

Validation of Simulations of Airport Surface Traffic with the Surface Operations Simulator and Scheduler

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The National Aeronautics and Space Administration (NASA) is developing automation for managing flight traffic on the airport surface to reduce taxi times and increase traffic throughput, without compromising safety. The scheduler is the part of the automation that calculates the advisories that assist the controller with clearing, holding, and sequencing flights. The Surface Operations Simulator and Scheduler (SOSS) is a fast-time airport surface operations simulator that connects to schedulers. SOSS is used to develop and test schedulers to determine if they can produce benefits. To show that schedulers developed with SOSS are credible, a validation of SOSS was performed to demonstrate that it is an accurate model of real operations. Surveillance and Federal Aviation Administration (FAA) operational performance data recorded from real operations at Charlotte Douglas International Airport were used to build a SOSS traffic scenario. The traffic scenario was run through SOSS to create simulated flight tracks. The flight tracks were analyzed to generate simulated taxi time and runway throughput metrics. Actual taxi time and runway throughput metrics were generated from the surveillance and FAA operational performance data. The simulated and actual metrics were compared. After the initial simulation, the average difference between simulated and actual taxi times on a flight by flight basis was not zero. A model tuning was performed by running the SOSS simulation multiple times while varying SOSS parameters to drive the average difference between the simulated and actual taxi times to zero. The SOSS parameters used were the pushback duration times and the taxi and ramp target speeds. Results show that the average difference between the simulated and actual taxi times was driven to zero. In addition, the standard deviations of the simulated taxi times and the actual taxi times were almost the same. However, the standard deviation of the flight by flight taxi time differences was large. This is because SOSS cannot simulate on an individual flight basis the exact actions taken by each flight in reality, which is an issue for all simulators. Despite this issue, SOSS was found to be a statistically accurate simulation of real airport operations, and schedulers developed and tested using SOSS have potential for producing benefits in real airport traffic management automation systems.

Nomenclature

<i>ASQP</i>	= Airline Service Quality Performance
<i>ASDE-X</i>	= Airport Surface Detection Equipment, Model X

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<i>ATCT</i>	= Air Traffic Control Tower
<i>CAI</i>	= Common Algorithm Interface
<i>CLT</i>	= airport code for Charlotte Douglas International Airport
<i>FAA</i>	= Federal Aviation Administration
<i>NASA</i>	= National Aeronautics and Space Administration
<i>SOSS</i>	= Surface Operations Simulator and Scheduler

I. Introduction

NASA is researching and developing automation that provides advisories to ramp, ground, and local controllers, who manage air traffic on the airport surface.¹ The advisories tell the controller when to clear or hold flights at key airport surface locations, such as gates, spots, and runway crossings and thresholds. The advisories are designed to minimize taxi time and sequence departure and runway crossing operations to maximize throughput. The purpose of the automation is to improve the efficiency of surface operations without compromising safety and to possibly reduce controller workload.

The scheduler is a primary part of the airport surface advisory automation. It is the mathematical algorithm that calculates the advisories that will be displayed to the controller. Many different formulations for schedulers are being studied. Some formulations include optimization programs like mixed-integer linear programs or dynamic programs, while other formulations are based on a set of heuristics.²⁻¹⁰ Any scheduler that is selected for actual deployment should demonstrate in simulation that the advisories it provides meet the goals of the automation, i.e., improved traffic efficiency and no increase in controller workload.

NASA tests schedulers and surface advisory automation in both fast- and real-time (human-in-the-loop) simulations. Relative to real-time simulation, fast-time simulation can process many scenarios and uncertainty cases for a modest cost of software development and staffing. Real-time simulation includes hands on interactions between human operator and automation and provides broad and crucial data about those interactions.^{11,12} To complement its state-of-the-art real-time simulation facilities, NASA has been developing a fast-time simulation of airport surface operations named the Surface Operations Simulator and Scheduler (SOSS).¹³⁻¹⁵ The purpose of SOSS is to develop and test schedulers. Schedulers that show promise are selected for further testing in real-time simulation.

The development and testing process in SOSS must accurately predict the benefits that the scheduler and accompanying automation will produce in real operations. To this end, surface operations simulated in SOSS need to be realistic. Validation is the process of measuring the differences between simulation and reality.¹⁶ If the differences are too large, the benefits predicted by the simulation lack credibility. Typically, when the differences are large a simulation is tuned. This is the process of reducing the average differences by adjusting parameters of the simulation. Another option, when differences are large, is to forgo attempting to calculate absolute benefits the system would produce in the real world, and only calculate relative benefits between two simulations.

This paper presents a validation of a SOSS simulation of airport surface traffic at Charlotte Douglas International Airport (CLT) during peak traffic hours. The traffic scenario is derived by extracting real flight schedules from recorded surveillance and FAA operations and performance data. A simple first-come-first-served scheduler loosely models control actions taken by controllers and pilots. SOSS simulates the traffic scenario to produce several validation metrics, taxi times and runway throughputs. The simulated metric values are compared with metric values calculated from the recorded field data to measure how well SOSS was able to simulate the operations that actually occurred. Two SOSS parameters, taxi speed and pushback duration times, are used to tune the simulation so that the simulated average taxi times match those calculated from the recorded field data.

This paper begins by introducing the Surface Operations Simulator and Scheduler. Then, it describes the validation process, the data used to drive the process, and the metrics used to do the comparison. Finally, results of the validation are presented.

II. Introduction to the Surface Operations Simulator and Scheduler

The Surface Operations Simulator and Scheduler (SOSS) models operations on the airport surface. These operations include flight readiness, pushback procedure, taxi, takeoff, and landing. First the airport operations are described and then the SOSS models are presented.

A. Airport Operations

Flight readiness is the process of getting flights ready for pushback. Typically flights are not ready to pushback exactly at their scheduled departure time because the times required to load passengers, baggage, food, and fuel and

for the crew to complete their safety check lists are uncertain. Results from Ref. 17 showed that from May to June 2012 at Dallas Fort Worth International Airport large airline flights pushed back on average 52 seconds early with a standard deviation of 148 seconds. Although SOSS has the ability to model the timing uncertainty of this process, it was not used in this study. The uncertainty in the actual pushback times did not have to be modeled because the actual pushback times for each flight in the scenario were available in the field data.

The pushback procedure starts when a flight begins to pushback from the gate and ends when the pilot is given clearance from ramp control to begin taxiing. During this procedure several things are happening. The aircraft is being moved by the tug from the gate to the drop off point (which is usually close to the ramp taxiway centerline), and the pilot is completing his pushback procedure which includes spooling up one or more engines. It is uncertain how much time these procedures take. In Ref. 16 the pushback procedure duration averaged 202 seconds with a 189 second standard deviation. Moreover, there were outlier flights with pushback durations as little as 77 seconds and as large as 7 minutes.

The taxi procedure moves flights from the area near the gates and terminals, called the ramp, out to the runways. While the flight is taxing, it crosses a location on the airport surface called the spot. The spot is the dividing point between the non-movement area and the aircraft movement area. The non-movement area includes the ramp and is controlled by the airline ramp control tower, while the aircraft movement area includes the taxiways and runways and is controlled by the FAA Air Traffic Control Tower (ATCT). Table 1 and Fig. 1 illustrate the areas covered by the non-movement and aircraft movement area and the spots. Control responsibility for flights is handed off between ramp controllers and air traffic controllers at the spot.

The takeoff and landing procedures prevent runway incursions by ensuring that flights safely enter and exit runways and consecutive departure or arrival operations follow wake-vortex and departure fix separation constraints. If there is more than one crossing point on the runway, more than one flight may cross the runway at a time. However when flights are crossing the runway, departures and arrivals are not permitted. Generally, the runway limits the operations rate of an airport because only one departure or arrival or set of crossing flights can use the runway at a time.

B. SOSS Models

The SOSS airport surface model is a node/link network representing gates, ramps, spots, taxiways, crossings, and runways. Figure 1 illustrates the network for Charlotte Douglas International Airport (CLT). Table 1 contains a key that matches the node/link colors with the areas of the airport that they represent. The runway queue is at the entrance to the runway where departures waiting to takeoff line up. The runway names for south flow configuration and the direction of takeoffs and landings are denoted in Fig. 1. Arrivals use runways 18R, 18C, and 23, while departures use 18C and 18L. 18C is used for arrivals and departures.

Flight surface routes in SOSS are defined as ordered lists of nodes through the node/link network. Each departure possesses a route that takes it from its gate to its runway entrance, and each arrival has a route that takes it from its runway exit to its gate. Routes cross through one and only one spot.

SOSS models the pushback procedure for departures along their first link. This link is between the gate node (first node) and first ramp node (second node) in the route. Generally, a flight's traversal time for a link is the length of the link divided by the speed of the flight, which is defined as the kinematic duration. In this study, the kinematic duration was not used as the traversal time for the first link for departures. Instead the user defined pushback time duration was used as the traversal time. The pushback time duration was one of the parameters used to tune SOSS as described later in the paper.

A SOSS simulation is initialized with a traffic scenario. The traffic scenario contains a list of flights scheduled to depart or arrive during the simulation. Specific information about each flight in the list is required to build the traffic scenario. Call sign, aircraft type, gate number, runway number are needed for all flights. Additionally, scheduled

Table 1. Node/Link Color Key

Node/Link Color	Type of Movement Area	Area of Airport
blue	non-movement	gate
blue	non-movement	ramp
yellow	both	spot
green	aircraft movement	taxiway
cyan	aircraft movement	runway queue
magenta	aircraft movement	runway takeoff point
orange	aircraft movement	runway exit point
red	aircraft movement	runway crossing point

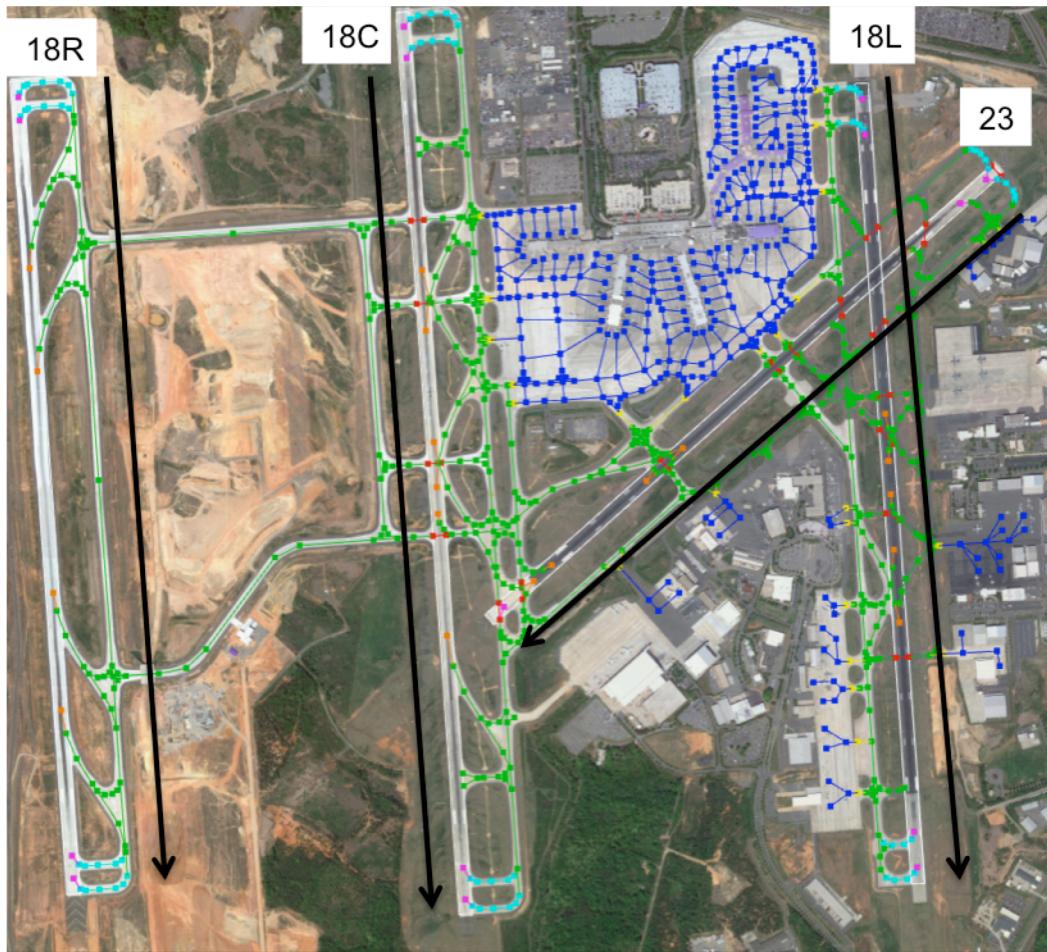


Figure 1. Node/link network model of Charlotte Douglas International Airport

gate pushback times are needed for departures, and actual wheels-on times are needed for arrivals.

The aircraft movement model uses kinematic equations of motion to move flights along links from one node to the next. Each type of aircraft has specified acceleration and deceleration values and set of target speeds. The model attempts to move the aircraft at the target speed. If the aircraft is stopped, the model accelerates it up to the target speed and then maintains its speed. If the aircraft speed is higher than the target speed the model decelerates the aircraft until it slows to the target speed. The target speed for each aircraft is selected based on the type of aircraft and the location of the aircraft on the airport surface. If the aircraft is located in the ramp area or runway queuing area the target speed is slower than if the aircraft is located on a taxiway. User parameters can be used to increase or decrease the target speed. The parameters for changing ramp speeds and taxi speeds were used to tune SOSS as described later in the paper.

The process of accelerating or decelerating the aircraft to its target speed is interrupted when other traffic impedes the aircraft. SOSS takes conflict detection and resolution actions to keep aircraft properly separated on the node link network. This is accomplished by predicting when two flights are going to conflict and slowing down or stopping one of the flights. There are several type of conflicts that may occur. Tail-on conflicts occur when a trailing flight overtakes a flight traveling in the same direction on the same link. Intersection conflicts occur when multiple flights simultaneously arrive at intersection nodes, which are nodes connected to more than one link. Finally, head-on conflicts occur when two flights are traveling on the same link in opposite directions. Head-on and intersection conflicts create the opportunity for gridlock which occurs when a pair or group of flights enter into a conflict and there is no way of resolving it.

Flight separations at the runway are determined by navigational safety and wake-vortex spacing constraints. In practice, controllers enforce a separation using a distance-based rule. SOSS enforces a separation by holding a flight at the entrance of the runway until a specified amount of time from the previous operation has elapsed. The time is calculated to achieve the correct distance between operations.

Reference 15 describes the approach used to calculate the separation times for runway operations at CLT. Tables 2-6 show the separation times in seconds. The weight classes of the aircraft are denoted by small (S), large (L), heavy (H), and B757. The B757 has its own weight class because its weight is in the large class, but it creates more turbulence than other large aircraft. Columns specify the weight class of the leader, and rows specify the weight class of the follower. For example according to Table 2, the separation time between a leading H and a trailing L was 120 seconds.

Table 2. Separation Matrix for Consecutive Departures on all Runways (seconds)

	S	L	H	B757
S	60	60	120	120
L	60	60	120	120
H	60	60	90	90
B757	60	60	90	90

Table 3. Separation Matrix for a Departure After an Arrival on 18C (seconds)

	S	L	H	B757
S	50	50	50	50
L	60	60	60	60
H	70	70	70	70
B757	60	60	60	60

Table 4. Separation Matrix for a Departure Before an Arrival on 18C (seconds)

	S	L	H	B757
S	40	40	40	40
L	28	28	28	28
H	24	24	24	24
B757	28	28	28	28

Table 5. Separation Matrix for a Departure on 18L After an Intersecting Arrival on 23 (seconds)

	S	L	H	B757
S	7	7	7	7
L	5	5	5	5
H	4	4	4	4
B757	5	5	5	5

Table 6. Separation Matrix for a Departure on 18L Before an Intersecting Arrival on 23 (seconds)

	S	L	H	B757
S	40	40	40	40
L	40	40	40	40
H	40	40	40	40
B757	40	40	40	40

More than one table is needed to specify the separations because CLT has both mixed use runways and intersecting (crossing) runways. For example, 18C accommodates both arrivals and departures so Tables 3 and 4 are required to specify the different separation requirements depending on whether an arrival proceeds or trails a departure. Similarly because 18L crosses 23, operations on 18L depend on operations on 23. Tables 5 and 6 define the separation requirements for departures on 18L depending on if they proceed or trail an arrival on 23.

SOSS connects to schedulers through a socket and uses a protocol called the Common Algorithm Interface (CAI) to communicate with them. NASA's real-time simulation facilities also use the CAI to communicate with schedulers. Because both SOSS and the real-time simulation use the CAI, a scheduler that has passed development and testing using SOSS can be easily integrated into the real-time simulation environment.

Figure 2 shows the SOSS system design. The arrows between the SOSS and Scheduler boxes depict scheduler calls that are made through the CAI. The user sets up the frequency and timing of the scheduler calls. For each call, SOSS sends to the Scheduler the current location, speed, route, and estimated times of arrival at key nodes in the airport node/link network of each flight operating on the surface. The Scheduler uses this information to calculate scheduled times of release for each flight at specific nodes in the airport node/link network. In a real-time simulation or in the field a scheduled time of release would be an advisory that would be displayed to a controller. The scheduled times of release are sent from the Scheduler to SOSS. SOSS controls each flight so that it does not leave a node before its scheduled time of release. If a flight arrives at a node before its scheduled time of release, SOSS holds the flight at the node until its release time. If a flight arrives at a node after its scheduled time of release, SOSS allows the flight to continue on its route without stopping. Not all nodes have scheduled times of release; only the nodes selected by the Scheduler have them. This is similar to actual surface operations where flights are only controlled at specific locations on the airport. In this study, SOSS used a very simple first-come-first-served scheduler.

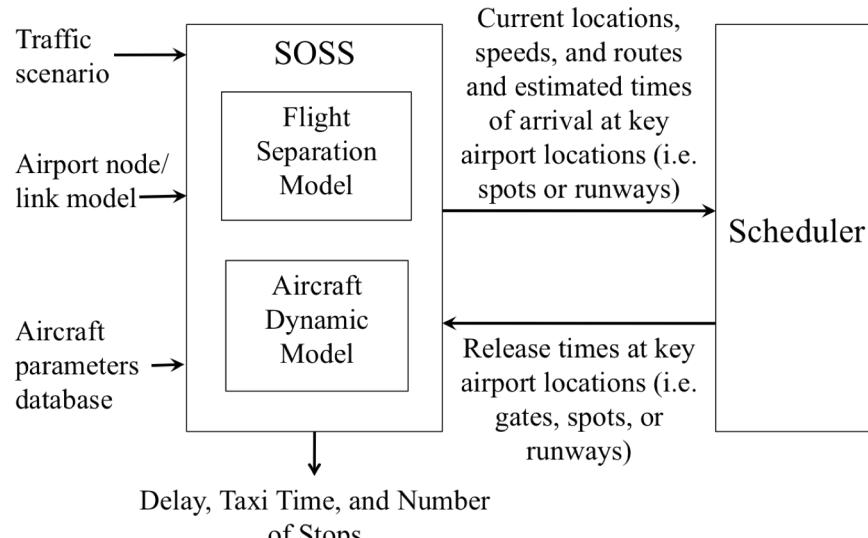


Figure 2. Diagram of SOSS System Design

III. Validation

The validation process determines if the SOSS simulations are an accurate approximation of operations in the real world. It is accomplished by comparing metrics produced by SOSS simulations with those calculated from recorded surveillance and operational performance data. After the initial simulation, the simulated metrics did not compare well with actual metrics. SOSS was tuned to make the metrics compare better.

A. Comparison of Simulated Metrics to Actual Metrics

Figure 3 depicts the process for measuring the difference between a SOSS simulation and real operations. The validation process begins with recorded surveillance and FAA operational performance data. These data are fed along two different paths depicted in the Fig. 3. Along the top path, a SOSS scenario file is created from the surveillance data. Then, the scenario file is used to initialize a SOSS simulation. Simulated flight tracks generated from the SOSS simulation are fed into the metric generator. The metric generator calculates simulated taxi times for each flight and simulated operation rate histories for each runway. Along the bottom path in Fig. 3, surveillance data and FAA operational performance data are fed directly into a metrics generator. The metrics generator calculates actual taxi times for each flight and operation rate histories for each runway. The simulated metric values are compared with the actual metric values.

Model Tuning

After the initial simulation, the simulated taxi times did not compare well with the actual taxi times. The goal of the model tuning was to bring the simulated taxi times closer to the actual taxi times. The model tuning was accomplished by executing a series of SOSS simulations. For each simulation, SOSS input parameters were varied

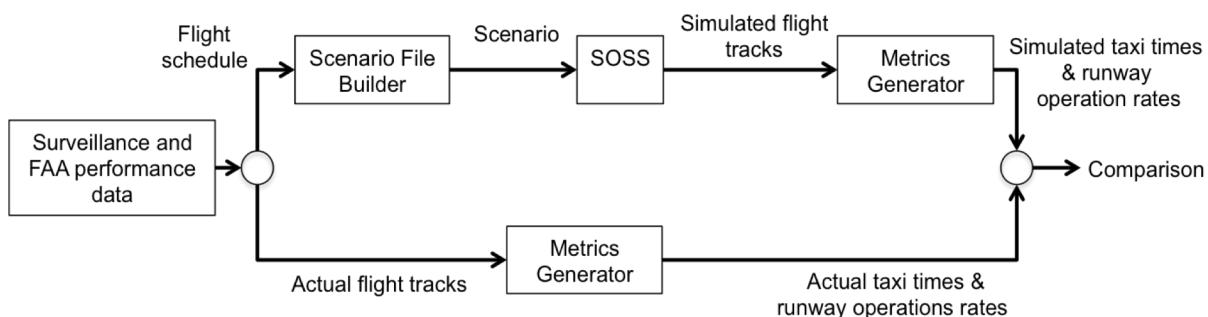


Figure 3. Diagram of Validation Process

to move the simulated taxi times closer to the actual taxi times. The definition of the taxi time metric used in the model tuning is described in the metrics section. The SOSS input parameters used in the model tuning were the pushback duration time and the parameters that increase and decrease the ramp and taxi target speeds.

IV. Data

No single data set contained all of the information required to perform the validation. The three required data sources were Airport Surface Detection Equipment, Model X (ASDE-X), FlightStats, and the Airline Service Quality Performance (ASQP) system. This section describes each data source and the information that was used from it. Table 7 summarizes the data contained within the different sources. In addition, it lists the number of flights that were extracted from each source for the date and time period that was selected for the validation.

Table 7. Summary of Data Used from Data Sources

Source	# of Flights	Data
ASDE-X	192	call sign, origin, destination, runway assignment, aircraft type, wheels-on time
FlightStats	181	call sign, origin, destination, gate assignment, gate-out
ASQP	107	call sign, origin, destination, gate-in, wheels-off time

Since three data sources were used, flights had to be cross referenced between sources. Call sign alone was not sufficient for cross referencing because call signs are not mutually exclusive between flights, i.e. two different flights may use the same call sign. In this study, cross referencing across data sources was accomplished by matching call sign, origin, and destination.

A. Airport Surface Detection Equipment, Model X (ASDE-X)

Flights on the airport surface at CLT are tracked by multiple surveillance sources. Multiple sources are required for redundancy, accuracy, and coverage of the airport surface. The ASDE-X system integrates data from the multiple sources into a single stream of data that is used to drive tower and ramp controller displays and compute performance metrics for the FAA and airlines. Despite multiple sources, there are still coverage gaps in some terminal alleys and near some gates. In addition, tracks in the non-movement area are masked on tower air traffic controller displays because tower air traffic controllers are not responsible for flights in the that area.

The ASDE-X data used in this study was obtained from ITT Excelis^{18,19}. ITT Excelis provides more data than is available in the raw surveillance data alone. For each flight, they also provide processed data such as the runway assignment, the aircraft type, and the wheels-on or wheels-off time.

The ASDE-X data contained tracks for each flight that operated at CLT. In this study, airborne tracks were filtered out of the data so tracks for arrivals generally started with wheels-on and ended just inside the non-movement area. Tracks for departures generally started around the edge of non-movement area and ended with wheels-off. Most flights had little track coverage in the non-movement area because that data was masked. Figure 4 illustrates tracks for a departure on runway 18C.

As discussed later in the paper, the ASDE-X data were used to generate the traffic scenario. For most flights in the scenario, derived data from ITT Exelis, as opposed to track data, provided all of the necessary information. However some flights in the scenario were either missing data or their data was inaccurate. The data may have been the flight's runway assignment or gate-in, gate-out, wheels-on, or wheels-off time. For these flights, the track data would be used to visually estimate the missing data from a plot of the track data on a map of CLT similar to Fig. 4.

ASDE-X contained 192 flights that operated during time period chosen for this study. Since ASDE-X provides surveillance data from the airport, it was assumed that 192 was the actual number of flights that operated during the time period. However, there is a possibility that there were some flights that operated in reality, but were filtered or dropped out of ASDE-X. The missing flights, if there were any, would have been military or other special flights.

B. FlightStats

The FlightStats website²⁰ contains information about the on-time performance of flights. FlightStats gets its information from government, airline, airport, and reservation systems. In addition to on-time performance, FlightStats provides the departure and arrival gate that a flight used. The gate information from FlightStats was used to populate the gate assignment in the SOSS traffic scenario file. The FlightStats data set contained 181 flights that operated during the date and time period selected for this study.



Figure 4. Flight Tracks for Departure on 18C in ASDE-X

C. Airline Service Quality Performance (ASQP)

The Airline Service Quality Performance system²¹ (ASQP) gives airline-reported on-time performance, flight delay, and cancellation statistics. It is driven by reports submitted by the airlines in accordance with Department of Transportation regulations. Airlines with one percent or more of total domestic scheduled passenger revenues must report on flights operating in any airport in the 48 contiguous states. In addition to those airlines that are required, some airlines voluntarily report. At the time of the writing of this paper, there were 14 airlines reporting.

Included in the ASQP data is the so called Out-On-Off-In (OOOI) data, which refers to gate-out, wheels-off, wheels-on, and gate-in times. Typically, sensors onboard the airplanes capture the times that these events occurred and automatically send them via the Aircraft Communication Addressing and Reporting System (ACARS) to the airline database system. OOOI data was used to calculate actual taxi times as described in the Metrics Section.

The ASQP data set contained 107 flights that operated during the date and time period selected for this study. The 85 flights that were in the ASDE-X data set, but not in the ASQP data set, were flights not operated by one of the 14 ASQP airlines.

V. Traffic Scenario

The traffic scenario contains the list of flights that are scheduled to operate during the simulation. It is one of the input files that drives a SOSS simulation. A traffic scenario has a date and a time period which define when the simulation starts and ends. Only flights which operated between the start and end times on the date are included in the traffic scenario.

A. Building the Traffic Scenario

When building a traffic scenario for a validation study, a primary goal is to identify and include all of the flights that actually operated during the selected time period. If some flights are missed and not included in the traffic scenario, the traffic densities in the simulation will be lower than they were in reality, and this will distort the simulation metrics. A favorable feature of the ASDE-X data set was that it captured possibly (with the exception noted in the Data Section) all of the flights that operated at CLT during the selected time period. This data source was used to verify and identify the flights and include them in the traffic scenario.

Multiple pieces of information were needed for each flight entry in the traffic scenario. These data were call sign, aircraft type, gate assignment, runway assignment, and start time. Start time for departures is the gate pushback time, and start time for arrivals is the wheels-on time. Since all of these were not included in a single data source, the

data had to be extracted from both the ASDE-X and FlightStats data sets. Aircraft type, runway assignment, and wheels-on time were selected from ASDE-X, and gate assignment and gate-out time were selected from FlightStats. Cross referencing between ASDE-X and FlightStats was performed as described in the Data Section.

ASDE-X contained 192 flights, and FlightStats contained 181 flights. All of the flights found in FlightStats were able to be cross referenced into the ASDE-X flight set. However, there were 11 flights that were found in ASDE-X but not in FlightStats. The flight tracks in ASDE-X were used to visually estimate the gate assignment and gate-out time for these flights. Fortunately these flights did not have a large affect on traffic in the ramp area around the main terminals because all of these flights were general aviation flights that were using gates in the general aviation terminal, which is on a separate side of the airport from the main airline terminals. These flights did not interact with the main traffic until they reached the runway.

B. Selecting the Date and Time Period

The date and time period for the validation were selected based on multiple factors, including weather, airport runway configuration, and traffic density. Because this study was an initial validation of the SOSS CLT model, it was desired to simulate conditions at CLT that occurred often and during good weather. The south flow configuration (see Section II.B) was selected because (i) it is used slightly more often than the north flow configuration, (ii) it uses all four runways (as opposed to the north flow configuration that uses only 3 runways), and (iii) it has slightly higher arrival and departure rates than the north flow configuration.

It was desired to simulate current or at least recent traffic conditions, thus the date of the traffic scenario needed be close to the current date. This study started in March 2013. At the time, ASQP had not yet published data for March and February, so January was the closest month for which data was available from all three data sources. January 23 was a clear weather day at CLT. The airport was in south flow configuration for the majority of the day. The only period the airport was in the north flow configuration was during a few hours in the early morning.

The time period was selected to capture a peak traffic density period during the day. Figure 5 shows the airport operations rates on January 23. The number above a peak denotes the number of operations (both arrivals and departures) that occurred in that peak. The blue box denotes the time period that was selected. This period was selected because it was during a late morning rush with the highest departure peak of the day, 26 departures per 15-minutes. In addition, this period contained the peak with the second highest number of operations, 193 operations.

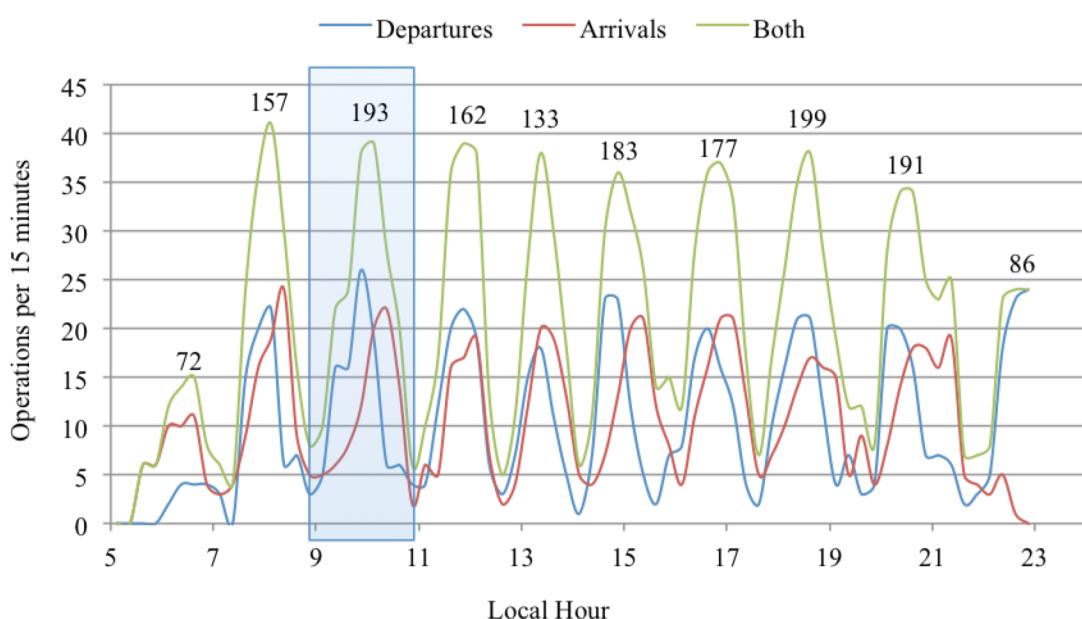


Figure 5. Airport Operation Rates at CLT on January 23, 2013

VI. Metrics

Two metrics were selected for doing the comparison between simulation and actual operations. These metrics were runway throughput and taxi time. This section describes how these metrics are calculated.

A. Runway Throughput

Runway throughput is the time history of the number of operations that occurred during a 15-minute sliding time bin. Two throughputs are calculated, arrival and departure. Arrival throughput is generated by counting the number of wheels-on times for arrivals within a 15-minute sliding time bin. Departure throughput is generated by counting the number of wheels-off times for departure within a 15-minute sliding time bin.

The simulated and actual departure throughput histories should be as close as possible. When they are close, it verifies that the average separations in the separation matrices (Tables 2-6) were a good model of the actual departure runway operations.

B. Taxi Time

Taxi time is the time required for a departure to transit from the gate to the wheels-off point or for an arrival to transit from the wheels-on point to the gate. The taxi time does not include time spent waiting at the gate. Reducing taxi time is desirable because during taxi engines are on, fuel is burned, and emissions are released.

Taxi time for a departure is calculated as

$$\text{taxi time departure} = \text{wheels-off time} - \text{gate-out time}, \quad (1)$$

and taxi time for an arrival is calculated as

$$\text{taxi time arrival} = \text{gate-in time} - \text{wheels-on time}. \quad (2)$$

For the validation study, the focus is on the difference between simulation and reality. Hence, the taxi time error for a individual flight is defined by the following equation:

$$\text{error} = \text{simulated taxi time} - \text{actual taxi time}, \quad (3)$$

where actual taxi time actual means the taxi time calculated from ASQP.

To understand the size of the error relative to the size of the actual taxi time, the taxi time percent error is calculated as

$$\text{taxi time percent error} = (\text{error} / \text{actual taxi time}) * 100. \quad (4)$$

The taxi time percent error measures the percent difference between the simulated taxi times and the actual taxi times.

A taxi time error and percent error is calculated for each flight in ASQP, 107 flights out of a total of 192 flights. The taxi time errors and percent errors were averaged across the 107 flights and standard deviations were calculated. The taxi time percent error was the metric that was driven to zero for the model tuning.

Taxi times for some of the 85 other flights may have been able to be derived from the FlightStats and ASDE-X data sets, but for this study that was not attempted. This is because the data for the non-ASQP airline flights were found to be more likely to have errors than the data for the ASQP airline flights. Identifying and fixing flights with inaccurate data was very time consuming because it required visually checking ASDE-X flight tracks.

VII. Results

Results are presented for the model tuning, runway throughput metrics, and taxi time metrics.

A. Model Tuning

The SOSS model was tuned to make the difference between simulated and actual taxi times zero. The metric that was selected for this process was the taxi time percent error as described in the Metrics Section. The taxi time percent error metric was averaged across both the arrivals and the departures. The tuning process drove both the

Table 8. Values of SOSS Tuning Parameters and Metrics

Parameter	Initial Value	Final Value
Pushback duration	3 min. and 22 seconds ¹⁷	5 minutes and 46 seconds
Ramp speed	10 knots	13.7 knots
Taxi speed	15 knots	17.4 knots
Average departure error	-2 min. 10 sec. (-12%)	25 sec. (0%)
Average arrival error	42 sec. (20%)	44 sec. (0%)

average arrival and departure taxi time percent errors to zero. The SOSS parameters used to achieve the model tuning were the pushback duration, the ramp target speed, and the taxi target speed.

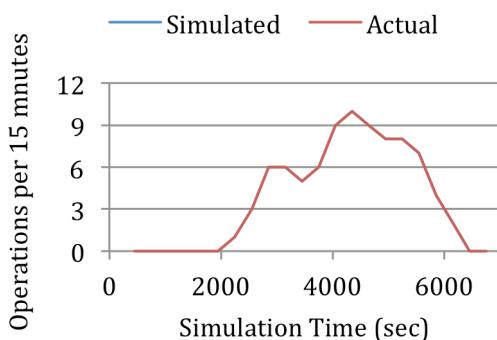
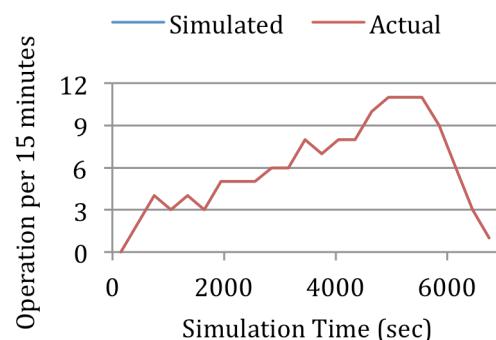
The initial and final values of the tuning parameters and the error metrics are listed in Table 8. For average departure and arrival errors, the first value is average error, Eq. (3), and the value in parenthesis is average percent error, Eq. (4). Inspection of the final values of these errors shows that even though the tuning process drove the average percent errors to zero, the final values of the average errors were not zero. In an exercise not reported in Table 8, the simulation was tuned to drive the average errors to zero. This produced very similar values of the tuning parameters.

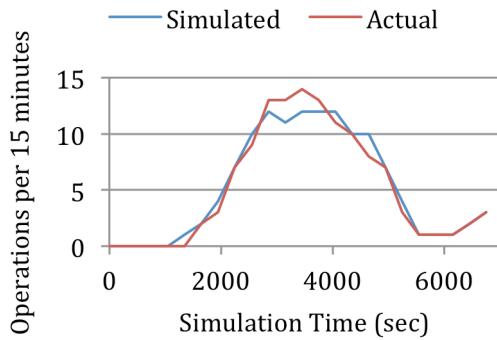
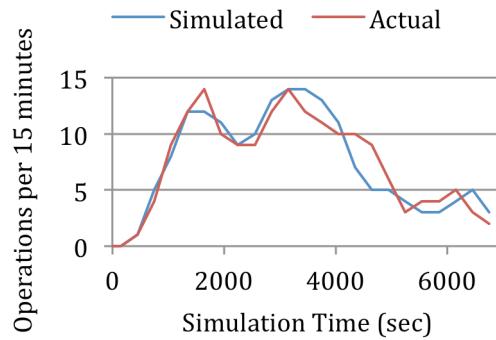
The negative initial value for average departure error in Table 8 meant that initially for departures actual taxi times were on average larger than simulated taxi times. The final pushback duration value adjusted for this by making the simulated pushback durations longer, 5 minutes 46 seconds versus 3 minutes 22 seconds. The positive initial value of the average arrival error meant that for arrivals simulated taxi times were on average larger than actual taxi times. The faster final ramp and taxi target speeds adjusted for this by shortening simulated arrival taxi times.

All flights in the SOSS simulation had a pushback duration of 5 minutes and 46 seconds. Flights in actual operations had a wide variety of pushback durations. Similarly, in SOSS all flights in the ramp had a target speed of 13.7 knots and all flights on the taxiways had a target speed of 17.4 knots. However, flights in actual operations reached speeds higher or lower than these speeds. These differences illustrate the difficulty in predicting operations on the airport surface. It is not known on a flight-by-flight basis how long a pushback procedure will take, or what speeds an aircraft will attain in the absence of other traffic. This highlights the fact that although the model tuning drove the average departure and arrival taxi time percent errors to zero the standard deviations were not zero.

B. Arrival Throughputs

Figures 6 and 7 show the simulated and actual arrival throughputs for runways 18R and 23, respectively. Both runways were used as arrival-only runways during the time period chosen for this study. The simulated and actual throughput curves lie directly on top of each other, which is why only a red curve shows in the figures. The blue curve is underneath. The fact that the curves lie on top of each other suggests that the arrival flights in the traffic scenario were correctly set up. This is to be expected since the wheels-on times for arrivals in the simulation were derived from the actual wheels-on times, as described in the Traffic Scenario Section.

**Figure 6. Arrival Throughput on 18R****Figure 7. Arrival Throughput on 23**

**Figure 8. Departure Throughput 18C****Figure 9. Departure Throughput 18L**

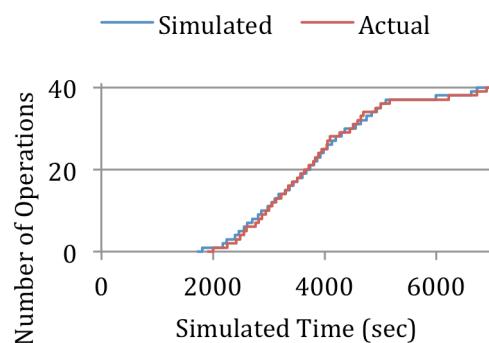
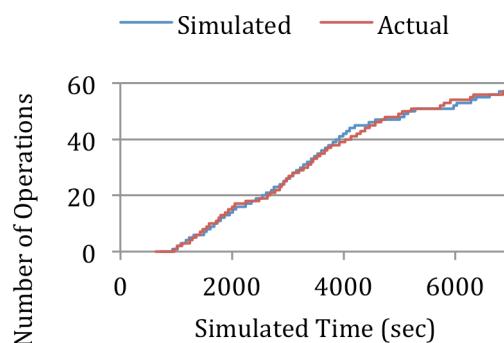
C. Departure Throughputs

Figures 8 and 9 show the simulated and actual departure throughputs for runways 18C and 18L, respectively. Here the simulated and actual curves do not lie exactly on top of each other. This is because departure throughputs are generated by counting the number of wheels-off times in a 15-minute bin and the simulated wheels-off times are not identical to the actual wheels-off times. It is desired that simulated wheels-off times be as close as possible to actual wheels-off times, but inaccuracies in the simulation produce differences.

As denoted in Fig. 8 at about 3,400 seconds, the simulated departure throughput on runway 18C does not peak at the same level as the actual throughput. This indicates a loss of throughput in the SOSS simulation. The difference between the two peaks is 2 departures per 15 minutes which is 14% of the actual peak value. A similar loss in throughput shows at about 1,800 seconds for 18L in Fig. 9. However at the next peak at 3,300 seconds, the simulated and actual curves achieve the same maximum.

The loss of throughput on 18C was investigated further by viewing playback visualizations of the simulation between 2,000 and 3,500 seconds. It was observed that the loss occurred because departure operations on 18C briefly dried out at about 2,800 seconds, which is the time when the loss first shows in Fig. 8. 18C dried out because two departures headed for 18C were caught in a traffic jam in the ramp. The traffic jam caused the two flights to arrive at the entrance to 18C late. Visual inspection of the ASDE-X tracks for these two flights revealed that in actual operations they were able to avoid the traffic jam.

Figures 10 and 11 show the cumulative departures on runways 18C and 18L, respectively. Because the simulated and actual curves do not differ from each other by more than several operations, it is seen that the loss in throughput noted in Figs. 8 and 9 does not have a large affect on the cumulative departures.

**Figure 10. Cumulative Departures 18C****Figure 11. Cumulative Departures 18L**

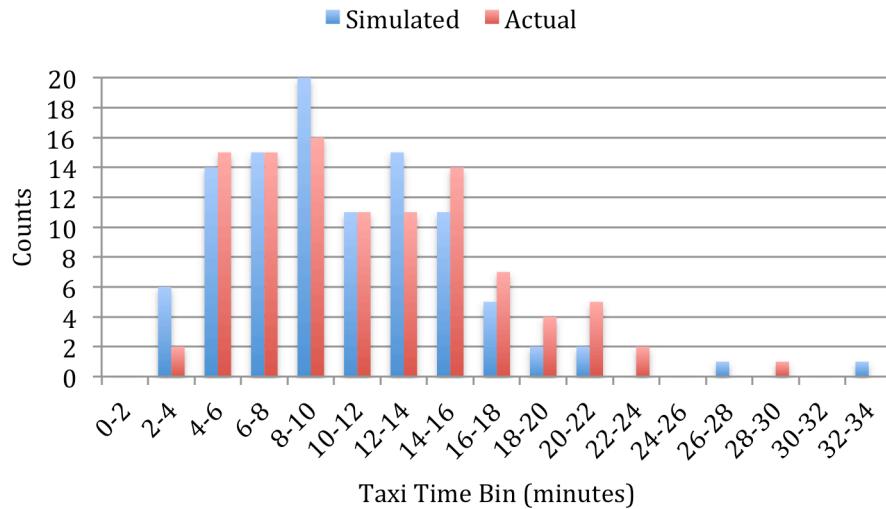


Figure 12. Histograms of Simulated and Actual Taxi Times

D. Taxi Times

Figure 12 shows histograms of the simulated and actual taxi times. Only the 107 ASQP flights were included in these histograms. The average simulated taxi time is 10 minutes and 29 seconds and the average actual taxi time is 11 minutes and 4 seconds. The average taxi times are not equal after model tuning because average taxi time percent errors were driven to zero, not the average taxi time errors. The simulated taxi time standard deviation is 5 minutes and the actual standard deviation is 5 minutes and 10 seconds. These results show that statistically SOSS is an accurate model of real operations.

Figure 13 shows histograms of the arrival and departure taxi time percent errors. Only the 107 ASQP flights were included in these histograms. Included are the standard deviations in taxi time percent error, Eq. (4), and taxi time error in parenthesis, Eq. (3). The average taxi time percent errors were set to zero by the tuning process. The numbers in the x labels surrounded by parenthesis are negative.

The arrival with 100% error in Fig. 13 is an outlier. Inspection of ASDE-X tracks showed that this flight in reality reached taxi speeds as high as 29 knots in the ramp, which is much larger than the 13.7 knots target speed that was used in simulation.

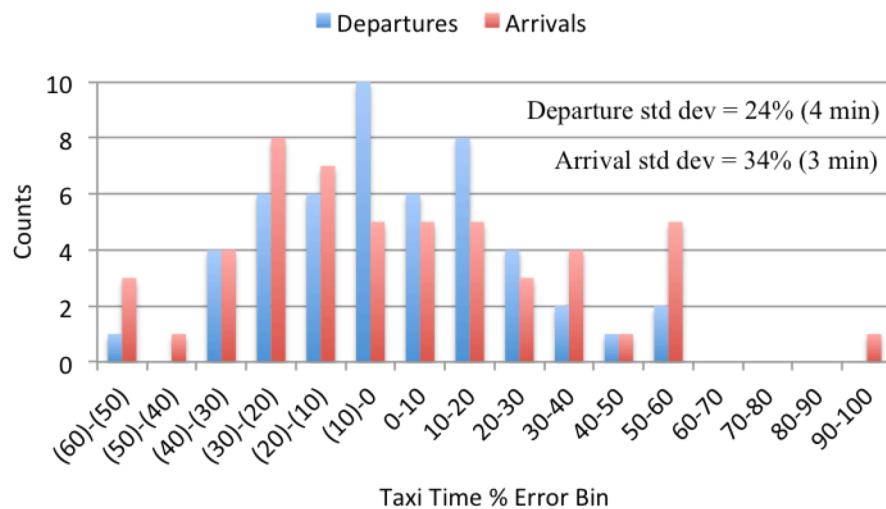


Figure 13. Histograms of Departure and Arrival Taxi Time Percent Errors

VIII. Future Work

There are several next steps that this research could take. In this paper, only one traffic scenario was investigated. This was due to the work required to compile a traffic scenario from the field data. A future study could investigate more traffic scenarios, including scenarios with less traffic. The model tuning should be performed for each new scenario. The values of the tuned parameters for the different parameters would be compared. Ideally, the values of the tuned parameters should be approximately stable across scenarios if the pushback durations and ramp and taxi target speeds were similar for the different scenarios.

Another future study would be to analyze the field data and measure the actual pushback procedure durations for each flight. The actual pushback durations could be used within SOSS to model exactly how long each flight took to pushback. This would eliminate the uncertainty in the model due to pushback procedure duration. With this uncertainty eliminated, the uncertainty due to taxi and ramp speeds, traffic interactions, and runway queue dynamics would be isolated and could be analyzed.

IX. Conclusion

This study showed that the Surface Operations Simulator and Scheduler (SOSS) was able to accurately on a statistical basis model real operations on the Charlotte Douglas International Airport surface. Using model tuning, the simulated and actual distribution of taxi times had the very close averages and standard deviations. In addition, the simulated and actual runway departure rates were approximate. The simulated runway departure rate peaked 14% less than the actual departure rate. However, the difference in peak departure rate was small enough and for a short enough period that it did not adversely affect the cumulative number of departures. Despite the success in matching the distributions of simulated and actual taxi times, on an individual flight basis SOSS did not predict well the exact actions of a particular flight. It was difficult to predict the duration of a specific flight's pushback procedure and what speed a pilot used to taxi across the airport surface. Any simulation of airport surface traffic must contend with the difficulty of predicting these parameters.

The pushback duration time and ramp and taxi speeds that were derived from the SOSS model tuning are good estimates of the average pushback durations and taxi and ramp speeds occurring in real operations. The tuned pushback duration of 5 minutes and 46 seconds is higher than the average duration measured in Ref. 17 at Dallas Fort Worth International airport. However, it compares well with unpublished estimates of pushback durations at Charlotte Douglas International Airport (CLT) that the authors have observed in actual operations. In addition, average ramp and taxi target times of 13.7 knots and 17.4 knots align well with observations of the flight speeds observed in the ASDE-X data. However, speeds observed in the ASDE-X data can be much higher, as high as 28 knots for an outlier flight.

There were some limitations to this study. The study was accomplished for a specific airport surface and a specific traffic scenario. The results of this study may not hold for other airports or traffic scenarios. The model tuning process may need to be performed again for a different airport or a different traffic scenario. For example, observations of traffic at on the surface of CLT have shown that average taxi speeds change with the level of traffic. During periods of very little traffic, pilots tend to taxi faster, and during periods of heavy traffic, pilots tend to taxi slower. This observed effect would cause the tuned target speeds in SOSS to be different for a traffic scenario with little traffic.

Because SOSS can on average realistically and accurately simulate operations on the airport surface, it is a good environment for developing and testing airport surface traffic schedulers. SOSS can be used to measure the anticipated benefits that a scheduler would produce if it were installed as part of an airport surface traffic management system and used at a real airport.

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