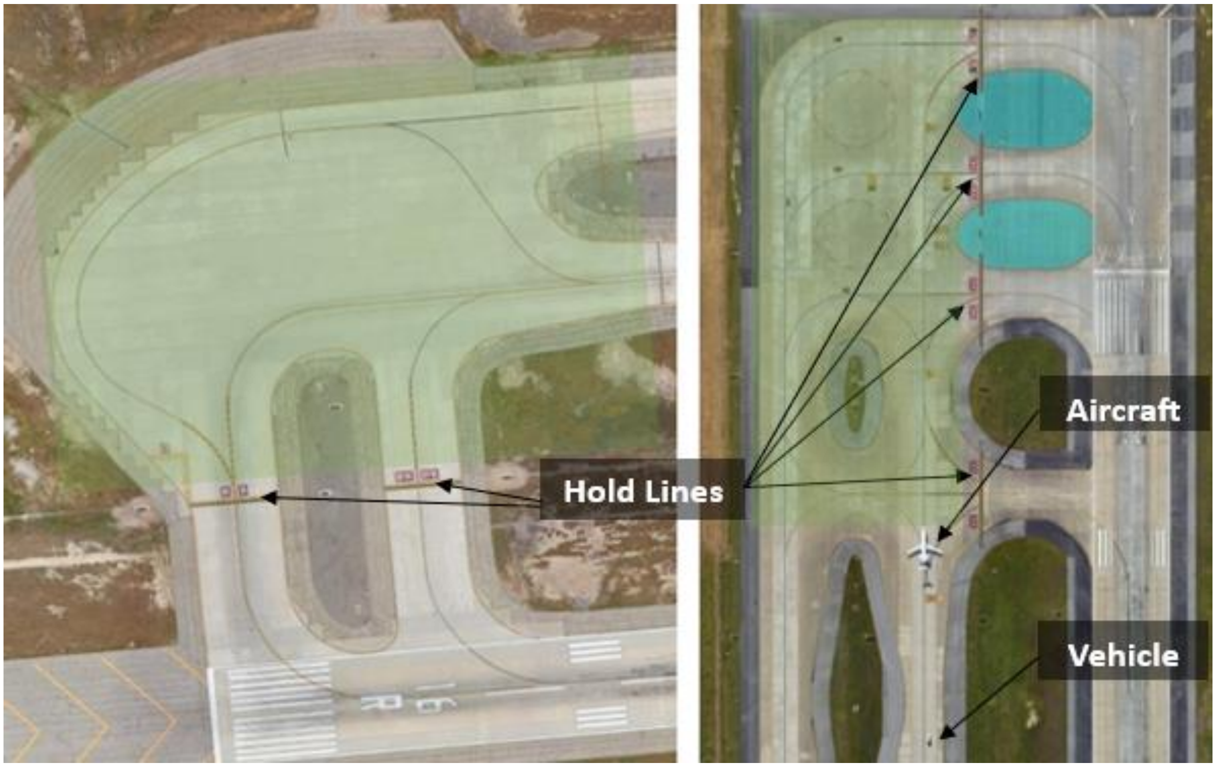


Figure 9: Hold line area of SLC International Airport (Left) and Atlanta's Hartsfield-Jackson International Airport (Right) [26]

Tug Detaches from The Aircraft

The pilot will initiate the command for the tug to detach. The tug then lowers the aircraft attachment until the nosewheel is back on the ground and the weight of the aircraft is on its nosewheel. Then the mechanism releases the nosewheel and the tug attachment mechanism is retracted back into the default position. Successful detachment can then be visually confirmed by the pilot via the tug's cameras (Figure 10). When detachment is confirmed, the tug waits for a command from the pilots' controls that signal it to move away from the aircraft and continue to its next destination. This detachment process may also be performed in an emergency.

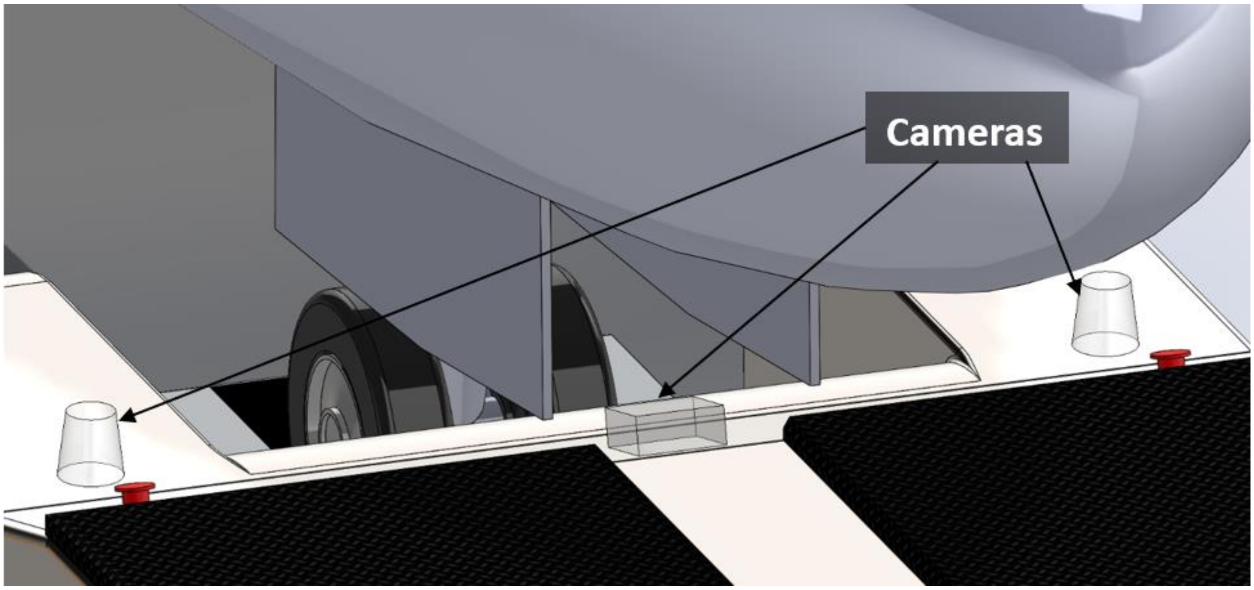


Figure 10:Aircraft Attachment view showing cameras which would give pilot visual confirmation of detachment.

Tug Autonomously Returns to Indicated Location

Once the tug has moved away from the aircraft, it seamlessly transitions to autonomous navigation, moving to a designated point – such as the terminal, a charging station, or another aircraft in need of towing—while meticulously avoiding any breach of the runway hold line, air traffic pathways and other areas the tug is prohibited to operate in (Frame 11 through Frame 16). The FAA tracks data on “hotspots” (locations where the most incidents occur) at each airport [27]. The tug will have a programmed knowledge of these hotspots and will decrease speed while navigating through them for an extra factor of safety.

While the specific return trajectory of the tug may vary based on the unique layout of each airport, it will typically adhere to the shoulder of the taxiway. Although the tug will be low enough to drive under wings of other aircraft if needed, this would not be necessary for most airports and would always ensure safe distance from aircraft components such as engines and landing gear. Moreover, the tug would be equipped to explore alternative routes within the airport apron, always in accordance with established airport regulations such as the requirement to defer the right-of-way to aircraft in compliance with FAA regulations [28].

In the interview with Dr. Nettey, the notion of the tug retracing its path along the taxiway, even maneuvering beneath aircraft wings if necessary (Figure 11) was emphasized, suggesting this would be the best route for the tug. As mentioned previously, Dr. Nettey also highlighted the critical importance of the tug never crossing the runway hold line after it has detached from the aircraft.

Figure 11: Autonomous tug underneath wing of Boeing 737-800 [29]

During autonomous operation, the tug's speed will be dynamically adjusted by consideration of numerous factors such as safe turning speeds, prevailing wind conditions, weather conditions and specific speed regulations of the airport zones it navigates. Sensors on the tug will always be active and transmit useful data to the computing hardware (or “brains”) of the tug. This data will be analyzed, and algorithms will determine safe speeds and routes for the tug to travel. This data will also be transmitted to the Tug Operations center. If at any point the tugs’ computing hardware fails to plan a path or encounters a potentially unsafe scenario, it will stop. A human operator in Tug Operations can then use the tug’s cameras to assess the situation and grant permission for the tug to continue operating autonomously or seize control of the tug remotely. At any point, autonomous control can be interrupted by Tug Operations, or by personnel physically near the tug using emergency stop buttons and onboard controls.

While autonomously navigating, the tug utilizes sensors such as LiDAR, radar, ultrasonic sensors, infrared and stereoscopic cameras, and GPS (Figure 3: Approximate dimensions of electric autonomous tug.Figure 3) to detect surrounding objects or individuals, ensuring awareness even in adverse conditions like snowstorms or darkness. Each sensor will detect its surroundings, crucial for determining safe navigation. It is imperative that the tug remains within designated areas of the airport. The tug incorporates a GPS system to ensure it will not operate outside of these areas. The tug's computing hardware will compare predetermined electronic boundaries with its GPS position to determine its operational bounds. This practice is already utilized commonly for many other applications, such as drones avoiding no-fly zones and is referred to as "geofencing" [30]. The tug will be able to detect expected obstacles, unexpected obstacles, and FOD using previously mentioned sensors. Redundancy is applied through means of several sensors relaying data to the computing hardware at the same time. The tug will also include other necessary safety features such as safety lights, reflectors, and headlights per FAA requirements [28].

Experimental Concept Validation

To test the capabilities of the proposed tug, a small-scale prototype was developed to demonstrate the ability to avoid obstacles, operate as an autonomous and remote-controlled vehicle and successfully tow aircraft around the airport. To prove the design, the tug towed a model plane a specified distance, detached, and returned home while avoiding an obstacle in its path. This experiment provides validation for the principles that would be used by a full-scale tug.

The Elegoo Smart Robot Car V4.0 was used as a mule to demonstrate basic capabilities [31]. The mule uses an ultrasonic sensor to sense objects in the world around it and provide input information to drive itself. A camera provides a live video feed from the mule and can swivel to view different perspectives. It uses Arduino-based software that allows for two types of operation, remote control operation and autonomous operation using guidance parameters. A scale model Boeing 737 was modeled and built, and the mule was also modified to include a tow hook and accommodate for the payload weight (see Figure 13).

The experiment consisted of first moving the mule while towing the plane ten feet under remote control, then detaching from the plane, turning back towards home and in autonomous mode sensing, then avoiding an obstacle in its way. This experiment design models the necessary requirements for the full-scale tug: towing capability, remote control and autonomous operation and obstacle detection and avoidance. The path of the mule is shown in Figure 12.

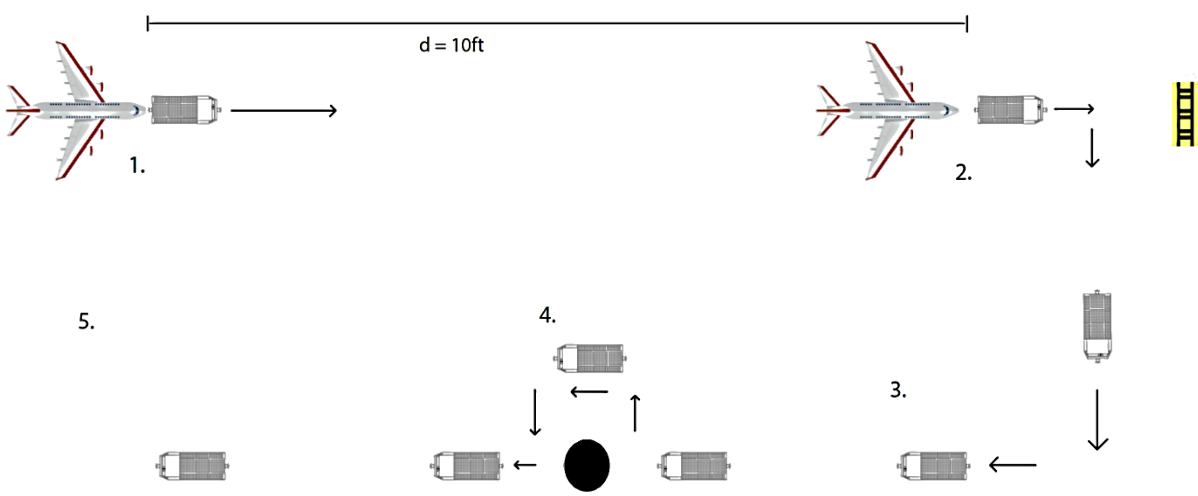


Figure 12:Experiment schematic. Tug pulled plane ten feet, detached from plane, and returned home autonomously while avoiding an obstacle.

It was found that the mule was able to successfully tow the payload and return home while avoiding an object in its path. As seen in Figure 13, a live video feed was provided from the mule to assist in remote operation. This experiment provided validation for the full-scale design.

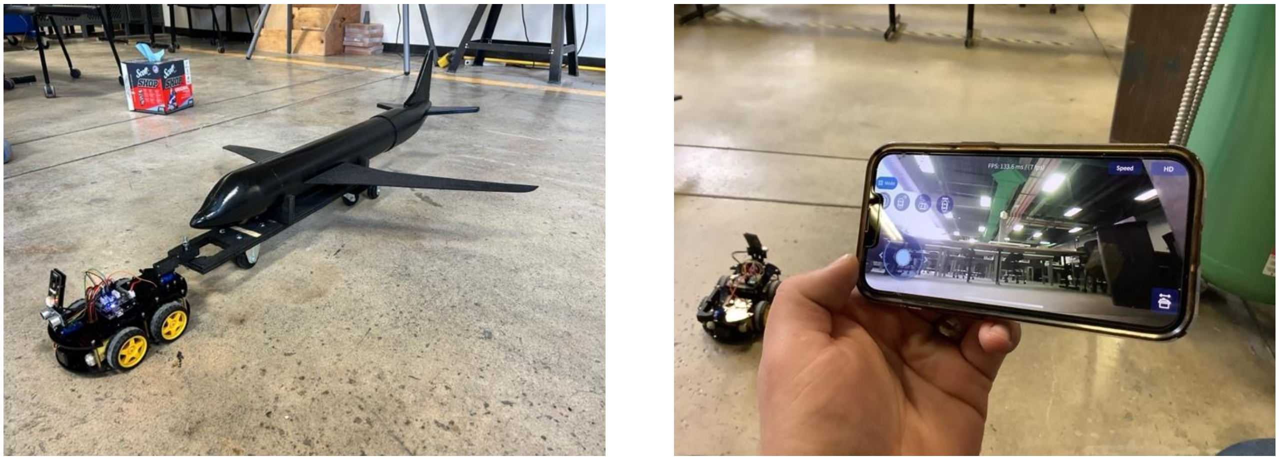


Figure 13: The model 737 and mule pictured (left) and live video feed provided from mule (right)

Safety Risk Assessment

In assessing the safety risks associated with operating the proposed tug, the five-step method of safety risk management hazard assessment was followed [32]. The objectives of this analysis were to describe the system, identify potential hazards, analyze the risks, assess the risks, and devise mitigation strategies to prevent or minimize their impact.

Describe the System

Autonomous vehicle technology, although not novel, has been subject to ongoing research and development over the past decades [33]. Currently, most vehicles that use autonomous technology such as passenger cars and trucks operate at level two as defined by the Society of Automotive Engineers (SAE) standard [15]. For the proposed tug, the goal is to achieve level three autonomy, according to the SAE standard. Unlike the busy environment encountered by passenger vehicles on public roads, airports typically have fewer vehicles, pedestrians, and other unpredictable obstacles. Consequently, the guidance system will require less complexity to guide it through the airport compared to the public roads that passenger vehicles travel on. The object detection system must still be meticulously programmed to detect and respond to people, other vehicles, aircraft, buildings, and similar elements present in the airport environment.

Identify Hazards

To address potential failures of the tug in a rigorous and organized way, a safety risk assessment was made to incorporate certain mitigation measures for the risks. These can be seen in Table 3.

Table 3: Safety Risk Assessment. Red (unacceptable), Yellow (acceptable), Green (low risk)

Type of Risk	Assessing Risk	Mitigation Method
Tug doesn't recognize person, cart, aircraft, etc.	Potential hazard to ground workers, pilots, and buildings.	Use of multiple types of sensors and limiting top speed.
Tug has runway incursion.	Hazard to planes taking off and landing.	Geofencing, use of object detection to detect hold line, sensors, emergency shut off switch, and fall back to Tug Operations.
Computer Hardware failure	Potential Hazard to airport workers.	Build with high quality hardware, provide proper sealing and venting, redundant systems and notify ground crew that tug needs service.
Tug doesn't detach properly	Low potential for injury, time delays would be the biggest concern.	Use of cameras to visually verify that landing gear is unloaded properly.
LIDAR interference	Hazard to ground workers and moving vehicles.	Use multiple sensors for redundancy, notify pilot/Tug Operations that interference is happening.
Algorithm encounters a situation it does not know how to handle	Hazard to ground workers and moving vehicles.	Training AI to avoid incidents and if not possible then notify Tug Operations
Bad weather conditions affect sensors' ability to work, i.e. snowstorm, dust blocking cameras, etc.	Hazard to airport workers, moving vehicles, pilots, etc.	Redundant sensors, drop tug speed in bad weather conditions and if tug is struggling notify Tug Operations
Low profile makes vehicle hard to see resulting in collision with other moving vehicles.	Hazard to moving vehicles.	Reflective stickers, flashing lights, etc. Limit tug top speed at night due to lower visibility.
Damaging Landing Gear	Hazard to pilots, passengers, ground workers, emergency response, etc.	Use of sensors and camera to ensure that landing gear is not moving around. If movement is detected notify pilot and ground crews.

Analyze Risks

While the chances of the tug failing to detect objects like people, carts, or airplanes are relatively low, they can't be ignored. Another closely related potential issue is the possibility of the algorithms encountering situations where they struggle to navigate, potentially leading to errors and accidents. Specific data for level 3 electric vehicles was not readily accessible, however insights from studies on other autonomous vehicles suggest a minimal chance of crashes due to failures in the autonomous system. For instance, a report from the National Highway Traffic Safety Administration (NHTSA) reveals approximately 273 crashes involving Tesla vehicles equipped with Advanced Driver Assist Systems (ADAS) between 2021 and 2022 [34]. When considering the nearly 35 million miles traveled collectively by Tesla vehicles using ADAS during the same period [35], the average incident rate was one every 128,000 miles. This data underscores the infrequent crashes involving autonomous systems, indicating a relatively safe track record over extensive use.

Similarly, a critical failure scenario involves the tug's failure to recognize signs indicating entry into a runway, known as a "runway incursion" [36]. This failure mode is deemed high risk due to its potentially catastrophic consequences. However, a 95% accuracy rate for the AI model was found, indicating reliable sign identification [37]. Although the study focused on training the AI model with standard road signs, its findings are applicable to airport signage due to their close correlation. This high accuracy instills confidence in the tug's ability to identify signs, significantly reducing the risk of runway incursion incidents. While errors are possible, the AI model's robust performance suggests infrequent occurrences unlikely to compromise overall safety.

The next item of failure is computer hardware failure on the proposed tug. This would involve any electronic sensors, motherboards, etc. Lots of things can cause computer hardware components to fail, such as heat, water intrusion, cold, dust, age and more [38]. It is expected that without mitigation and the exposure to harsh conditions experienced by tugs, the lifespan of the tug’s computer hardware would be significantly affected [39]. It can also depend on other factors such as manufacturing quality, proper installation of the part, etc.

Another concern revolves around the aircraft's landing gear and the potential for damage due to longer towing distances. Unlike current practices, the proposed tug will tow the aircraft from the terminal to the end of the taxiway just before the runway hold line (Frame 10), increasing the stress on the landing gear. While the likelihood of damage during towing or automated detachment would appear low due to the prevalence of similar towbar-less systems at airports, caution is necessary, given the differences from current procedures.

Adverse weather conditions pose unique challenges for autonomous vehicles due to the potential distortion of sensor input received by the computing system. Factors such as rain, snow, dust, and fog can disrupt the accuracy of the virtual map constructed by the central processing unit (CPU), leading to errors in decision-making. Limited quantitative data is available on testing in adverse weather and there are ultimately limitations to how well autonomous vehicles can perform in adverse weather. Many car manufacturers emphasize driver responsibility if necessary [40].

Another prevalent concern for autonomous vehicles revolves around the use of light detection and ranging (LiDAR) systems. These systems assist in mapping the surrounding environment of a moving vehicle through laser technology. By measuring the time taken for laser beams to reach objects and reflect back to the sensor, the system determines the distance of obstacles from the vehicle and their shape, aiding the CPU in making decisions to navigate around potential obstructions. A study investigated the extent of interference among LiDAR systems in different scenarios. The results "showed that the performance of LiDAR sensors may be degraded, due to several environmental factors, such as sunlight, reflectivity of an object, cover contamination", and interference from an opposing LiDAR [41]. Interference poses a risk to autonomous systems due to compromised input data. Like adverse weather, LiDAR interference can also cause flawed decision-making, potentially resulting in harmful outcomes.

The final issue associated with the proposed tug pertains to its low-profile design, which, while avoiding some risks, introduces others. Given its diminutive stature, individuals who are not actively aware of the presence of a low-profile tug may inadvertently find themselves in hazardous situations.

Assess Risks and Devise Mitigation Strategies

One of the most significant mitigation strategies is redundancy. This is particularly vital for sensor systems, given the potential for sensors to fail or provide inaccurate data due to factors such as adverse weather or interference. Incorporating redundant sensors and systems into the proposed tug proves to be an exceptionally effective mitigation method for several of the listed issues. Utilizing redundant sensors allows for cross-verification of incoming data from multiple sources, which reduces the likelihood of accidents related to autonomy to an acceptable level.

In terms of ensuring the safety of the nose gear of planes during towing operations, mitigation measures will involve using sensors, cameras, and a cradle system as previously mentioned. These technologies serve to verify that the landing gear is not only securely mounted but also remains stable and undamaged while being towed. By employing sensors and cameras, operators can continuously monitor the position and movement of the nose gear throughout the towing process and ensure a safe detachment of the tug once at the hold line. Additionally, routine safety inspections of the nose gear complement these technological safeguards, ensuring that it remains in optimal condition for flight.

Various methods can enhance the visibility of moving vehicles, including lights, and reflective paint/stickers [42]. While the study referenced primarily examines heavy industrial trucks with higher profiles, the principles of visibility enhancement remain relevant. Implementing these measures on the tug should significantly reduce the risk of accidents.

Runway incursions pose a significant safety threat at airports, warranting the utmost attention. While the likelihood of the tug entering an active runway accidentally is minimal, given the high recognition accuracy of autonomous vehicles [37], preventing such incidents is a top priority. To address this concern, the tug would use image recognition to avoid crossing hold lines, implementing geofencing to mark runways as off-limits, and installing shutdown switches for swift deactivation if needed (Figure 6). Additionally, remote control capabilities allow the tug operations crew to execute emergency stops, ensuring prompt and safe responses to potential issues.

Regarding tug algorithm recognition and processing risks, insights from two studies indicate that autonomous systems generally demonstrate low probabilities of failing to recognize objects while operating autonomously [34], [35]. First and foremost, the AI model utilized for object recognition during autonomous operations must undergo extensive training, as mentioned in previous sections. This training involves exposing the AI model to thousands of images to familiarize it with various objects. As highlighted in [37], models trained using image recognition achieved an impressive accuracy rate of 97% in recognizing street signs. There is encouraging progress in pedestrian and vehicle detection, highlighting significant achievements in this field [43]. Therefore, the primary mitigation approach lies in thoroughly training the AI model.

In situations where the tug encounters scenarios which it lacks the ability to solve, the tug will promptly pull over to a designated safe location away from moving traffic to prevent any potential hazards. Subsequently, it will signal the tug operations team for assistance who will intervene by taking control and guiding the tug back onto its intended path. The incident will then be reported for software development to address and patch the identified error. In the rare event that the tug fails to identify an object, and a collision occurs, incorporating impact-absorbent materials into the design of the proposed tug becomes essential to mitigate the extent of damage sustained during the crash. Additionally, implementing lower speeds for the tug in certain locations or scenarios serves as a secondary mitigation method. Aircraft taxiing speeds are typically regulated to ensure safe operations, and adhering to these speed limits further minimizes the risk of accidents resulting from unrecognized subjects.

Projected Impact of the Team’s Design and Findings

A benefit-cost analysis was created in order to demonstrate the commercial benefit of the design. The evaluation encompasses every stage of the design process, from the initial idea to the implementation of the proposal. The design, development, and production phases were all considered as well as a ten-year projected cost/benefit summary.

Multiple simulations were run using AEDT to estimate fuel use and emissions and at four major airports: Salt Lake City International Airport (SLC), Hartsfield-Jackson Atlanta International Airport (ATL), Denver International Airport (DEN), and Los Angeles International Airport (LAX). The most commonly departing aircraft at those airports were the Embraer ERJ-175, McDonnell Douglas DC9, Boeing 737-700, and Boeing 737-700 respectively [44]. To ensure these numbers are consistent and conservative, operations were examined at each airport using the standard average taxi out time and distance programed into AEDT [45]. These were analyzed for average fuel use and emissions produced. Because of the COVID-19 pandemic's impact on normal trends, the decision was made to use 2019 data instead of more recent data. The results of this analysis are found in Figure 14.

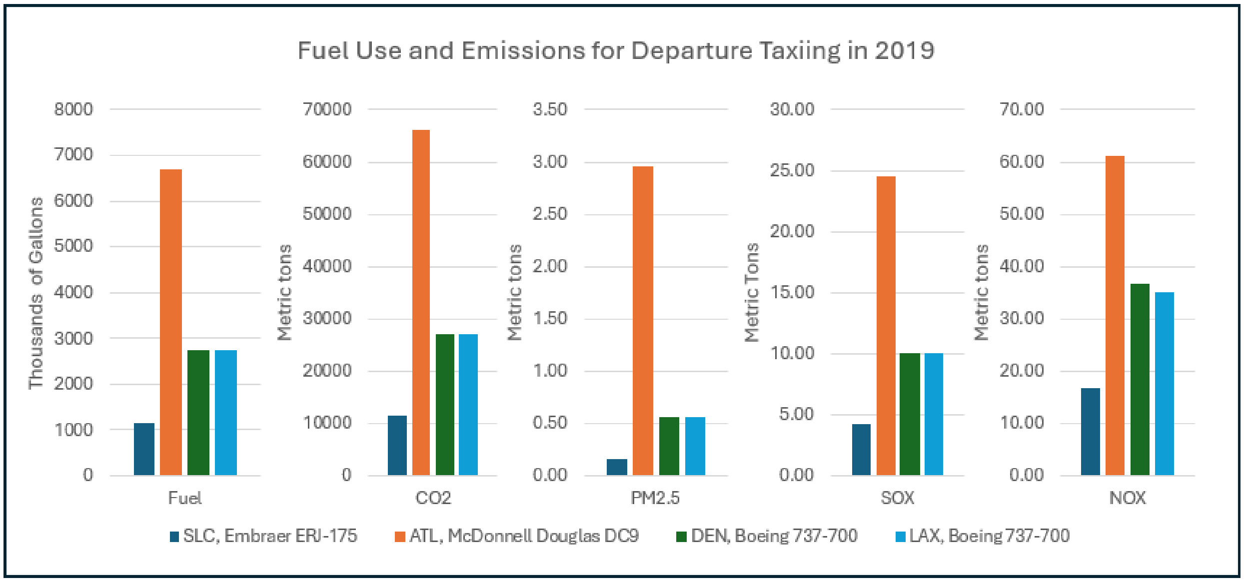


Figure 14:The most commonly departing aircraft at 4 different airports are compared by the total fuel usage and emissions production for departure taxiing operations during 2019.

AEDT simulations estimate fuel used for departure taxiing. The cost of that fuel in 2019 dollars could then be determined [46]. To illustrate the impact of the reduction in CO2 emissions, it was determined how many trees would need to be planted [47], and how many cars would need to be taken off the road [48] for one year to have the same impact as adopting the proposed tugs for departure taxiing the indicated aircraft. Results are compiled for each of the four analyzed airports and shown in Table 4.

Table 4: Shows the quantity of the most commonly departing aircraft along with fuel used and CO2 produced in 2019.

	SLC	ATL	DEN	LAX
Aircraft model with most departures	Embraer ERJ-175	McDonnell Douglas DC9	Boeing 737-700	Boeing 737-700
Number of Departures	25,944	66,169	48,063	48,063
Fuel use (Millions of Gallons)	1.16	6.71	2.73	2.75
Fuel cost ($) [46]	$2,171,191	$12,549,849	$5,110,211	$5,150,495
CO2 (Metric Tons)	11,442	66,139	26,931	27,144
Equivalent Trees Planted	525,531	3,037,720	1,236,938	1,246,695
Equivalent Number of Cars Removed for one year	2,487	14,378	5,855	5,901

Cost-Benefit Analysis

DEN was chosen for the cost-benefit analysis. It was assumed that 20 tugs will be purchased and utilized. DEN recently received a large grant in order to, "allow DEN to increase our electrical capacity while maintaining high levels of reliability and resiliency" [49]. In this analysis, a one-time electrical infrastructure cost will not be included due to DEN already having current plans to further electrify the infrastructure. Other airports will have to incur this additional cost if the current electrical infrastructure can't handle charging additional tugs. Depending on the airport size, the number of tugs needed to provide the maximum number of departures will vary.

Alpha, Beta, and Production Phases

As seen in Table 5 below, a university team is utilized for the alpha stage. The beta stage involves a professional Research and Development (R&D) team consisting of mechanical, electrical, and software engineers. They would create a prototype and test a full-scale tug. The costs for the alpha and beta stages are $56,700 and $1,016,059 respectively.

Table 5: Alpha and Beta Stages

Item	Rate	Multiplier	Qty. (hrs)	Subtotal	Remarks
Design and Research (Alpha)					
Undergraduate Team	$20/hr	8 Students	120	$19,200	24 weeks, 5hrs/week
Faculty Advisor	$50/hr	2 Advisors	450	$22,500	Project Advisors
Materials	---	---	1	$15,000	Cost of materials and expenses
Alpha Subtotal				**$56,000**	One-time Costs
Professional R&D (Beta)					
Engineering Team	$58/hr	10	960	$556,800	24 weeks, 40hrs/week
Prototype	---	1	---	$40,000	Material costs, small scale model
Testing and Validation	---	1	---	$10,000	Meets specs and requirements
Hardware/Materials	---	1	---	$350,000	For one unit, plus additional costs
Airport Consultants	$29/hr	3	120	$10,875	24 weeks, 5hrs/week
Contingency Budget				$48,384	Based on 5% of total costs
Beta Subtotal				**$1,016,059**	One-time Costs

Notes: Engineering team salary based on the average salaries of mechanical, electrical, and software engineers [50]. Airport consultant salary retrieved from the Bureau of Labor Statistics [51].

The tug would then be manufactured, marketed, and distributed to airports. Table 6 breaks down the costs of each step in this process. The employees who will be working with the tugs will need to be trained and proficient in the proposed technology before operating them. It also explores the cost of advertising them and the implementation costs at the airport. Each airport will need to evaluate their electrical infrastructure and make changes in order to accommodate the additional charging of the tugs. The total cost for 20 production tugs with the associated costs of marketing and distribution is $6,373,000.

Table 6: Production, Marketing, & Distribution Phase

Item	Multiplier	Cost	Remarks
Raw Materials	1	$280,000	Acquiring all equipment and materials for production
Autonomous system	1	$30,000	Adding autonomous capabilities
Manufacturing	---	$80,000	Assembly and testing
Marketing and Sales	---	$60,000	Advertising estimate
Training	---	$10,000	Training on new procedures
Distribution	1	$1,150	Shipping and setup
Subtotal			**$461,150**
Total		**20**	**$6,373,000**

Notes: Shipping was calculated using average prices to ship a car across the country [52]. The autonomous system components were estimated using current car manufacturer prices [53].

The breakdown for the total cost over the course of a ten-year timeline is shown in Table 7. The electric tugs will still need to be charged but the cost of doing so is far less than fueling standard ICE tugs. The total cost over a ten-year period is $11,397,276. Maintenance will include tire changes when needed (estimated to be once per year). There will also be a need for remote tug operators to manually take over if needed at any time.

Table 7: Ten Year Cost Summary

Item	Rate	Multiplier	Cost	Remarks
Alpha Phase	---	---	$56,700	Table 5
Beta Phase	---	---	$1,016,059	Table 5
Production	---	---	$6,373,000	Table 6
Subtotal (Year 1)			**$7,445,759**	
Maintenance	$2,000	20	$40,000	Estimated maintenance costs / year
Training	---	---	$5,000	Training new employees
Charging Costs	$28.95	365	$211,335	Charging all tugs
Tug Operations	$60,000	2	$120,000	Estimated salary of tug operator
Contingency	---	---	$18,817	5% of the continuing costs
Subtotal (Yearly)			**$395,152**	
Total (10 Years)			**$11,397,276**	

Notes: The charging costs were estimated to be five times as much as a current electric tug due to the increased distances that the tug will travel [54].

Value Assumptions & Prevention Benefits

The value assumptions in Table 8 are given through the FAA which give an estimated value on life, injuries, aircraft damage, and more [55]. For this analysis, on the benefit side, the cost of fuel for taxiing the aircraft out to the runway (departure) as well as the value of life and injury prevention benefits will be considered. At the time of publication, fuel costs $2.70 per gallon [44]. The fuel savings were determined using the amount of fuel consumed at the DEN, multiplied by ten years. For this scenario, the fuel savings for ten years would be $73,750,932. This number will fluctuate depending on the price of fuel.

The risks associated with the proposed idea would involve accidents with the tug and either aircraft or vehicles as seen in Table 9. An average of 50,000 departures per year were used based on the data collected for the DEN in Table 4. There would be a lower risk in fatalities and serious injuries by implementing the tugs but also a slightly increased risk of aircraft or damaged vehicles as seen in Table 10.

Table 8: Value Assumptions

Item	Rate	Remarks
Value of Life (VSL)	$9,600,000	Value of Fatality
Value of Injury	$1,008,000	Value of Serious Injury
Aircraft Damaged	$200,000	One Aircraft (Repairable Damage)
Ground Vehicle Damaged	$25,000	Repairable Damage
Fuel Savings	$73,750,932	Potential fuel savings (10 years)

Notes: [56]

Table 9: Risk Summary (DEN - ~50,000 departures in 2019 of Boeing 737-700) make note about ten-year period.

Item	Unit	Qty	Subtotal	Remarks
Operational Risks				
Risk of A/C - A/C Accident	.02 / 1 mil	500,000	0.01	Risk potential over ten years
Risk of A/C - Vehicle Accident	.1 / 1 mil	500,000	0.05	Risk potential over ten years
Risk of Vehicle - Vehicle Accident	.1 / 1 mil	500,000	0.05	Risk potential over ten years
Total Operational Risk			**0.05**	**Assume higher risk value**

Notes: [56]

Tangible Benefits

The final accident prevention and fuel savings was estimated to be $74,761,332. This would give an overall benefit to cost ratio of 6.56 and amount to about $63.4 million saved over the course of ten years if the proposed tugs were adopted.

Table 10: Benefit vs Cost

Item	Unit	Qty.	Subtotal	Risk	Total	Remarks
Benefit						
Value of Fatality (VSL)	$9,600,000	2	$19,200,000	0.05	$960,000	Tables 8, 9
Value of Serious Injury (VSI)	$1,008,000	1	$1,008,000	0.05	$50,400	Tables 8, 9
Fuel Savings	$73,750,932	---	$73,750,932	---	$73,750,932	Tables 8
Accident and Fuel Savings					**$74,761,332**	
Cost						
Aircraft Damaged	$200,000	1	$200,000	0.05	$10,000	Tables 8, 9
Vehicle Damaged	$25,000	1	$25,000	0.05	$1,250	Tables 8, 9
Development/Implementation					$11,397,276	Table 7
Total Cost					**$11,408,526**	
Benefit to Cost Ratio					**6.56**	

Notes: [57]

Intangible Benefits

It is important to note that the proposed system has many other potential benefits not included in the above analysis. It would help in avoiding the dangers of jet-blast and FOD. There would be significant decreases in noise and emissions for ground crew workers and residents that live close to the airports. It would reduce the time that the jet engines are turned on and associated maintenance. As the old tugs are replaced with autonomous tugs, the old ones could be liquidated to reduce the up-front costs. The new tugs could also potentially be used for other functions such as towing aircraft to hangars for storage or maintenance.

The Flight Plan 21 by the FAA lays out four key pillars, each with distinct objectives to pursue [58]. Among these, electrically powered, autonomous-capable tugs fit into the first initiative of the fourth pillar. This initiative revolves around climate action, enhancing sustainability, and mitigating aircraft noise impacts. These tugs effectively address these concerns, contributing to the fight against the ongoing climate crisis. As detailed in this paper, their adoption assures substantial emissions reductions and the potential to alleviate noise pollution in airport surroundings. Ultimately, integrating these tugs into operations will support the United States in reaching its goal of achieving net-zero greenhouse gas emissions by the year 2050 [59].

Conclusion

This paper addresses the Airport Environmental Interactions Challenge, focusing on noise reduction, air quality improvement, and carbon emission reduction by GSE at airports. By implementing the described electrically powered, autonomous tugs, we aim to reduce carbon emissions during the LTO cycle. Industry expert consultations, surveys and airport tours influenced our design process. Utilizing AEDT, the fuel savings were calculated, showing a favorable benefit-cost ratio over ten years. Adoption of these new eco-friendly tugs will help to mitigate the environmental impact of airports.

Appendix A: Contact Information

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Appendix B: Description of the University and School

Utah Valley University (UVU) is a public institution of higher education located in Orem, Utah. The university was established in 1941 as Central Utah Vocational School and has since grown to become the largest public university in the state of Utah, with over 40,000 students enrolled in a wide range of programs. There are over 100 bachelor's and 50 associate degrees offered in various fields, including business, education, engineering, health sciences, humanities, science, and technology.

UVU is also "one of a few in the nation offering a dual-mission model that combines the rigor and richness of a first-rate teaching university with the openness and vocational programs of a community college. The unique model, which focuses on student success, engaged learning, rigorous academic programs, and faculty-mentored research, is transforming higher education by making it more affordable and accessible to students of all backgrounds" [60].

Appendix C: List of Industry Contacts

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Online Survey of Aircraft/Airport Experts | 63 Respondents

Appendix E: Evaluation of Educational Experience

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?
   a. While understanding how to use software such as SolidWorks and studying engineering classes that deal with mechanical continuity are great, having an actual project where these subjects all come together provides a detailed and hands on experience that only accelerated the personal know-how in the engineering problem-solving process. This knowledge prepares us participants to eventually contribute engineering proficiency to future projects and become comfortable with the problem-solving process in a real-life situation.

2. What challenges did you and/or your team encounter in undertaking the competition? How did you overcome them?
   a. Understanding airport terminology and procedures that already exist was difficult, but necessary to ensure the proposed design was helpful and could be implemented successfully. Great amounts of research were undertaken to overcome this challenge. Many interviews with airport executives, employees and others were also conducted.
   b. It was challenging to think of everything that could potentially go wrong with an autonomous vehicle and ensure that our proposed design would address every concern and employ redundant measures of safety. To overcome this, many other

types of autonomous equipment and vehicles were analyzed, and their methods of safety were researched.

3. Describe the process you or your team used for developing your hypothesis.
    a. Following a pattern of an initial idea, experimentation, and research, the hypothesis gradually changed until it became what this current paper is about. Interviews with actual flight operators, personal visitation of the Salt Lake Airport, and analyzing cost benefit led us to that hypothesis.
4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?
    a. The airport tour was extremely helpful because it helped us physically see other tugs, airplanes, lines on the tarmac, etc. We also talked to airport employees about our proposed design and their frustrations with current procedures and tugs. In the general aviation section, we got to see a demonstration of how electric towbarless tugs currently operate.
    b. Expert interviews helped us understand airport terminology and procedures, as well as providing insight into design specifications that would be necessary to make sure our design could be implemented safely at an airport.
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?
    a. This project allowed the team to deep dive into the intricacies of airport operations. Understanding and adhering to the rules and operations of airports expanded the possibility of improvements on all fronts. Pursuing a career in this realm would prove to be challenging, constant, and exciting work.

b. FAA terminology is vast and intricate. Being able to identify the correct terms in the correct situations proved to be challenging but beneficial. Operators that were interviewed proved helpful in clarifying such terminology to better help readers follow along the complicated scenarios.

Faculty

1. Describe the value of the educational experience for your student(s) participating in this competition submission.
    a. Students gained invaluable experience working on a complex research project requiring extensive research, analysis using industry tools, collaboration, technical communication, in-person visits to airports, and having conversations with airport officials, technicians, managers, and other experts. Students got to see for themselves how an airport really works. They also spent extensive amounts of time studying FAA, SAE, and other government and industry standards as well as dozens of scholarly papers and various proposals. Some students learned how to use tools such as the FAA's AEDT software and methods like Failure Modes and Effects Analysis. As well, students learned how to rigorously research, propose, and defend an idea to improve a process and the type of work required to attempt to ensure a potential solution doesn't cause more problems than it fixes and is financially feasible.
    b. Doing research as a team / teamwork in general.
    c. Learning how to code an Arduino based robotic car and work with things like ultra-sonic sensors and servos.
    d. Computer Aided Design (CAD)

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?
    a. Yes. Students volunteered to be part of the competition without any compensation or other benefit, in addition to full-time coursework, internships, and other commitments.
        i. I feel like, as juniors, these guys went above and beyond what undergrads usually do.
3. What challenges did the students face and overcome?
    a. Large amounts of research to become familiar with FAA terminology.
    b. Becoming familiar with airport operations via both in-person visits and online research
    c. Learning how to interview experts.
    d. Distributing the online survey and finding enough respondents
    e. Coordinating the writing of the various sections of the paper among various team members
    f. Learning how to use FAA software.
    g. Learning how to properly research and cite sources in the paper.
    h. Experiencing what it's like to answer a research question where there is no known or even correct answer.
    i. Taking an Arduino-based "kit" and modifying it to perform the desired functions.

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

    j. Yes, with the right group of motivated students it's an excellent learning experience.

k. Probably should collaborate with school of aviation for future submissions to better align with curriculum and knowledge.

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

    a. None that I can think of.

Appendix F: References

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