

# Investigation of NASA's Spot and Runway Departure Advisor Concept at PHL, CLT, and LAX Airports

Stephen Atkins, Brian Capozzi, Andrew Churchill, Alicia Fernandes, and Chris Provan

Mosaic ATM, Inc.  
Leesburg, United States

**Abstract**—NASA has developed the Spot and Runway Departure Advisor (SARDA), which plans spot crossing times and runway sequences to more efficiently manage departures on an airport surface, and extensively studied the concept and algorithms in the context of Dallas/Fort Worth International Airport. This paper reports on a study of the SARDA concept at three new airports – Philadelphia International Airport (PHL), Charlotte-Douglas International Airport (CLT), and Los Angeles International Airport (LAX). The investigation of SARDA at these new airports included both fast-time simulation experiments as well as a human factors evaluation. A fast-time simulation was developed for PHL, CLT, and LAX airports, capable of simulating both baseline operations and operations with NASA's SARDA concept in use. Multiple traffic scenarios were simulated at each airport and metrics detailing the differences between the SARDA and baseline operations analyzed. Results supported the conclusion that SARDA provides substantial benefits at all three airports. To complement the simulations, structured interviews were conducted with retired air traffic controllers who had experience at the focus airports. The human factors study provided a qualitative, alternative investigation into how SARDA would operate at these airports, and identified issues not observable through the simulations as well as additional concept and algorithmic requirements related to off-nominal situations.

**Keywords**—*Airport surface traffic management; departure reservoir management*

## I. INTRODUCTION

With the relatively recent introduction of advanced airport surface surveillance technologies and the prospect of a common automation platform for the air traffic control tower, airport surface traffic management concepts realistically promise near-term capacity, safety, and environmental benefits. NASA's Airspace Systems Program has developed the Spot and Runway Departure Advisor (SARDA), which

plans spot crossing times and runway sequences to more efficiently manage departures at an airport [1]-[7]. NASA's initial research focused on operations at Dallas/Fort Worth International Airport (DFW). One aspect of NASA's continuing SARDA research is to study its application at other airports to identify new algorithmic requirements and validate the universality of the concept. This paper reports on an effort to study the application of the SARDA concept to three new airports – Philadelphia International Airport (PHL), Charlotte-Douglas International Airport (CLT), and Los Angeles International Airport (LAX).

The airports were chosen for their diversity in geometric and operational characteristics, intended to broadly exercise the SARDA concept. The investigation of SARDA at these airports included both fast-time simulations as well as a human factors study consisting of focused interviews with subject matter experts (SMEs). The purpose of the fast-time simulations was to simulate how SARDA would affect the operations at each of the three studied airports. To measure SARDA's impact, two simulations were performed for each traffic scenario, one using baseline models for current day operations and the other using models of SARDA and controllers following the SARDA advisories. Results compare various metrics between the two simulations, as well as comparing across scenarios and between airports.

To ensure results are independent, the experiment used a different simulation platform than was used in NASA's prior work. In addition, the fast-time simulations used new models of the SARDA concept and how controllers would use the SARDA-provided advisories, rather than using NASA's SARDA software from DFW.

The purpose of the human factors evaluation was to provide a qualitative, alternative investigation into how SARDA would operate at these airports, focusing on the differences from DFW and the use of SARDA during off-nominal conditions. This report describes the simulated benefits of SARDA at these airports, the observations made through interviewing SMEs, and

suggests requirements for extending the SARDA concept for off-nominal situations, motivated by characteristics of these airports that were not present at DFW. A single version of SARDA was compatible with all of the airports studied, suggesting broad applicability of the SARDA concept. The quantitative results suggest that NASA's SARDA concept, with straight-forward extensions to accommodate new operational issues not present at DFW, has the potential to provide substantial benefit at each of the three studied airports. In the human factors (HF) study, controllers perceived the SARDA concept as valuable but expressed concern that automation would not be as flexible as controllers are able to be today. The study identified numerous requirements for SARDA pertaining to both routine and off-nominal traffic management situations, based on controller recommendations. Refining and validating the SARDA concept under off-nominal conditions should be a focus of NASA's continuing research.

Section II describes NASA's SARDA concept. Section III describes our mathematical model of the SARDA algorithms. Section IV presents the fast-time simulation approach and results. Section 0 presents the human factors (HF) study. Section VI summarizes the implications of the simulation and HF results for the SARDA concept.

## II. BACKGROUND

SARDA is a collection of automation capabilities designed to aid controllers in the air traffic control tower to improve the efficiency of airport surface traffic movement. Additional details on NASA's SARDA concept and prototype implementation may be found in [1]-[7]. SARDA is comprised of the Spot Release Planner (SRP) and Runway Scheduler (RS) which originally were separate algorithms but have been combined to share an underlying runway planner. Conceptually, SRP and RS operate as independent systems, much in the way NASA's Traffic Management Advisor (TMA) and Final Approach Spacing Tool (FAST) were independent systems that worked cooperatively to provide a complementary solution for airborne arrival management [8]. A NAS implementation architecture for SARDA has not been identified.

The objective of SRP is to generate an optimal schedule for releasing aircraft into the active movement area to maximize runway throughput (by causing efficient departure sequencing) while minimizing runway queuing and other movement area taxi delay. Outputs from SRP, which are advisories to ATC Tower and ramp controllers, are the optimal spot and gate release sequences and times.

The objective of RS is to generate an optimal sequence for departures and runway crossings on a single departure runway. Outputs from RS are

departure queue assignments for each departure to that runway, departure sequence and predicted takeoff times on that runway, and the sequence and timing of runway crossings on that runway. RS assumes arrivals on mixed-use or dependent runways are immovable constraints on the departure/crossing schedule. At an airport with multiple departure runways, separate instances of SRP and RS would operate for each departure runway. Coordination between multiple departure runways may be required at some airports either because the runways are dependent (e.g., they cross, are parallel and closely-spaced, or share an airspace route or fix) or because the spot-crossing times for flights going to different runways from the same spot must be coordinated.

### A. Spot Release Planner

The Spot Release Planner computes a solution for all of the flights within some planning horizon (e.g., 15 minutes) at a periodic rate (e.g., every 10 seconds). The high frequency of re-computing the solution using the newest available information is how SRP reacts to unexpected events, such as an un-planned runway configuration change. The solution from each SRP run overlaps significantly with the prior solution in terms of the flights that were included in the computation. SRP applies a freeze sequence concept to allow flights that will push back further into the future to move in the schedule in the next solution. Flights that are scheduled to be one of the next  $N$  to leave their gate are frozen in the schedule so that they may be controlled to achieve the schedule. This approach allows SRP to freeze the gate and spot times for flights about to push back while RS continues to re-compute the runway times for those flights.

The spot and gate release times are computed in a three-step process, described in Section III. The first step solves for the optimal takeoff time or runway crossing time for each aircraft on that runway. In the second step, the scheduled spot release times are calculated from the scheduled runway times, to provide a small queue at the runway. The SARDA concept states that aircraft crossing the spots at the planned spot times will naturally – with little or no control – queue at the runway in the planned sequence. Thereby, SARDA attempts to construct a desired departure sequence by controlling spot crossing times. The third step calculates the gate release time from the scheduled spot release time.

Variability and the resulting uncertainty in taxi times both within the ramp and in the active movement area (AMA) will result in delivery errors at the runway, both in sequence and queue length. Errors in forecasting the departure rate of the runway will also produce errors in the planned queue length. In most cases, the SRP-imposed gate delays will be small enough that flight operators may plan to depart at the scheduled time and then incur the short delay

prior to pushback. The gate delays are also intended to be short enough that they will not delay the next arrival to that gate. If a flight will not be ready at its scheduled time, the SARDA concept requires that the flight operator provide an updated time at which the flight will be ready. If SARDA schedules a flight to pushback that is not ready, that could result in less demand at the runway than planned and possibly waste runway capacity. As uncertainty in departure ready times increases, the target runway queue length will also need to increase.

At airports with multiple departure runways, a single instance of the SRP, rather than a separate SRP for each runway, would allow gate release times for flights going to different runways but parked at adjacent gates to be coordinated to avoid situations in which a pushback blocks another flight and causes it to be late relative to its scheduled gate release time. SARDA does not currently model ramp operations to this level of detail, but may need to at some airports.

### *B. Runway Scheduler*

The Runway Scheduler plans the combined schedule of departures and runway crossings on a departure runway. The sequence of events, not the absolute times, is advised to the Local Controllers. This allows the timing of events to shift based on the actual movements and separations between aircraft. At an airport with mixed-use runways, arrivals are included in the RS schedule as constraints. Airport configuration planning is responsible for coordinating the arrival and departure rates over a longer time horizon to allow the TRACON can plan arrival operations accordingly. Since SARDA advisories are not presented to TRACON controllers, the arrivals are assumed to not be controllable by SARDA. Uncertainty in the arrival times may prevent SARDA from specifying where within the departure and crossing sequence the arrival operations will occur in a way that is acceptable to controllers. Since this could affect the efficiency of the departure/crossing sequence, additional research on the robustness of the SARDA runway scheduling is warranted for mixed-use runways. Some airports with dependent departure runways will likely require a single, coupled RS, rather than an independent instance of RS for each departure runway.

RS uses the same underlying runway planner as SRP, reacting to the actual locations of taxiing aircraft each time the algorithm runs. The SARDA concept is that the Local Controllers (LCs) would use RS to select the departure sequence and determine when to taxi aircraft across the departure runway. At airports with a single departure queue, the departure sequence will be fixed before the aircraft are handed off to the LC, but RS may still be used to identify the most efficient times to perform taxi crossings. An unstudied alternative would be for the Ground

Controllers to use RS to actively control aircraft taxiing in the AMA to achieve the planned sequence at the runway. While not required at an airport with multiple departure queues feeding a runway, this alternative may be required to improve departure sequences when spot crossing time alone is not sufficient.

The runway planner assumes the taxi paths are known for every flight. When multiple departure queues exist, the SARDA concept includes the option for the runway planner to select the departure queue as part of the optimization. The runway planner runs periodically, revising the RS sequence based on the current situation. To ensure feasibility, RS respects the observed sequence of aircraft on a shared taxi path. Two aircraft that are on merging taxi paths but have not yet merged will be sequenced by RS according to the efficiency of the final runway sequence and their merge. However, RS does not advise “give way to” commands that would be used by controllers to achieve the RS sequence. If two aircraft are out of sequence on a taxiway, we assumed that RS would revise the sequence to match the physical order, rather than assuming the controllers would re-route the flights to re-order them.

### *C. SARDA Benefit Mechanisms*

SARDA provides benefits through a variety of mechanisms, attributable to the two SARDA components. The amount of benefit achievable depends on the traffic, airport geometry, and current performance of ATC controllers accomplishing these same objectives manually.

SRP and RS reduce departure delays by sequencing departures to minimize spacing between departures. Sequence considerations include wake vortex separation requirements and routes of flight. Compliance with TFM restrictions may also be improved. By planning runway crossings and considering the demand for runway crossing when sequencing departures, RS reduces taxi delays resulting from runway crossings.

SRP reduces the average lengths of the departure queues. By holding aircraft at their parking gates with engines off until the appropriate time to comply with the SRP spot crossing time with minimal spot delay, SRP will achieve operating cost and environmental benefits. Reducing the number of departures taxiing also reduces surface congestion which reduces taxi delays for both departures trying to reach their assigned runways and arrivals trying to reach their parking gates. Arrivals could experience reduced taxi times at airports where long departure queues block access to ramps. In addition, the number of times each flight must stop and then start moving again – e.g., to yield to another aircraft, advance in a queue, or wait for a controller’s attention.

By reducing the length of the departure queue, SRP provides the potential for the departure sequence to better achieve flight operator objectives. For example, a flight that is late but important for business reasons will not be forced to join the end of a long departure queue but could be prioritized at the front of the virtual queue holding at the parking gates.

Airport Surface Traffic Management (ASTM) is a broad set of problems and a broad set of possible control mechanisms relating to the management of aircraft on the airport surface. SARDA does not attempt to address all of the potential ASTM functions or opportunities to optimize airport surface operations. SARDA does not set the runway configuration and does not control runway, parking gate, spot, or taxi route assignments. SARDA does not advise taxi speeds, specify required times at taxi intersections other than the spot, or specify “give way to” sequencing commands. SARDA does not affect arrivals, except for taxiing across departure runways. Other automation systems that support these ASTM functions may need to interoperate or be integrated with SARDA in a deployed architecture.

### III. SARDA MODELING

The model of NASA’s SARDA concept that was developed for this work consists of three components. In addition to models of the two SARDA components, a common Runway Planner (RP) algorithm provides the underlying runway scheduling that is used by both SRP and RS.

The Runway Planner (RP) sequencing algorithm schedules SARDA-managed runway operations (departures and runway crossings) to maximize throughput for that single runway, while operating around the spacing constraints generated by operations not managed by SARDA (arrivals and dependent-runway operations). This sequence is used by the RS, which advises ground and local controllers on sequence decisions at various points on the surface. In addition, the RP must provide estimated runway operation times that can be used by the SRP to compute departure gate and spot release times. A separate instance of RP is used for each runway planned by SARDA. At airports with dependent departure runways, a single RP will need to be capable of planning the dependent runways.

The RP algorithm used in our model of SARDA is an approximate dynamic programming algorithm built on a constrained position shift (CPS) model similar to that described by Balakrishnan and Chandran [9] [10]. CPS requires an initial natural (i.e., uncontrolled) runway sequence and states that no flight can be moved more than  $k$  positions from its position in the natural sequence, where  $k$  is a maximum position shift parameter chosen by the user.

In addition to modifying the formulation to improve computation time, the formulation relaxes the triangle inequality assumption in time-based pairwise aircraft spacing. This assumption states that for any ordered flights 1, 2, and 3, the required minimum spacing between flights 1 and 3 is no greater than the sum of the pairwise spacing requirements between flights 1 and 2 and between flights 2 and 3.

Operationally, this assumption implies that for any sequence of operations, the required spacing for a flight can be computed based only on the flight immediately preceding it in the sequence. A simple case where this assumption is violated is the case of a heavy departure followed by a runway crossing and then a small departure. The triangle inequality would imply that the small departure only needs to be spaced from the runway crossing. In reality, the small departure would likely need to take additional delay based on the required wake vortex separation from the earlier heavy departure. While the RP algorithm does not require the triangle inequality to hold in order to search for a more efficient sequence, it is only guaranteed to find the globally optimal sequence (subject to the CPS constraint) when the triangle inequality holds.

Each time the RP algorithm runs, the runway schedule is passed to the SRP and RS models. The SRP uses the scheduled runway times to compute gate and spot release times for each flight. The spot release time is computed by subtracting the unimpeded taxi time for a flight from its handoff spot to the runway entry point. An additional buffer is subtracted from that time to account for taxi time uncertainty related to surface congestion, runway crossings, and variations in taxi speed as well as uncertainty in the departure rate on the runway. At airports where the taxi time from spot to runway vary substantially, an alternative approach that models the expected congested taxi time for each flight, rather than using estimated un-delayed taxi time and a constant buffer, may provide better performance. The resulting spot release time advisory is used by ground controller model in the simulation. The gate release time is similarly computed with the additional step of subtracting the time required to push back from the gate and the unimpeded taxi time between the gate and the spot. At some airports, a prediction of the congested taxi time to the spot may be required. The resulting gate release time advisory is provided to the simulation’s ramp controller model and the flight is held at the gate until this release time.

The RS uses the final sequence of flights returned by RP. The simulated ground and local controller models could use the RS sequence to provide sequencing advisories at merge points on the airport surface. However, to better match NASA’s SARDA’s concept, in the current simulation, RS only controls the sequence of flights at the runway and is

not used during taxiing to the runway. The RS sequence is also used for clearing departures and crossings at the runway. The combined runtimes for RP, SRP, and RS are typically no more than 1 to 2 seconds per runway, which was sufficient for fast-time simulation and, therefore, further computational improvements were not required for this project.

#### IV. FAST-TIME SIMULATION

A fast-time simulation was developed for PHL, CLT, and LAX airports, capable of simulating both baseline operations and operations with NASA's SARDA concept in use. The Metroplex Simulation Environment (MSE) [11] was used as the platform for these simulations. Baseline operations at each airport modeled current-day operations – derived from data analysis and discussions with subject matter experts. In addition, models for how ramp, ground, and local controllers use information from SARDA were developed. Six traffic scenarios were generated for each airport - two 24-hour scenarios and four unique peak-period 6-hour scenarios. The scenarios were selected from periods of historical data recorded from July 2011 through June 2012. Variations in the traffic characteristics attempted to broadly challenge SARDA.

Scripts were created to run a baseline simulation and a SARDA simulation for each of the 6 traffic scenarios at each of the 3 airports. Each script called MSE with the appropriate configuration files for the airport, test condition (baseline or SARDA), and traffic scenario. Each MSE simulation run generated a set of files containing a large number of raw simulation metrics. The pair of baseline and SARDA simulation metrics files was then processed by a Matlab post-analysis tool, which automatically generated an HTML document containing a pre-defined set of graphs and tables used to visualize and compare the baseline and SARDA simulation results.

Computation time varied from 92 seconds for a 6-hour PHL scenario of baseline operations to 6 hours for a 24-hour LAX simulation of SARDA operations, using a 2.4 GHz Intel Core 2 Duo CPU. Arrivals are simulated from the arrival fixes to the parking gate, while departures are simulated from the parking gate to the departure fixes. The SARDA algorithms consist of two primary computational demands that are not present in the baseline case. The dynamic program used to compute the optimal runway schedule was solved every simulated minute. In addition, the DP requires forecast demand information, which requires running a service to predict the motion of every flight forward in time. The most significant contributor to processing time, by far, was the estimation of the demand, not the DP algorithm.

#### A. PHL Results

The primary benefit of the SARDA algorithms at PHL was the reduction in the lengths of the departure queues and the corresponding reduction in the amount of time aircraft engines were running on the airport surface. Fig. 1 compares the maximum queue lengths for runway 27L in the baseline and SARDA simulations during scenario PHL-4. The graph clearly illustrates how SARDA achieved its departure reservoir management objective, dramatically reducing the maximum queue length. SARDA reduced the average amount of time spent by each departure in a runway queue by approximately 75% (4 minutes). This equals a total savings of about 34 aircraft-hours of departure queue time per day.

SARDA achieved this benefit by holding departures at gates – average gate holding was comparable to the average queue time reduction. A side-effect was that SARDA reduced traffic congestion in the ramps; the average Departure Ramp Taxi Duration went down by approximately 1 minute per flight. SARDA also reduced the average AMA Movement Duration (i.e., the taxi time from spot to runway queue) by approximately 40 seconds, due to less traffic congestion in the AMA. While these results are averaged across the six scenarios, each scenario showed positive benefits.

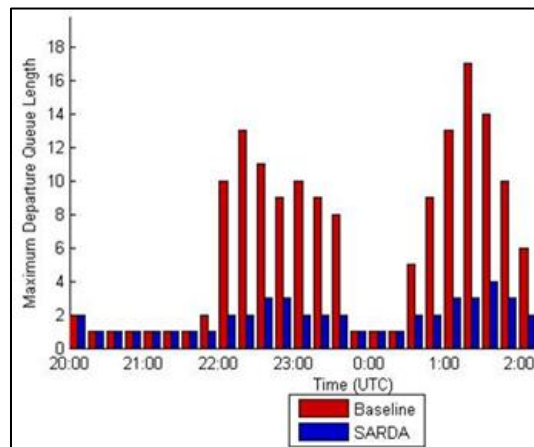


Figure 1. PHL-4 Runway 27L Departure Queue Length

While many PHL departures taxi across an active arrival runway, there are almost no crossings of a departure runway. Consequently, this SARDA concept element did not operate at PHL. However, in the Baseline simulations, some departures to runway 27L were delayed crossing runway 27R due to the departure queue filling the space between 27L and 27R. By managing the departure queue length, SARDA reduced the runway crossing delay by about 50 seconds per flight on average.

The cumulative effect of these impacts was that SARDA dramatically reduced the Departure Taxi

Time (i.e., the time aircraft engines are running on the airport surface – OUT to OFF), as shown in Table I. Scenarios 1 and 2 are the 24-hour scenarios.

TABLE I. PHL – SARDA REDUCTION IN TAXI TIME

Traffic Scenario	PHL - 1	PHL - 2	PHL - 3	PHL - 4	PHL - 5	PHL - 6
Reduction in Average Departure Taxi Time (seconds)	303	299	335	542	341	227
Reduction in Total Departure Taxi Time (minutes)	2962	3001	1268	1998	1261	776

However, due to the large gate holds applied by SARDA, the Total Surface Dwell Time was slightly higher. This metric equals the time between when the flight is ready to leave its gate and when it takes off. Departures took off about 40 seconds later in the SARDA simulations than they did in the Baseline simulations. SARDA was not able to increase the efficiency of runway operations relative to the Baseline simulations. PHL traffic consists of almost entirely Large aircraft, reducing the opportunity for departure sequence optimization and the baseline controller logic was able to construct efficient sequences with alternating directions of flight from the multiple departure queues, using a heuristic employed by human controllers.

During the SARDA simulations, some flights were delayed at their gates too long resulting in instances when there was no demand at the runway. Consequently, runways were used slightly less efficiently than in the Baseline simulations. This resulted from attempting to achieve the maximum reduction in taxi time and being too aggressive with the target queue length. SARDA plans spot crossing times and corresponding gate departure times based on forecasts of how long each flight will take to reach the runway. Similar to an operational system, the simulation does not perfectly predict these taxi times since they depend on the actual congestion encountered by the aircraft. To counter the effect of this uncertainty, SARDA applies a buffer designed to maintain constant demand at the runway. Larger uncertainty requires a larger buffer. However, a larger buffer results in a longer average departure queue length and, therefore, smaller fuel savings benefits. The existence of the uncertainty creates this tradeoff. A different point along this tradeoff would have avoided the loss of runway efficiency.

SARDA achieved a small reduction in the Total Surface Dwell Time for arrivals (measured as IN time minus ON time) in all scenarios. Flights spent an

average of 49 seconds less to reach their parking gate after landing, due to less surface congestion allowing shorter ramp and AMA taxi times. By reducing the time spent in the departure queues and runway crossing queues, as well as the level of congestion in the ramps and AMA, SARDA was able to reduce the number of taxi stops by departures (by about 70%) as well as the total duration of those stops. Taxi stops by arrivals were also reduced by a small amount, consistent across all of the scenarios. Following from the reduction in taxi times and aircraft stops, SARDA achieved substantial savings in the total fuel consumed on the airport surface, detailed in Table II. The fuel burn model is described in [12].

TABLE II. PHL – FUEL SAVINGS DUE TO SARDA

Percent Reduction in Surface Fuel Burn	PHL - 1	PHL - 2	PHL - 3	PHL - 4	PHL - 5	PHL - 6
Arrivals	18%	12%	18%	37%	30%	14%
Departures	36%	36%	36%	51%	36%	32%

### B. CLT Results

SARDA applied significant gate holds at CLT, averaging about 4 minutes per departure. SARDA modestly reduced the Departure Ramp Taxi Duration, by reducing traffic congestion. On average, departures took 47 seconds less to taxi between their gates and spots, not including spot queuing time. Spot queuing was minimal, generally caused by traffic congestion rather than SRP spot release times. SARDA reduced the average AMA Movement Duration for departures by 14 seconds. This secondary effect – that reducing the number of departures taxiing simultaneously reduces taxi times apart from queuing time – is an important SARDA benefit mechanism.

SARDA reduced the departure queue lengths dramatically. The maximum queue lengths on runways 18C and 18L were between 8 and 12 in each of the Baseline simulations. In the SARDA simulations, the maximum queue lengths on these runways were 3. As with PHL, a slightly longer target queue length would reduce the occurrences of the queue length being zero and runway capacity being lost in the SARDA simulations. As a result of managing the queue length, SARDA reduced the average Departure Queue Duration by 77% and 2.8 minutes per flight, which equals a total savings of 30 aircraft-hours of departure queue time per day. There was some variation across the scenarios, but all of the scenarios showed large benefits.

In the simulation, all of the runway 18R arrivals crossed runway 18C (a departure runway) at taxiway Sierra. However, SARDA did not provide a runway crossing benefit at CLT, possibly due to the

homogeneity of the departure weight categories and the single crossing intersection.

The cumulative effect of these impacts was that SARDA achieved a dramatic reduction in the Departure Taxi Time, shown in Table III.

TABLE III. CLT – SARDA REDUCTION IN TAXI TIME

Traffic Scenario	CLT -1	CLT -2	CLT -3	CLT -4	CLT -5	CLT -6
Reduction in Average Departure Taxi Time (seconds)	210	208	268	279	259	190
Reduction in Total Departure Taxi Time (minutes)	2370	2359	1085	1066	1055	722

CLT traffic consists of almost entirely Large aircraft, reducing the opportunity for departure sequence optimization to improve runway capacity. Since the CLT RNAV departure procedures use the same initial heading for each runway, we modeled departures as not having diverging headings available for reduced inter-departure separation. Consequently, SARDA was not able to increase the efficiency of the runway sequence relative to the Baseline simulations. Similar to PHL, during the SARDA simulations, there were occasionally brief periods of time when flights were delayed at their gates but there was no demand ready at the runway. Due to the dependency between runway 18L and arrivals to runway 23, a departure reaching 18L just a few seconds late could result in an entire departure slot being wasted. This caused a small increase in the Total Surface Dwell Time for departures. Departures took off about 16 seconds later in the SARDA simulations than they did in the Baseline simulations. This negative effect could have been avoided by using a larger uncertainty buffer to target a longer departure queue.

TABLE IV. CLT – FUEL SAVINGS DUE TO SARDA

Percent Reduction in Surface Fuel Burn	CLT -1	CLT -2	CLT -3	CLT -4	CLT -5	CLT -6
Arrivals	2%	-1%	2%	1%	2%	2%
Departures	23%	23%	28%	30%	29%	21%

By reducing the time spent in the departure queue, as well as the level of congestion in the ramps and AMA, SARDA reduced the number of taxi stops by departures (by about 75%) as well as the total duration of those stops. Taxi stops by arrivals were also reduced by a small amount in five of six scenarios. These improvements allowed SARDA to reduce the

total fuel consumed on the airport surface, detailed in Table IV.

### C. LAX Results

The total daily operation count is higher at LAX than at CLT or PHL, but LAX traffic exhibits less banking. The results for LAX exhibited large variations between the scenarios. Several of the scenarios (2, 4, and 6) exhibited less departure queuing in the Baseline simulations and, therefore, less gate holding and benefit in the SARDA simulations. The average amount of gate holding that SARDA applied varied considerably between the scenarios (Table V). Scenarios LAX-1 and LAX-2 are 24-hour simulations; the other scenarios are each 6 hours long. LAX-3 and LAX-5 were the high congestion scenarios. LAX-1 exhibited high congestion during a portion of the day.

TABLE V. LAX – GATE HOLDING

Traffic Scenario	LAX -1	LAX -2	LAX -3	LAX -4	LAX -5	LAX -6
Average SARDA Gate Hold (seconds)	186	110	248	103	230	33

In the Baseline simulations for the high congestion scenarios, some departures were blocked short of reaching their spots by traffic on the adjacent taxiway. In these scenarios, SARDA reduced this phenomenon, reducing the per-flight average ramp taxi duration by several seconds. The maximum queue length measured in a Baseline simulation was 22 aircraft. SARDA maintained the maximum queue lengths at or below 4 aircraft. As a result of managing the queue length, SARDA reduced the average Departure Queue Duration in every scenario. The magnitude of the reduction varied across the scenario.

LAX operations involve considerable runway crossings; almost all arrivals must cross a departure runway. However, SARDA did not measurably improve the efficiency of runway crossing, possibly due to the sufficient performance of the controllers in the Baseline simulations. Runway crossing optimization may need to be coupled with taxi routing to take advantage of multiple crossing intersections.

The cumulative effect of these impacts was that SARDA reduced the Departure Taxi Time in the congested scenarios, but achieved less benefit in the other scenarios (Table VI).<sup>1</sup> Although LAX traffic includes a mixture of weight classes, SARDA was not able to measurably increase the efficiency of the runway sequence relative to the Baseline simulations. LAX has a single departure queue for each runway

<sup>1</sup> The LAX baseline simulations did not model the manual gate holding program currently used at LAX.

and, therefore, no opportunity to re-sequence departures at the runway. The departure sequence is formed by the order in which flights join the single queue. The limited control points – the gate and spot release times – may not have achieved the originally planned sequence. SARDA was re-run such that the planned sequence would change to match the physical aircraft order on the surface, making an analysis of compliance with the originally planned sequence difficult. The planned sequence might be better achieved if the ground controller uses the RS sequence to control aircraft during AMA taxi.

TABLE VI. LAX – SARDA REDUCTION IN TAXI TIME

Traffic Scenario	LAX - 1	LAX - 2	LAX - 3	LAX - 4	LAX - 5	LAX - 6
Reduction in Average Departure Taxi Time (seconds)	151	42	268	48	220	2
Reduction in Total Departure Taxi Time (minutes)	2189	606	1425	205	1172	6

In four scenarios, flights took off slightly later on average in the SARDA simulation than they did in the Baseline simulation, resulting from small gaps in demand at the runway due to over-ambitious gate holding and uncertainty in taxi times and runway throughput. In one scenario (LAX-3), flights took off slightly earlier in the SARDA simulation than in the Baseline simulation. In the other high congestion scenario (LAX-5) the Total Surface Dwell Time was the same in the SARDA and Baseline simulations.

In the Baseline simulations of the high congestion scenarios, some arrivals experienced large taxi delays because the long departure queues blocked them from reaching their gates. SARDA reduced the average Arrival AMA Taxi Duration in these scenarios by approximately 90 seconds per flight.

TABLE VII. LAX – FUEL SAVINGS DUE TO SARDA

Percent Reduction in Surface Fuel Burn	LAX - 1	LAX - 2	LAX - 3	LAX - 4	LAX - 5	LAX - 6
Arrivals	-1%	-1%	17%	0%	14%	0%
Departures	16%	6%	25%	8%	22%	1%

By reducing the time spent in the departure queue, as well as the level of congestion in the AMA, SARDA reduced the number and duration of taxi stops. SARDA had the largest impact on the high congestion scenarios, where arrival taxi stops were also reduced. SARDA achieved savings in the total

fuel consumed on the airport surface, detailed in Table VII. Benefits vary across the scenarios.

## V. HUMAN FACTORS STUDY

A human factors evaluation of SARDA at the three airports was conducted in parallel with the fast-time simulation experiment. The goal was to provide an independent evaluation of the SARDA operational concept at the three airports, identifying issues that might not be observed through the simulations. The results of the assessment will inform future development of the SARDA concept and refinement of SARDA algorithms. The assessment was not intended to evaluate existing SARDA algorithms or user interfaces.

The HF assessment took the form of structured interviews with retired air traffic controllers knowledgeable with the airports. Five of six participants were retired Tower controllers from one of the study airports. The sixth participant was a retired controller from Orlando International Airport (MCO) who has contributed to a variety of FAA and NASA research on new automation concepts. Structured interviews are particularly helpful in the concept exploration phase of technology development as they create contexts in which practitioner experts can explore the concepts before they are ready for field evaluation.

Participants’ reception of the SARDA concept was mixed. All participants spoke favorably about the concept and its ability to support efficient airport operations. However, the participants also pointed out cases in which controllers routinely adapt and they believed would be difficult for the computer to predict and quickly provide a solution that was as effective as those currently used by controllers. SARDA will need to match controller performance and reduce workload in the presence of “unusual” situations that are actually routine in surface traffic management. During normal operations, controllers currently are able to construct efficient departure sequences at the runway. SARDA must be able to match this performance in a way that is acceptable to controllers and enable efficient sequences during off-nominal conditions, which is when the number of constraints and their dynamic nature make maintaining efficient runway sequences difficult for controllers to accomplish manually.

Airport geometry and standard operating procedures dictate when and where ground controllers begin sequencing aircraft and when they hand off aircraft to local control. In addition, whether or not the sequence is final when handed to local control differs between airports. This study found that SARDA may need to recommend an efficient departure sequence to the ground controller before aircraft leave the ramp area and adapt to the available



controllability to achieve the planned sequence, which will vary in different situations and at different airports. In some cases, the queues that form in the ramp must be sequenced efficiently, requiring ramp participation. These differences between airports create a requirement for the SARDA concept to be flexible in how it accomplishes a common objective.

The participants identified requirements for how SARDA will need to react to uncertainty. For example, when two aircraft are out of order on a taxiway, SARDA should re-plan the sequence to accommodate the relative location of the aircraft in some situations and should expect the controllers to assign new taxi routes that will achieve the original SARDA-planned sequence in other situations. Participants commented that some TFM restrictions are not currently available when the current SARDA concept wants to know that data.

The concept of gate holding flights was familiar at all of the airports, although only LAX routinely uses the practice in current operations. Controllers expressed a concern that gate holding may require arrivals to be held in the AMA because their gates were occupied and that this would increase AMA congestion and controller workload and be unacceptable to flight operators. Controllers were concerned that spot holding would lead to ramp congestion and workload increases if arrivals need to be held in the AMA due to the spot being blocked. Controllers were unsure that “ready to push” times could be predicted accurately enough to plan gate/spot holding in advance of the pilot’s ready to push call. The concept should be expanded to enable aircraft to be held in holding areas in the AMA when longer delays are required. All of the requirements for the concept and algorithm identified through the HF study can be met within the current SARDA framework.

## VI. CONCLUSION

A fast-time simulation was developed for PHL, CLT, and LAX airports, capable of simulating both baseline operations and operations with NASA’s SARDA concept in use. Six traffic scenarios were simulated at each airport and metrics detailing the differences between the SARDA and baseline operations analyzed. To complement the fast-time simulations, structured interviews were conducted with retired air traffic controllers. This human factors experiment identified issues not observable through the simulations, focusing on additional concept elements and algorithmic requirements that might be required to accommodate off-nominal situations.

Results supported the conclusion that SARDA provides substantial benefits at all three airports, without significant modifications to the SARDA concept from DFW. SARDA benefits were fairly consistent at PHL and CLT, but varied considerably

with the traffic scenario at LAX. SARDA benefits were from reductions in departure queue length and reduction in surface congestion due to departure reservoir metering. SARDA reduced the amount of time aircraft spent with their engines running, the number of times aircraft had to stop/start, and the fuel consumed on the airport surface. Benefits from SARDA improving runway crossing efficiency or from improving departure runway sequence efficiency were not observed at any of the airports.

At PHL, the presence of multiple departure queues allowed the local controller in the baseline simulation to select an efficient departure sequence. At CTL, uniform weight class traffic and no diverging heading departure procedures did not afford an opportunity to optimize the runway sequence. At LAX, controlling the departure sequence only through the gate and spot release times resulted in poor control over the final departure sequence. Unlike DFW, LAX and CLT have single departure queues which freeze the final sequence earlier during aircraft taxi.

These results broaden the scope of NASA’s SARDA research and demonstrate its applicability, with minor extensions, to airports beyond DFW. The applicability of SARDA at these three airports and the diversity in their operational characteristics and surface geometries suggest a generalized SARDA implementation could operate and provide benefit at any busy airport.

### A. Observation

Observations from the simulation and HF experiments motivated potential new requirements to address unique situations at some airports. For example, the runway planner underlying SRP and RS assumes that the runway assignment is known. At some airports, the runway assignment may be flexible and not selected until the flight enters the AMA. For example, some departures at PHL are initially assigned to depart runway 35 at Kilo. If the flight refuses this intersection departure, which many departures do after taxi commences, then the flight will be assigned to runway 27L. At these airports, the potential reduction in the departure queue length may be less, due to the uncertainty in runway assignments and the need to ensure sufficient demand at each runway. SARDA will need to adapt the target queue length depending on the level of uncertainty.

In the current implementation of the SARDA concept, the gate and spot release times are calculated without detailed consideration of aircraft movements in the ramp area. At some airports, there may be a need to ensure that the gate release schedule appropriately spaces push backs from adjacent gates that would block one another. If taxi times between gates and spots vary significantly, SARDA may need to model the congested taxi time on a flight-by-flight

basis. At some airports, RS and SRP may need to operate across all of the departure runways, rather than treating each runway independently. At airports where spots are shared by arrivals and departures, SARDA's planning of spot crossing times may need to also consider arrivals to avoid conflicts.

### B. Future Work

The human factors evaluation performed in this work and prior NASA work focused on air traffic control perspectives and did not consider the operational acceptability of gate and spot controlled times to the flight operators. At many airports, the control to achieve the spot release times and sequences efficiently must be accomplished by the flight operators' ramp controllers. Consequently, flight operators must be included in future research, both to ensure they will be able to provide accurate departure demand data to SARDA and to ensure they will be willing and able to comply with SARDA advisories. NASA is currently performing research to study this aspect of SARDA.

The SARDA benefits and acceptability will likely vary with the quality of the departure demand data (e.g., when departures will be ready to block out) that is available to the algorithms. A sensitivity analysis of SARDA's behavior and performance to the quality of data and variability in surface operations is planned as future work. Studies are needed to demonstrate the SARDA concept can operate across runway configuration changes and identify new algorithm requirements.

The fast-time simulations in this work did not consider traffic scenarios with traffic flow management restrictions. Future work should simulate SARDA in the presence of TFM disruptions. Dynamic TFM restrictions (e.g., fixes closing, Miles-in-Trail restrictions changing, APREQ release times being assigned after taxi starts) create a challenge for SARDA. SARDA needs to be able to adapt and provide a longer departure queue when uncertainty is higher. In addition, SARDA must ensure flights do not receive double penalties. If a departure is delayed due to a traffic management initiative, that delay must be considered when SARDA is calculating gate delays to avoid the flight being unfairly delayed twice.

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## AUTHOR BIOGRAPHIES

**Stephen Atkins** received his Ph.D. in Aeronautics and Astronautics from the Massachusetts Institute of Technology, Cambridge, MA, USA.

**Brian Capozzi** received his Ph.D. in Aeronautics and Astronautics from the University of Washington, Seattle, WA, USA.

**Andrew Churchill** received his Ph.D. in Civil Engineering from the University of Maryland, College Park, MD, USA.

**Alicia Fernandes** received her Ph.D. in Cognitive Systems Engineering from Ohio State University, Columbus, OH, USA.

**Chris Provan** received his M.S. in Operations Research from Cornell University, Ithaca, NY, USA.