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Self-Driving Aircraft Towing Vehicles:
A Preliminary Report

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Abstract

We introduce an application of self-driving vehicle technology to the problem of towing aircraft at busy airports from gate to runway and runway to gate. Autonomous towing can be supervised by human ramp- or ATC controllers, pilots, or ground crew. The controllers provide route information to the tugs, assisted by an automated route planning system. The planning system and tower and ground controllers work in conjunction with the tugs to make tactical decisions during operations to ensure safe and effective taxiing in a highly dynamic environment. We argue here for the potential for significantly reducing fuel emissions, fuel costs, and community noise, while addressing the added complexity of air terminal operations by increasing efficiency and reducing human workload. This paper describes work-in-progress for developing concepts and capabilities for *autonomous engines-off taxiing* using towing vehicles.

Introduction

Congestion at airports is recognized as one of the most prominent problem areas in the international airspace. Airports are expected to address this problem through expansion of their airfields. However, the addition of runways and taxiways will increase the complexity of air terminals, which will penalize the efficiency of the system by adding to human workload, thus restricting the potential benefits of the surface expansion. The increased complexity will also increase the risk of human error, resulting in potentially hazardous situations. In addition, the increasing number of taxiing aircraft will contribute significantly to an increase in fuel burn and emissions. The quantities of fuel burned as well as different pollutants, such as carbon dioxide, hydrocarbons, nitrogen oxides, sulfur oxides and particulate matter, increase with aircraft taxi duration, and also vary with throttle setting, number of running engines, and pilot and airline decisions regarding engine shutdown during delays.

The economic pressures and increasing environmental awareness have recently fostered the development of new taxi operation technologies and procedures. The contribu-

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tion of this paper will consist of presenting a case for surface taxiing operations based on ‘self-driving’ towing vehicles. *By autonomous engines-off taxiing, we mean a towing vehicle that will, on command, autonomously navigate to an assigned aircraft, attach itself, tow the aircraft to an assigned location (a runway for departures, a gate for arrivals), autonomously detach itself, and navigate to an assigned location, either a staging area or to service another aircraft.*

The remainder of this paper is structured as follows. We provide an overview of the state of the art of surface operations technologies relevant to the introduction of self-driving towing vehicles, and argue the case of autonomous towing. Then we propose a set of autonomy requirements for self-driving towing vehicles, as well as a set of additional requirements to ensure effective human supervision and awareness of the autonomous operations. We close with a description of a fast time simulation environment for airport surface movement, which will be used to collect statistics for evaluating the advantages and disadvantages of introducing tug autonomy into surface operations.

The Case for Autonomous Towing

In recent years, airlines and international agencies have expressed a growing interest in ‘engines-off taxiing’, i.e., in which the main engines are not used at all to taxi the aircraft to and from runways (Wollenheit and Muhlhausen 2013). The case for engines-off taxiing is clear: as one advocate (Richard 2013) put it: “Airplanes waste a lot of fuel on the ground. To taxi around airports, from passenger gates to runways, planes are powered by their main engines which simply aren't optimized for that task. This creates a lot of unnecessary CO2 emissions, air pollution, and noise.”

Current Industrial Efforts in Engines-off Taxiing

To our knowledge, there are three basic approaches to engines-off taxiing being proposed in industry, all of which have strengths and weaknesses. The most obvious approach is a concept called “Operation Towing” (Wollenheit and Muhlhausen 2013), which simply involves the use of human-driven aircraft towing vehicles. Operation towing has the following advantages:

1. They require little if any logistical or operational changes to current airport operations: human drivers of towing vehicles exist now and can be put into service easily to implement full towing operations.
2. They lead potentially to reduction of workload for the flight crew, which they can use more efficiency for other purposes, such as engine warm up or safety checks;
3. There is an increase in redundancy for taxi safety due to an extra pair of eyes monitoring the surface.

A disadvantage of this approach is the addition to complexity in operations in the form of the need for added coordination among human players. In particular, more human voice communication for the purpose of coordination is required. As noted in a number of studies (e.g. Brinton et. al. 2002), voice communication is inefficient as a means of coordination due to the capability to deliver only a single instruction at a given instant, the potential for miscommunication of the spoken word, and frequency congestion.

A promising variation of Operation Towing is the “TaxiBot” (Richard 2013), in which a tug driver manages the pushback phase of the departure, but the aircraft pilot remotely controls the tug movements for taxiing to the runway. This removes, at least partially, the added need for additional human coordination of operational towing, but introduces added pilot workload, and new safety issues may emerge with respect to the ability of the pilot to effectively control an external towing vehicle. Furthermore, this solution incurs the overhead of requiring additional flight controls into the cockpit display for operating the tugs. Finally, using TaxiBot for arriving aircraft would presumably involve the need for human tug drivers to meet the aircraft at the runway, and it is hard to see the advantages of transferring control from tug driver to pilot in the case of arrivals. So TaxiBot is in fact a hybrid of Operation Towing and pilot-driven towing, which again adds to the complexity of procedures. To our knowledge, TaxiBot has only been used for departures, and therefore is only a partial solution to the overall problem of enabling engines-off taxiing.

A third promising development is the use of electrically powered landing gears for medium-sized aircraft in civil aviation (“Electric Taxi” or ‘Wheel Tug”), again pilot-controlled (Tarantola 2013). This approach eliminates the potential control and complexity issues associated with TaxiBot, because the pilot is not in this case controlling a separate vehicle, but rather merely a separate engine on the aircraft. This solution also eliminates the added surface traffic incurred by separate towing vehicles. However, this approach again provides only a limited solution to the general problem, insofar as the auxiliary engines are not powerful enough currently to pull larger airplanes. In addition, this solution requires airlines to retrofit their fleet with the new engine, which are significant investments.

To our knowledge, no industrial effort has considered the use of self-driving vehicle technology to realize engines-off taxiing. We suspect that main reasons for not considering this option are the changes that must be made to the operating infrastructure in order to integrate autonomy. These changes include more surface traffic (unattached self-driving tugs will increase the density of surface traffic), different procedural protocols (e.g., tug navigation decisions will replace communication between controllers and pilots), and the complexity of human-machine interactions (ground controllers, pilots and self-driving tugs will need to somehow be able to operate effectively together).

Why Self-driving Towing Vehicles?

The case for autonomous engines-off taxiing is summarized as follows. First, recent advances in self-driving automobiles make it technologically feasible to apply this technology for the purpose of taxiing planes to the runway from the terminal gate and vice-versa. Arguably, deploying self-driving vehicles for this purpose offers fewer technical challenges than deploying them on roadways and highways. On the one hand, routes between gates to runways and runways to gates are typically pre-determined, with little or no possibility for alternatives. In addition, to ensure safety, constraints on taxiing operations are rigid and unambiguous. Rules such as separation constraints between taxiing aircraft and those governing right-of-way at intersection points are clearly documented and enforced by ramp and ATC controllers. These rules and procedures reduce the overall uncertainty in the operational environment and therefore potentially simplify the models that would need to be employed by self-driving vehicles.

Nonetheless, the introduction of autonomy into surface operations significantly impacts how humans (specifically ramp controllers, ground personnel and pilots) perform their work. Consequently, making a strong case for autonomous taxiing requires addressing the challenges of human-machine interaction, hybrid human-machine control, incremental deployment strategies, and minimizing changes to existing infrastructure and procedures (Bayouth, Nourbakhsh and Thorpe 1997). The solution we propose views the challenge to be one of *providing logistics rather than autonomy* (borrowing an adage used by (Aethon 2013)). Logistics is the problem of coordinating a complex operation involving many people and machinery. Our solution involves the use of autonomy, but must also address broader issues involving human-autonomy interaction and complex motion planning. The result is a three-pronged architecture combining enhanced automated planning tools, human-machine interfaces supporting human awareness and supervision of autonomy, as well as robotic technologies for autonomous sensing, navigation, communication and control.

Requirements and Challenges

In order to effectively transform taxiing operations to incorporate autonomous towing vehicles, the following four requirements must be met:

1. The tugs must be safe: they do not run into obstacles or people;
2. The impact of their incorporation into normal operations is perceived to be minimal; humans don't need to change their behavior (much);
3. Changes to the airport infrastructure are minimal; there is no need for a major redesign of taxiways or ramp areas; and
4. Their use improves surface logistics, and their utilization makes humans better at their jobs.

There are three classes of challenges in integrating autonomy into airport surface operations:

1. Technical challenges: autonomous towing must accommodate large unpredictable, real time variation in the environment; must achieve customer-acceptable reliability levels, and provide intrinsic safety of use and operation;
2. Economic challenges: tug-based operations must achieve the required affordability (ideally, payback within 12 months), providing no external hidden costs to the customer, and provide a robust business model; and
3. Social challenges: if labor replacements are involved, then the use of autonomy must provide an equivalent or greater benefit to some portion of the labor pool to offset the potential job loss; furthermore, they must operate in a way that feels common and familiar to humans, and must be perceived as completely safe, simple and non-intimidating.

Technical Approach

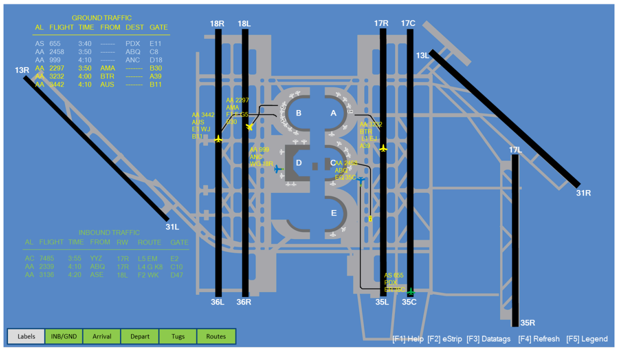
As noted above, a self-driving tug-based surface movement system will require technological innovations in logistics, specifically in the following three areas: 1) automated strategic and tactical planning for surface movement; 2) human machine interface, designed for ATC supervision of the semi-autonomous tugs; and 3) a set of capabilities for enabling autonomous tug navigation.

Human-Machine Interface

A human machine interface (HMI) for surface operations allows human controllers to supervise a fleet of tugs as they move aircraft from gate to runway and runway to gate. Accomplishing safe navigation of the air terminal area and maintaining optimal performance requires efficient teamwork between the controllers, automated strategic and tactical planners and the tugs. The controller uses the HMI to interact with an automated planner (discussed below) and the tugs to provide additional input when necessary. For example, the controller may be required to provide additional information to the planner such as taxiway closures, new runway requests and other real time information that may be unavailable to the automated planners. Additionally, the controller will need to utilize the HMI to directly intercede with the tugs if unsafe conditions arise, such as an arriving aircraft landing on the wrong runway while the tug is attempting to cross with a departing aircraft.

To assist the controller in being an effective team member within the tug-based taxiing system, we have focused on developing key elements of an effective HMI, such as calibrating trust, maintaining situational awareness (SA) and managing mental workload. Calibrating trust is a critical element: the HMI needs to be able to assist the operator in knowing when to allow the automation to perform with minimal human intervention but also assist the controller in knowing when to intervene and to what extent. Failure of the HMI to assist in this endeavor will lead to sub-optimal performance of the system. Similarly, SA and mental workload are critical to optimal performance. SA is critical within an airport due to the large number of moving elements (aircraft and tugs). A lack of SA can cause the controller to misunderstand a situation leading to potentially drastic consequences. The HMI must also maintain an appropriate level of mental workload. Managing workload when supervising multiple semi-autonomous vehicles is a challenging problem under the best conditions; however within the controller domain, the number of autonomous vehicles and aircraft working in the airport area will vary due to rush hour, weather conditions and time of day. If unexpected events are factored into the problem, this domain becomes a challenging problem for managing workload.

Figure 1. HMI Conceptual Mockup



GROUND TRAFFIC

AL	FLIGHT	TIME	FROM	DEST	GATE
AS	655	3:40	------	PDX	E11
AA	2458	3:50	------	ABQ	C8
AA	999	4:10	------	ANC	D18
AA	2297	3:50	AMA	-------	B30
AA	3232	4:00	BTR	-------	A39
AA	3442	4:10	AUS	-------	B11

INBOUND TRAFFIC

AL	FLIGHT	TIME	FROM	RW	ROUTE	GATE
AC	7485	3:55	YYZ	17R	L5 EM	E2
AA	2339	4:10	ABQ	17R	L4 G K8	C10
AA	3136	4:20	ASE	18L	F2 WK	D47

Figure 2: Tower Surveillance Display

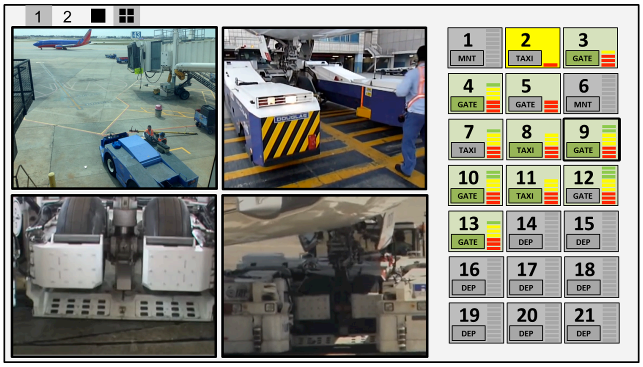
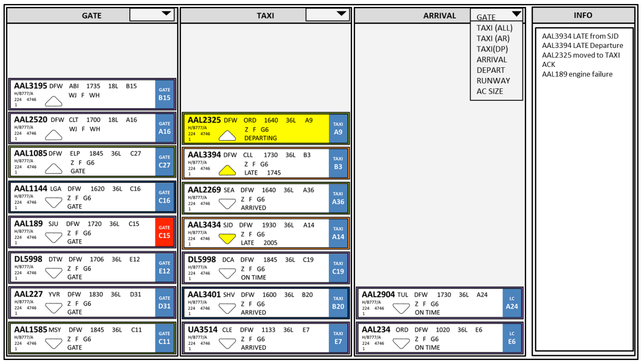


Figure 3: Tug Display



GATE

AAL3195 DFW ABI 1735 18L B15 H/B777/A 224 4746 1 WJ F WH — GATE B15
AAL2520 DFW CLT 1700 18L A16 H/B777/A 224 4746 1 WJ F WH — GATE A16
AAL1085 DFW ELP 1845 36L C27 H/B777/A 224 4746 1 Z F G6 GATE — GATE C27
AAL1144 LGA DFW 1620 36L C16 H/B777/A 224 4746 1 Z F G6 GATE — GATE C16
AAL189 SJU DFW 1720 36L C15 H/B777/A 224 4746 1 Z F G6 GATE — GATE C15
DL5998 DTW DFW 1706 36L E12 H/B777/A 224 4746 1 Z F G6 GATE — GATE E12
AAL227 YVR DFW 1830 36L D31 H/B777/A 224 4746 1 Z F G6 GATE — GATE D31
AAL1585 MSY DFW 1845 36L C11 H/B777/A 224 4746 1 Z F G6 GATE — GATE C11

TAXI

AAL2325 DFW ORD 1640 36L A9 H/B777/A 224 4746 1 Z F G6 DEPARTING — TAXI A9
AAL3394 DFW CLL 1730 36L B3 H/B777/A 224 4746 1 Z F G6 LATE 1745 — TAXI B3
AAL2269 SEA DFW 1640 36L A36 H/B777/A 224 4746 1 Z F G6 ARRIVED — TAXI A36
AAL3434 SJD DFW 1930 36L A14 H/B777/A 224 4746 1 Z F G6 LATE 2005 — TAXI A14
DL5998 DCA DFW 1845 36L C19 H/B777/A 224 4746 1 Z F G6 ON TIME — TAXI C19
AAL3401 SHV DFW 1600 36L B20 H/B777/A 224 4746 1 Z F G6 ARRIVED — TAXI B20
UA3514 CLE DFW 1133 36L E7 H/B777/A 224 4746 1 Z F G6 ARRIVED — TAXI E7

ARRIVAL

GATE
TAXI (ALL)
TAXI (AR)
TAXI(DP)
ARRIVAL
DEPART
RUNWAY
AC SIZE

AAL2904 TUL DFW 1730 36L A24 H/B777/A 224 4746 1 Z F G6 ON TIME — LC A24
AAL234 ORD DFW 1020 36L E6 H/B777/A 224 4746 1 Z F G6 ON TIME — LC E6

INFO

AAL3934 LATE from SJD
AAL3394 LATE Departure
AAL2325 moved to TAXI
ACK
AAL189 engine failure

Figure 4: e-strip display

Figure 1 shows a conceptual mockup of an HMI workstation for supervising tug autonomy. It is comprised of three components: live video monitoring, eStrip display and tower surveillance. Each of these components are being designed and evaluated with a focus on leveraging and expanding existing FAA technologies to provide the necessary features for trust calibration, and SA and workload maintenance.

The primary component of HMI is the tower surveillance display (TSD) (Figure 2). The design of our TSD extends current FAA technologies such as ASDE-X (McAnulty 2001) to provide additional information such as tug locations, routes, tug depots, and individual tug's status. It is also the tool that allows controllers to interact with the automated planners and autonomous tugs. Using the TSD the controller receives and confirms route information from the route schedulers, requests adjustments to the route and also has access to emergency commands to the tugs. A live video monitoring display is added to the controller console to allow for real-time monitoring of the tug's status (tug id, power, aircraft connection and location) and environment (Figure 3). Finally, an e-strip display imitates current flight strips by providing flight progress information e.g. flight number, status, aircraft type, and runway information (Figure 4).

Through the integration of multiple displays, the HMI delivers a comprehensive picture of ground operations, increasing controller situational awareness and improving airport safety in all weather conditions.

Tug Autonomy

Nominal autonomous tug operation (for the case of departures) is captured as the following sequence: a tug sits at a *tug depot*, a designated area of the airport surface where tugs recharge and return when not in service. When the tug receives a message, describing time, route, and gate, it travels to the specified gate following the provided route. As the tug approaches the specified gate, it navigates to a designated ready position. Once the ground marshal attending the gate signals readiness for attachment, the tug assesses the environment to verify the surroundings are obstacle-free before moving to dock with the aircraft.

Figure 5. A Tow-bar-less Tug

With so-called tow-bar-less tugs (Figure 5), the tug merely needs to position itself around the nose wheel and activate its capture mechanism. Once attached, the tug autonomy informs all stakeholders of readiness to push back and awaits command to do so. Once a taxi navigation plan is received from the centralized route planner and the aircraft crew and ground marshal both signal ready to push back, the tug pushes the aircraft away from the gate and begins navigation through its assigned route. When reaching a designated location in the takeoff queue near the runway, the tug autonomously detaches from the aircraft, moves to a safe position away from the aircraft, signals to the aircraft's crew through a cockpit display that it is detached, and navigates back to the depot along the route provided by the planner.

Direct route following and autonomous control is performed onboard the tug, which also hosts the system's physical sensors. The tug autonomy system faces similar challenges to those of driverless cars (Porikli and Van Gool 2014), but with the added complexities that towing a large body aircraft presents. For example, the Airbus A380 has a wing span of 79.75 meters and a potential ramp weight of 1,265,000 pounds (Airbus 2014), which must be managed throughout ground navigation by the tug located approximately 120 feet from the plane's center of mass.

The tug design strategy is built around the modified tow-bar-less tug, both to remove some variability in control that tugs with tow-bars contribute to the tug-aircraft system but also to provide applicability to the widest spectrum of potential aircraft. The proposed tug is instrumented with the following suite of sensors: LIDAR, providing 360 degree field of view (FOV), along with two electro-optical/infrared cameras, one forward facing and one rear-facing, to support all-weather day/night operation. The LIDAR provides obstacle avoidance and landmark recognition data. The forward camera supports recognition of airport runway, taxiway, and gate markings during navigation. The rear-facing camera supports docking/undocking operations as well as monitoring of aircraft state during towing.

The sparseness of airport runway and taxiway decoration makes an ideal perceptual environment for autonomous systems to operate, but it is not without some technical challenges for sensing and perception. Recent video test data collected at the South Jersey Regional Airport indicates a number of potential confounders for traditional visual pattern recognition and line following algorithms for use at active airports. These include eroded/weathered paint that may disrupt surface patterns, stains/discolorations and cracks that may interrupt or visually warp lines, and false edges presented by seams between the surfaces of the ramp area, runways, and taxiways. Tug visual perception must be robust to these confounders when encountered in sensor data.

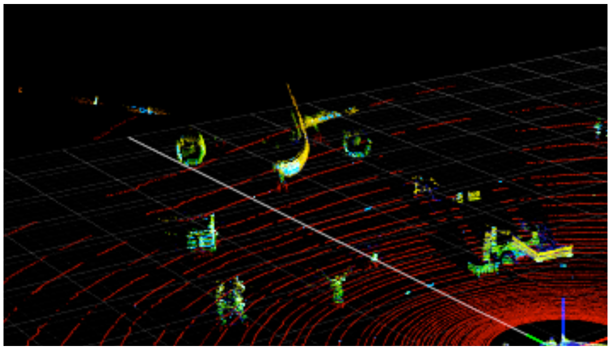


Figure 6. Visualization of LIDAR data collected at a gate at Atlantic City International Airport.

Initial LIDAR data collection by the authors at Atlantic City International Airport using a Velodyne HDL-64E (Figure 6) indicates that actions taken at airports to improve safety around manually controlled aircraft and ground vehicles will similarly benefit autonomous systems. The reflective surfaces applied to safety cones, vehicles, and, most importantly, the safety vests worn by airport personnel provide intense LIDAR readings that make detecting and tracking them much easier than would be otherwise possible and removing the need to modify airport infrastructure to support autonomous tugs.

In addition to the nominal scenario described above, the tug autonomy system must respond robustly to a number of contingencies. The system incorporates decision threads to support successful handling of each of these contingencies, including:

- Mechanical trouble during attachment or detachment, or during tow;
- Unexpected obstacle detection and avoidance
- Failure of communications

We are pursuing options for maintaining robust and safe operations in the presence of mechanical failures or other contingencies.

Tug Dispatching and Route Scheduling

Optimization of airport surface operations can be classified into the following sub-problems: runway sequencing and scheduling (Rathinam et. al, 2009); spot or gate release scheduling (Malik, Gupta and Jung 2012); gate allocation (Cheng, Sharma and Foyle 2001) and taxi route planning and scheduling (Visser and Roland 2003). Surface movement optimization is NP-hard (Reif 1979). Several types of constraints are involved, including push-back times, taxiway layouts, and runway and taxi-way separation. Planning is dynamic, with aircraft continuously entering and leaving the planning space, and replete with uncertainty and unexpected events. These complexities and the dynamic nature of the environment motivate approaches to automated planning that require reduced computational overhead while achieving useful results.

Surface planning with autonomous tugs is viewed here a centralized process, performed by a planning tool used by ramp controllers, or tower (ATC) operators. The tugs themselves don't decide where to go or how to get there; they only control their speed to keep safe and adhere to separation constraints on the taxiway.

The overall approach to planning and scheduling tug-based surface operations is an extension of the Spot and Runway Departure Advisor (SARDA) approach (Gupta, Malik and Jung 2012). The SARDA scheduler addresses the highly dynamic and uncertain planning environment by a multi-stage process. The next paragraphs summarize this process.

An airport surface can be represented graphically with nodes, representing locations (in terms of *x,y* coordinates) of gates, runway entrances, spots, or other intersections; and edges, representing traversable surface area. Figure 7 shows part of the Dallas Fort Worth International airport (DFW) as a graph. Traverse time between pairs of nodes is captured as a cost assigned to edges.

The scheduler pre-computes the shortest path routes between every pair of nodes using the Floyd-Warshall all-pairs shortest path algorithm, and stores it as a predecessor matrix (Cormen 2001). This matrix is invoked during scheduling time to retrieve routes for tug dispatching and aircraft taxiing.

A subset of nodes in the graph are designated as 'tug depots' that provide a re-charging station and designated locations for dispatching idle tugs. Tug depots should be strategically placed along the surface to reduce the time between dispatching an idle tug and reaching its assigned aircraft for attachment. Tugs can also be dispatched from locations other than depots; for example, a tug might have completed a towing operation to one gate, and be then dispatched to a near-by gate for the next departure towing task.

The SARDA scheduler contains two main components: a runway sequencer and scheduler, and a spot and gate release scheduler; to this system, we add a third component, a tug dispatcher. The spot and gate release scheduler selects times for pushback from the gate, and times for releasing the tug/aircraft for entry into the taxiway (the spot is the entry point into the taxiway from the ramp area). A *tug dispatcher* is a kind of resource scheduler: given an available tug, and an aircraft that needs to be towed, the dispatcher assigns the tug to the aircraft, and generates a shortest-path route for the tug to navigate to reach the assigned craft. Ordering the available tugs to determine the most efficient allocation can be decided using different criteria. We currently use a simple shortest distance criterion: the available tugs are ordered by distance between tug and attachment point (i.e. gate or runway exit), and the one with the smallest distance is assigned.

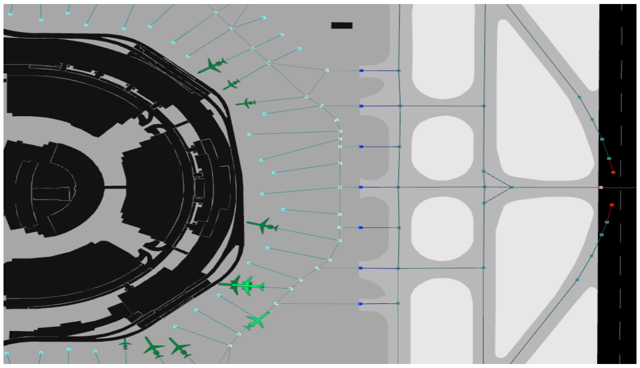


Figure 7. Visualization of Graphical Model of part of Dallas Fort Worth Airport.

Figure 8 shows the scheduling cycle and system components. The inputs to the scheduler consists of the current snapshot of the airport (the current locations of each active tug on the surface), scheduled push back and arrival times for the next 15 minutes, and various constraints such as aircraft-specific parameters and separation constraints. Because of the uncertainty in surface dynamics, these inputs are refreshed every 10 seconds. To control the number of changes made to the outputs of the schedule, a 'freeze horizon' is imposed which precludes major changes to be made to the current schedule.

The outputs of the scheduler, as depicted in Figure 8, are three schedules: a runway schedule, a spot and pushback schedule, and a tug schedule. Not depicted in the figure is the fact that the scheduler also generates routes (sequences of nodes) from the shortest-path matrix. The routes or release times are communicated to the tugs, which are considered the 'auto pilot' for pushback and taxiing.

The times computed by the scheduler represent each vehicle's earliest possible arrival time at each node. However, this set of routes may contain numerous conflicts (separation constraint violations). To resolve such conflicts, the system contains a flow model and a network event simulator to model arrivals at nodes representing intersections, and to determine the amount of time that aircraft must hold at current locations to maintain separation requirements, and to ensure other safe conditions (e.g. at intersection crossings, or to maintain wake vortex separation). The flow model assumes conflict avoidance on the surface to be the combined responsibility of the controller and tug. The controller identifies spatial violations in the schedule such as aircraft approaching head-on. The tug determines possible conflicts at the node it is currently approaching, and adjusts its speed accordingly. Together, the scheduler and deconfliction model approximate the taxi routings and resource utilization (gates and runways) that are most likely to be used by tower controllers at DFW.

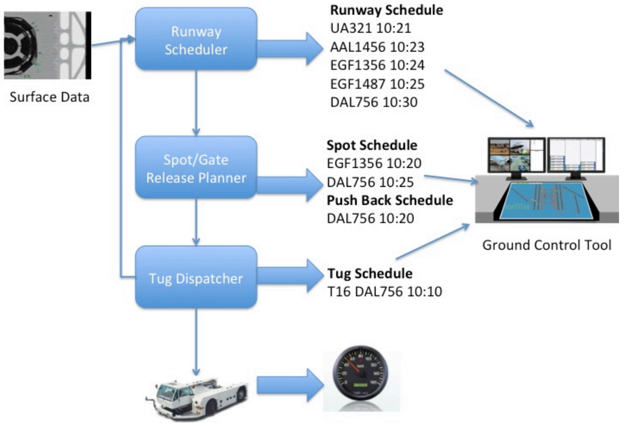


Figure 8. Surface Movement Scheduler Architecture

Simulation Tool and Performance Metrics

In evaluating the impact of autonomous engines-off taxiing, we have identified four performance metrics:

1. *Efficiency*, primarily in the amount of delay in taxi time and maximizing throughput;
2. *Complexity of logistics*, primarily in the form of workload for flight crew, tower personnel or ground crew;
3. *Safety* in the form of things like maintaining separation constraints and avoiding potentially dangerous events such as runway incursions; and
4. *Environmental and economic benefits* through reduced fuel emissions and reduced maintenance costs through less wear on airplane engines.

To collect statistics related to these metrics, we are utilizing a fast time Python-based simulator called ASSET (Airport Surface Simulator and Evaluation Tool). ASSET is based on the SARDA framework for scheduling, but with reduced capabilities that allows for rapid prototyping of route planning and scheduling algorithms.

ASSET contains three components: a scheduler, a simulator, and visualizer and analysis tools. The inputs to the simulator include a graphical model of an airport; a model of aircraft (including wing span, length and average taxi speed); and a scenario, a list of departure and arrivals for different aircraft, and the times at which they enter the surface system. The simulator, in conjunction with the scheduler, outputs the surface track information (i.e. the flow of traffic) over time. The simulator also models the 'intent' of the towing vehicles by automatically enforcing the separation constraints and other rules governing safe surface traverse.

The ASSET visualizer reads simulator output and displays the progress of the scenario on the airport surface (Figure 7 is a screen shot of the visualizer tool). The evaluation tool reads the simulator output into an SQL database, from which statistical inferences can be made and plotted, relevant to the four metrics listed above. As a baseline, we collect data from tug-less operations. Then we will add tug-based towing into the scenarios, which allows us to estimate the environmental impact of engines-off taxiing by deriving the percent reduction in the use of engine power from taxi time information. Future reports will document these results.

Summary

This paper has presented the idea of autonomous engines-off taxiing, the application of self-driving vehicle technology to enabling a fully automated taxiing system at busy airports. Aside from the technical problems of autonomous navigation, sensing and communication, the approach presented here recognizes the logistical challenges to be faced by autonomous engines-off taxiing. Adding a fleet of towing vehicles to the surface area immediately increases the traffic density on the surface, creating the potential for more delays. Secondly, the overhead of autonomous attachment and detachment also threatens to reduce the efficiency of operations by adding further delay. Third, the complexity of human-machine interaction in a dynamically changing environment threatens the efficiency of human decision-making. Despite these challenges, the solution presented here offers the potential for higher precision navigation, thus restoring at least some of the efficiency lost through increased surface density; decrease in human workload to pilots and controllers through automated decision making; and finally, the economic and environmental benefits that arise from engines-off taxiing.

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