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Evaluation of Pushback Decision-Support Tool Concept for Charlotte Douglas International Airport Ramp Operations

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***Abstract*—This paper proposes a new departure pushback decision-support tool (DST) for airport ramp-tower controllers. It is based on NASA's Spot and Runway Departure Advisor (SARDA) collaborative decision-making concept, except with the modification that the gate releases now are controlled by tactical pushback (or gate-hold) advisories instead of strategic pre-assignments of target pushback times to individual departure flights. The proposed ramp DST relies on data exchange with the airport traffic control tower (ATCT) to coordinate pushbacks with the ATCT's flow-management intentions under current operational constraints, such as Traffic Management Initiative constraints. Airlines would benefit in reduced taxi delay and fuel burn. The concept was evaluated in a human-in-the-loop simulation experiment with current ramp-tower controllers at the Charlotte Douglas International Airport as participants. The results showed that the tool helped reduce taxi time by one minute per flight and overall departure flight fuel consumption by 10-12% without reducing runway throughput. Expect Departure Clearance Time (EDCT) conformance also was improved when advisories were provided. These benefits were attained without increasing the ramp-tower controllers' workload. Additionally, the advisories reduced the ATCT controllers' workload.**

I. INTRODUCTION

A. Background

Airport *ramps*, also called *aprons* or *non-movement areas,* are the areas outside taxiways and runways used for airplane parking, loading/unloading, refueling, and maintenance. In U.S. airports, Federal Aviation Administration (FAA) controllers are not responsible for traffic movements in non-movement areas [1]. To ensure safety and efficiency in ramp areas, many large hub airports in the United States have *ramp towers* operated by airlines, airports, or third-party companies. Controllers in the ramp towers oversee aircraft traffic in the ramp areas, including departure pushbacks from the gates. Since ramp towers are not a part of the FAA's operations, their controllers may not be receiving the latest traffic and planning information from the FAA. Likewise, controllers at the FAA airport traffic control tower (*ATCT* or, simply, *tower* in this paper) may not be aware of activities in the ramp areas.

Currently, ramp-tower controllers, or *ramp controllers*, push departures off the gate on a first come, first served basis. However, pushing back departures and having their engines started too early may result in inefficient operations if the flight has a known delay. The proposed ramp controller decision-support tool (DST) will provide the ramp controllers pushback or gate-hold advisories for individual departures. The advisories are coordinated with ATCT operations by taking the ATCT's operational constraints into account, such as taxiway congestion, runway-queue lengths, and Traffic Management Initiative (TMI) constraints (e.g., miles in trail, or MIT). This new ramp controller DST is a modification of NASA's original Spot and Runway Departure Advisor (SARDA) concept. It was adapted for use by the ramp controllers at the Charlotte Douglas International Airport (CLT), and it is hereinafter referred to as *SARDA-CLT* to differentiate it from the two previous SARDA concept variants described later.

All SARDA concepts meter departures so that a part of their taxi delay is shifted to the gate, where the aircraft can wait with its engines turned off. Note that this approach may not necessarily reduce the total departure delay (i.e., the delay between pushback-ready and takeoff) if the runway throughput level stays the same. However, the taxi delay (i.e., the delay between engine-start and takeoff) may be reduced by shifting the wait time to the gate. Thus, fuel savings are one of the expected benefits of the tool. Reduced fuel burn also should decrease the airport's environmental footprint. In addition, departure metering is expected to lower the traffic level on the airport surface, and, thus, may help relieve the ramp and tower controllers' workload. Lastly, coordinated pushbacks, reduced taxi time, and a less-congested airport surface may in concert allow more flights to conform to their assigned takeoff time, such as Expect Departure Clearance Time (*EDCT*), with higher precision, or, in general, for all departures to achieve better takeoff time predictability. The last benefit offers the FAA and airlines the potential to improve the precision of traffic-flow planning in the National Airspace System.

B. Previous Works: SARDA-DFW and SARDA-CDM

The SARDA concept was initially developed as a tower controller DST for the Dallas/Fort Worth International Airport (DFW) ATCT (*SARDA-DFW*) [2-4]. SARDA-DFW provides runway usage advisories to the Local controller and spot-release advisories to the Ground controller. (A *spot* is a point located between the ramp and the movement area.) The SARDA-DFW concept was demonstrated and evaluated in human-in-the-loop simulations with retired DFW tower controller participants in 2010 [2] and 2012 [3-4]. The results of the 2012 experiment showed that, for departures, the SARDA advisories reduced taxi delay by 60% and fuel burn by 33% on average in heavy traffic scenarios [3]. The advisories also reduced the tower controllers' workload levels [4].

Although the results appeared promising, managing the ramp traffic was outside of the focus of those studies. Thus, the ramp operations were not simulated realistically (e.g., airplanes were automatically pushed back at the ideal moment and were allowed to pass through other traffic). With more realistic uncertainties and ramp traffic movements, the benefits might be reduced. Put differently, to realize the maximum benefits, good coordination among the ATCT, the ramp, and airlines would be necessary.

To address this gap, the SARDA Collaborative Decision Making concept (*SARDA-CDM*) was developed and published [5]. It requires data exchange between the ATCT and the ramp tower and assigns airlines a target pushback time and a target spot-release time window for each departure flight *x* hours ahead of time (the look-ahead period, *x*, should be tailored for each airport). Each flight is expected to push back as close to the target time as possible, and arrive at the spot within the assigned time window. These pre-assignments add strategic planning components to the traffic flow control, whereas the SARDA-DFW's tower controller advisories manage the tactical aspect.

Table I shows a comparison of the SARDA concept variants. *SARDA-CLT* is also listed for comparison and is explained in a later section. All three SARDA concepts use a common scheduler algorithm, the Spot Release Planner (SRP).

TABLE I. COMPARISON OF SARDA CONCEPT VARIANTS

	Ramp		Movement Area		
	Target pushback time assigned to airlines	**Pushback advisory for ramp controller**	**Target spot-release time window assigned to airlines**	**Spot-release advisory for Ground**	**Runway usage advisory for Local**
SARDA	**Strategic**	**Tactical**	**Strategic**	**Tactical**	**Tactical**
DFW	(Ideal pushback)	-	-	√	√
CDM	√	-	√	√	√
CLT	-	√	-	-	-

C. Other Ramp-Related Studies

As described in the next section, the present paper primarily focuses on the ramp operations, which often were overlooked in previous studies. However, implicitly, ramp operations have been included in past CDM and departure-management studies if their concept involved any form of pushback management.

Some of the departure management concepts meter flights at the entrance point to the movement area rather than at the gates. Ramp controllers must use their discretion to decide when to push back each aircraft to comply with the metering requirements, such as Target Movement Area Entry Time or the count of departures that are allowed to enter the movement area within a specific time window. Thus, this is an indirect way to manage pushback times. The Saab Sensis's Ground Management Program (GMP), currently used at John F. Kennedy International Airport (JFK) [6-7]; the FAA's Collaborative Departure Queue Management (CDQM) concept, tested at Memphis International Airport [8]; the FAA's Collaborative Departure Scheduling (CDS) concept [9]; and the FAA's latest airport surface CDM concept [10] all manage pushbacks in this manner.

Another type of departure management concept meters the departure flights at their gates. This approach is effective if the goal is to minimize the flights' engine-on time. The original departure CDM tool for JFK, developed by PASSUR Aerospace [11]; Europe's Airport CDM (A-CDM), being used at several European airports [12]; and Massachusetts Institute of Technology's Pushback Rate Control, tested at Boston Logan International Airport (BOS) [13-14], directly meter pushbacks. In JFK's CDM tool and the A-CDM, pilots are assigned a specific target pushback time, which is the time they are supposed to call the ramp controller. In the Pushback Rate Control, the current target release rate is provided to the gate controller located in the ATCT without specifying which aircraft is to be pushed.

D. SARDA-CLT for New Ramp Controller DST

This section describes the SARDA-CLT concept, the subject of the present study. With collaboration from American Airlines (formerly, US Airways) at CLT, SARDA-CLT was developed to adapt to their use in the ramp tower.

Three factors influenced the formation of SARDA-CLT from SARDA-CDM. First, SARDA-CLT was developed as a DST for the ramp controllers, and, therefore, the SARDA-CDM's tower controller advisory capabilities for the Ground and Local controllers were disabled (see Table I, the last two columns). The tool still was assumed to receive sufficient data via the FAA's data network to ensure coordinated pushbacks with the ATCT. An interesting question that arises here is how much benefit a ramp-tower DST alone can achieve by indirectly controlling the movement-area traffic only through pushback metering. If a reasonable level of benefit is achievable without a tower implementation, the ramp-only implementation could be an attractive alternative. To answer the question, later in this paper, the results of the present study's human-in-the-loop simulation are compared with the results of a previous fast-time numerical simulation study.

Second, CLT is one of American Airlines' major hub airports, where over 85% of the traffic is American Airlines flights. Since there is little concern regarding equitability and adverse gaming behaviors from airlines (e.g., requesting pushback even before the flight is ready just to secure a slot), target pushback time and spot-release time window constraints on the airlines were removed. While removal of the pre-conditioning of pushback orders may result in failure to achieve the theoretical best benefit level for the given set of scheduled departures, dropping these constraints makes it easier for American Airlines to adapt to SARDA-CLT in the future. Hence, SARDA-CDM's strategic components (the first and third columns in Table I) were replaced with tactical pushback advisories for ramp controllers (the second column). In addition, SARDA-CLT complies with American Airlines' current policy that, when any OA flight requests pushback, it should be approved immediately, barring any safety issues.

Third, American Airlines requested that the tool provide a pushback or gate-hold advisory at the moment the pilot calls to request a pushback, without the controllers' need to input to the SARDA scheduler which flight just called each time. This addresses controllers' workload issues when multiple aircraft call. This request, however, forced the pushback advisories to act like a simple pushback rate control, i.e., departures that had similar pushback times, the same fix, etc., showed the same pushback advisory, and all advisories were updated each time a new pushback was issued. Still, unlike in a pure rate-control scheme, flights with MIT or EDCT constraints could be advised to hold a little longer than others to wait for the next slot. Also, if a slot suddenly opened up, some gate-hold time advisories might jump down to a shorter hold time to take advantage of it.

The SARDA-CLT's scheduler, the Spot Release Planner (SRP), works as follows [15-16]. The scheduler takes as input the current snapshot of the airport, aircraft-specific parameters, separation constraints, scheduled pushback times, and scheduled arrival times for the aircraft in the next 15 minutes. Then, the departures are divided into five groups: (a) *scheduled_out* (aircraft whose scheduled pushback time is within 15 minutes, but pilot has not called for pushback), (b) *pushback_hold* (pilot has called for pushback, but controller has put the aircraft on hold), (c) *pushback_approved* (controller has approved its pushback, but aircraft has no surveillance-radar hits, yet), (d) *taxi_out* (aircraft with taxi approval and under surveillance), and (e) *unknown*. The arrivals are divided into four groups: (a) *scheduled_on* (aircraft scheduled within the 15-minute planning window, but not visible on radar), (b) *airborne* (on final with surveillance), (c) *taxi_in* (on airport surface and has not reached gate), and (d) *unknown*.

Next, the taxi estimator module calculates the relevant runway, unimpeded queue-entry time, and runway-crossing queue entry time for each aircraft. The scheduler also computes the required separation between each pair of departing aircraft. This consists of separation in either time or distance, and takes into account the most restrictive separation as the required value. The separation criteria consider the wake vortex separation, separation between aircraft going to the same fix, MIT separations, converging-runway separation, Arrival Departure Window for nonintersecting converging-runway separation, takeoff-landing mixed-use runway separation, crossing-takeoff separation, crossing-landing separation, and parallel runway separation. The nine previously mentioned groups of aircraft, along with the separation requirements, are passed to a runway scheduler that calculates the best runway usage schedule for arrivals and departures.

The runway scheduling problem can be solved for multiple objectives, including throughput (runway usage time for the last aircraft) and system delay (total delay for all aircraft). The runway scheduler for the simulation was implemented as a Mixed Integer Linear Program (MILP) and solved for optimal system delay using the commercial solver, Gurobi [17]. The scheduled_out departures were not considered in the MILP planner. Once the MILP provides an optimal runway sequence, scheduled_out aircraft are assigned to empty slots, provided the assignment does not cause a change in the time for the other aircraft following the inserted aircraft.

After the runway scheduler optimizes the takeoff time for each departure, the pushback estimator module calculates the required pushback time for each aircraft. Departures that will cause a gate conflict with incoming aircraft are given a higher priority in pushback slot.

The scheduler receives an updated airport condition snapshot every 10 seconds, which is then used to recalculate the schedule. A two-minute *freeze horizon* is implemented to increase the stability of the advisories. That is, for the flights held at the gate with an advised gate-hold time of two minutes or shorter, the hold time can no longer increase but only decrease.

Furthermore, the scheduler also provides a suggestion for possible use of a *Mike-Charlie* (MC) taxiway bypass route for arrivals (the thick solid magenta lines in Fig. 1). Note that the MC-bypass advisory component is unique to the CLT ramp application. This bypass sends arrivals back to the ATCT control from ramp; thus, it requires additional coordination with the ATCT. The purpose of the advisory is to assist resolving the major bottleneck of ramp traffic around the *single-lane* area, a narrow corridor between Spots 8 and 12, which allows only a single direction of traffic at a time (the thin, dotted blue line in Fig. 1). A set of fuzzy control rules is used to select which arrival to suggest a MC bypass.

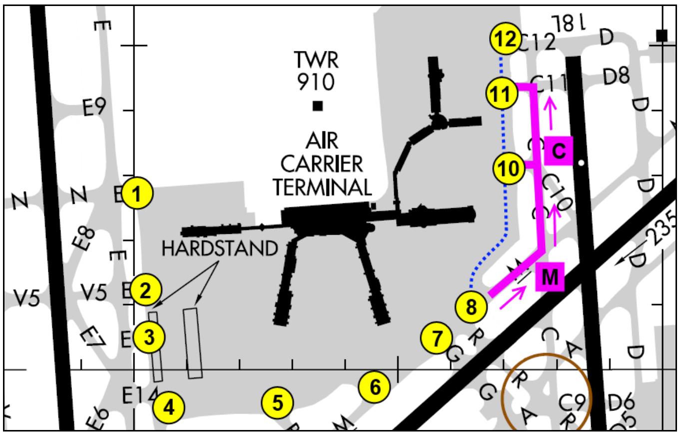

Figure 1. CLT airport ramp. (The MC taxiway bypass is shown in thick solid magenta lines. Yellow circles with a number are spots. The dotted, thin blue line between Spots 8 and 12 depicts the *single lane*.)

II. METHODS

A. Simulation Facility

The ramp-tower simulation study was conducted at the NASA Ames FutureFlight Central (FFC) facility. The two-story FFC facility hosted tower controller and pseudo-pilot stations on the first floor, and ramp controllers on the second floor (Fig. 2), where a 360-degree out-the-window (OTW) visual system was provided by the MaxSim system. Voice radio communication systems were supplied by SimPhonics.

Figure 2. Ramp tower simulator at NASA FutureFlight Central.

Upstairs, the space was set up to support a Ramp Manager (RM) station and four ramp sector controller stations: from left to right, RM, North, East, South, and West ramp controllers (Fig. 2). The four ramp controller participants used a surface radar display, Ramp Traffic Console (see the next section), and the OTW visual to survey and control traffic. The researcher station, shown in the foreground in Fig. 2, was used to initiate system startup, monitoring, and data recording.

The space on the first floor of the FFC was configured to support three tower controllers (Local East, Local Center, and Ground) and nine pseudo pilots. Six of the pilots controlled aircraft in the ramp area, while the remaining three pilots provided control in the movement area. The airport traffic was simulated using Surface Decision Support System (SDSS) software developed by Mosaic ATM, Inc., and Airspace Traffic Generator (ATG) software developed in-house at NASA, each of which also provided user interface for the tower controllers (SDSS) and the pseudo pilots (ATG), respectively.

B. Ramp Traffic Console

The paper strip system currently used at the CLT ramp tower is not compatible with the SARDA-CLT concept, as the concept requires the capability to show real-time updates of the advisories to the controller. Thus, the SARDA team developed a new electronic display, the Ramp Traffic Console (RTC). This Java-based user interface software displays virtual strips on a 27-inch touchscreen monitor (Fig. 3). Each sector controller was provided with one RTC display.

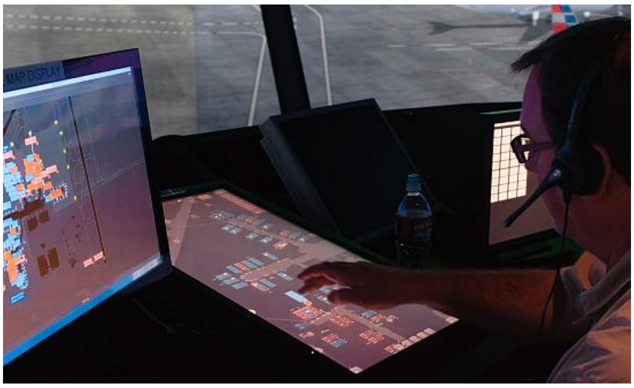

Figure 3. Ramp controller interacting with the RTC.

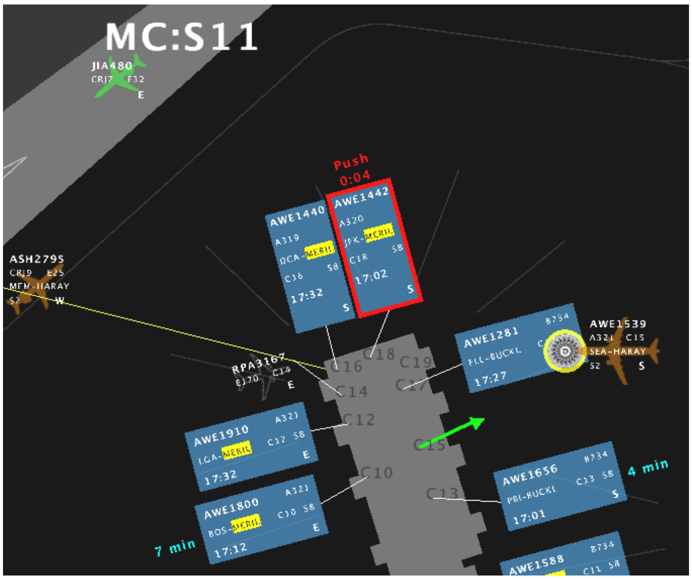

Figure 4. RTC screenshot.

On the RTC, rectangular virtual strips are shown on a map graphic. See Fig. 4 for an example screenshot. The virtual strips are movable and rotatable, just like the physical paper strips. Unlike the paper strip system, the RTC map can be zoomed in and out by using a two-finger pinch action and can be dragged around to show different viewpoints of the airport. The RTC also incorporates aircraft radar position readings on the same map view, eliminating the need to frequently crosscheck the separate radar display. On the RTC, radar-acquired target positions are depicted as a filled airplane icon, clearly distinguished from the virtual strips.

SARDA-CLT's tactical pushback advisories are displayed next to the departure strip in cyan color. For instance, if it says "7 min" (as shown at gate C10 in Fig. 4), a gate hold for seven minutes would be advised *if* the pilot requests a pushback now (note that the pilot has not requested it yet). For a flight currently being held, the RTC displays a countdown timer, which reaches "0:00" at the advised pushback time to assist the controller with timing the pushback approval. After passing the advised pushback time, a count-up timer is shown along with the pulsing text "Push" (shown at gate C18 in Fig. 4) to warn the controller. Flights currently being held at the gate also are marked with red outlines for additional saliency.

Furthermore, the controller's actions are used to inform the scheduler of the controller's traffic-management actions and intentions. For example, when the controller verbally issues a pushback approval to a pilot, the controller slides the flight's virtual strip away from the gate, which puts the virtual strip in a pushed-back state (in Fig. 4, marked with a yellow circle icon, shown next to the aircraft icon near gate C15) and, at the same time, signals to the scheduler that the pilot now has been instructed to push back. On the RTC, the ramp controller also can indicate a gate hold, spot change, hold in a hardstand, or MC-bypass request. The more information the controller inputs into the RTC, the more accurate the scheduler's prediction will become.

C. *Traffic Scenarios*

Two one-hour-long scenarios, labeled *Scenario 1* and *Scenario 2*, were created to mimic the traffic at CLT on the date of May 16, 2013. That date had clear weather, a *South-flow* configuration, and a distinct arrival and departure traffic profile with minimal overlapping. In South flow, departures used runways 18L and 18C, and arrivals used runways 18R and 23. The scenarios included a departure push followed by an arrival push, and were compressed slightly in time to fit all traffic into the hour-long test duration and create some overlap in the departure and arrival push. Fig. 5 shows the traffic demand for each scenario. Both scenarios were designed to model current-day heavy operations at CLT. Scenario 1 had 96 departures and 80 arrivals, whereas Scenario 2 had 84 departures and 72 arrivals. Fig. 5 shows that Scenario 1 had greater overlap between departure and arrival push. There was no planned gate-conflict situation in either scenario; yet, a delayed pushback still could have caused a new gate conflict with an arrival. General aviation, military, and cargo aircraft were not included in the scenario, since their impacts on the commercial airline operations are negligible at CLT.

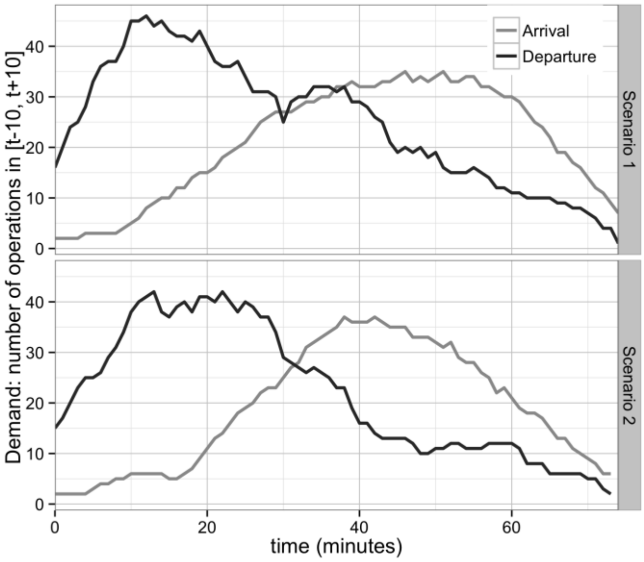

Figure 5. Aircraft counts for the two scenarios.

Scenarios were generated such that departure traffic began at the gates upon activation in the simulation, and arrival aircraft appeared about 10 nautical miles from the airport. Scenario data included the scheduled gate-out time (the time the scheduler used), as well as the actual flight-ready time, which is the time the pseudo-pilot is prompted to call the ramp controller for pushback. The scenario data files enabled us to model gate-out uncertainty in the simulation while ensuring repeatability across different runs. Similarly, the scenario data also included entries for aircraft-specific variations in pushback time, engine spool-up time, and taxiing speeds. TMI information also was stored in the scenario data. In this simulation, two types of TMIs were implemented: 1) MIT restrictions of 15 miles over the MERIL departure fix, and 2) EDCT for five aircraft in each scenario.

D. *Experiment Design*

The three-week-long experiment took place in September and October 2014. In each week, 16 data-collection runs were conducted, resulting in 48 runs total. Each week, a different pair of current CLT ramp controllers participated in the study. They alternated between East and South sectors in each run. The remaining ramp sectors (North and West) and the three tower positions (two Locals and one Ground) were staffed by confederate controller participants, and all of them stayed at the same position throughout the three weeks, except that the Ground controller was substituted by another confederate controller during Week 2. The alternating East and South ramp sector controllers created six Controller Seat assignments (i.e., two assignments per week for three weeks). The Controller Seats are important for even the confederate controllers, since performance of the same controller at the same position could be affected differently by who controls the East and South sector traffic. The RM position was staffed by a NASA researcher.

The SARDA-CLT advisories were presented in eight runs per week (*Advisory* runs), and the remaining eight runs were *Baseline* runs, where the controllers were not shown any advisories and were asked to operate traffic as they would normally. The RTC was used in both Advisory and Baseline runs. In Baseline runs only, the RTC presented a count of the active departures per each runway (the *active* departures are those that had initiated pushback but had not yet been airborne), and the ramp controllers were asked to meter the departures by targeting these counts to be 15 or smaller, to mimic the departure metering scheme currently practiced at the CLT ramp. These counts were not shown in Advisory runs, as the pushback advisories were expected to take care of the metering requirements automatically.

If a flight had an assigned EDCT, the Local controllers were asked to have it depart within a ±1-minute window or, if that was not possible, as close to the EDCT as possible. A tighter EDCT window than the one used in the current-day operations (±5-minute window) was applied in the simulation to improve takeoff time conformance and make the task more challenging to the controllers.

The MC-bypass operation required the RM to coordinate with the Ground controller via radio. In Advisory runs, a MC advisory computed by the scheduler was displayed next to the corresponding arrival aircraft symbol on the RTCs. (An example of a MC bypass going to Spot 11, “MC:S11,” is shown in Fig. 4, near the upper left corner.) Unless the East-sector controller canceled it via his/her RTC, the RM contacted the Ground controller and requested an approval to use the taxiways. Once it was approved, the RM indicated the confirmed state of the MC-bypass request via his/her RTC. This informed the East-sector controller that he/she now could send the arrival to the MC taxiways. In both Advisory and Baseline runs, any sector controller could initiate a MC-bypass request via his/her RTC; however, normally the East-sector controller handled MC-bypass operations.

Traffic performance data and scheduler performance data were recorded with time stamps. For subjective data, real-time workload ratings and questionnaire responses were collected.

For the real-time workload ratings, the ramp and tower controllers reported their workload ratings using quick hand signs at five-minute intervals when a beep sounded, and researchers recorded the ratings. The ratings used a scale of one to seven, where 1 meant very low and 7 very high. The post-run questionnaire collected the ramp controllers' workload ratings, including Mental Demand (thinking, deciding, calculating, remembering, searching, etc.); Time Pressure; Frustration (stress, annoyance, or irritation); Communication (exchanging information, discussion, negotiation, etc.); and Coordination (flow coordination, hardstand use, MC bypass, etc.). The first three ratings are a subset of the NASA Task Load Index (TLX) [18]. The last two ratings, Communication and Coordination, were added to assess the teamwork-related workload levels [19]. Additionally, the post-run questionnaire gathered responses related to usability and situation awareness from the ramp controllers. A post-study questionnaire also was administered at the end of each week to gather additional responses and feedback from the ramp controllers.

Independent variables were Advisory (Advisory vs. Baseline runs), Scenario (1 vs. 2), and Controller Seats (1 through 6). The design was 2×2×6, with two repetitions for each combination. Note that the CLT ramp controller participants were nested in each week. To reduce any learning and/or fatigue bias, the run order in each week was counterbalanced within and between the two Controller Seats corresponding to the week.

On the first day of each week, a classroom training session was provided to the two new CLT ramp controller participants, followed by hands-on training in the ramp-tower simulator. Once the new ramp controller participants were accustomed to the simulation setup, including the RTC and the traffic management tasks in each of the Advisory and Baseline runs, five to seven training runs were conducted with all of the remaining confederate-controller and pseudo-pilot participants. The training lasted until the researchers judged the participants to be ready. Then, the data-collection runs were started in the late morning of the second day and ended in the middle of the fifth day.

E. *Participants*

All six CLT ramp controllers were current at the time of the study and had been working in the CLT ramp tower for four to 25 years (Mean = 9.4 years, Standard Deviation = 7.9 years). One of the two confederate ramp controllers was a current Dallas/Ft. Worth International Airport ramp controller for the last 18 years, and the other was a retired Los Angeles International Airport tower controller with 20 years of experience in that tower and 25 years of experience in ATCTs overall. The two confederate tower controllers who staffed the two Local controller positions were retired CLT tower controllers with 30 and 20 years of experience in that tower. The two tower controllers who staffed the Ground position were both retired San Francisco International Airport (SFO) tower controllers with 20 and 16 years of experience in that tower, or 22 and 26 years of total experience, respectively, in various ATCTs. All the retired confederate controller participants had retired within the last four years, except one of the SFO tower controllers, who retired ten years ago. All the pseudo-pilot participants were either general aviation pilots or former FAA controllers recruited from the local area.

III. RESULTS

A. *Traffic Performance*

1) Departure Runway Performance: The number of aircraft that took off in a given time period was investigated to assess the departure runway performance, and no difference was found between Advisory and Baseline runs. This implies that there was no loss in runway usage caused by the SARDA's departure metering.

2) Departure Taxi Delays: Taxi delay is defined as the difference between the observed travel time and the unimpeded travel time for the same route. A taxi speed of 17 knots was used for calculating unimpeded travel times. For departure aircraft, taxi delay represents the total delay in the ramp, taxiways, and runway queues, but not at the gate. The Fig. 6 box plots show distributions of taxi delays. In Advisory runs, the variation in taxi delay was less when compared to Baseline runs, and there was a reduction in mean taxi delay in Advisory runs over all cases. Over the three weeks, the average taxi delay in Advisory runs was 346.8 seconds per aircraft (standard error, or SE = 3.8), whereas in Baseline runs, it was 403.2 seconds (SE = 4.5). This accounted for an average reduction in taxi delay of one minute per aircraft.

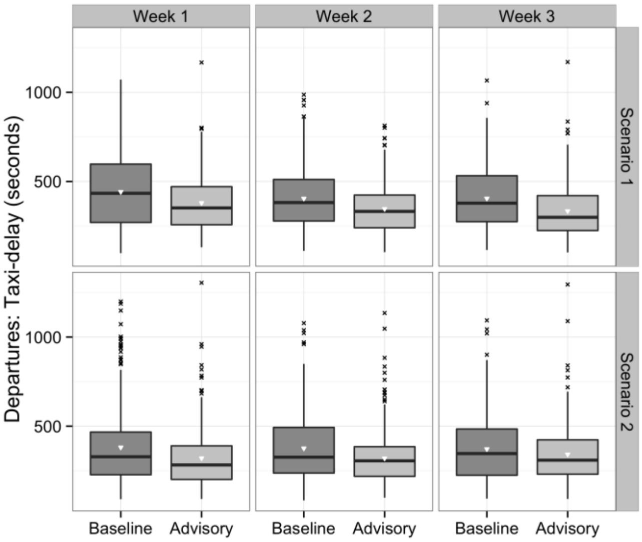

Figure 6. Departure taxi delay. (Horizontal bars indicate median, 25th, and 75th percentile; vertical whiskers show 1.5 interquartile range, or IQR; triangles show the mean.)

3) Departure Gate Delays: The gate delay is defined as the difference between the flight-ready time (the time the pseudo pilot was prompted to call the ramp controller) and the actual start of movement. Fig. 7 shows their distributions. On average, the ramp controllers held the aircraft at the gate 90 seconds longer in Advisory runs as compared to Baseline runs. Moreover, it is evident from Fig. 7 that the controllers held

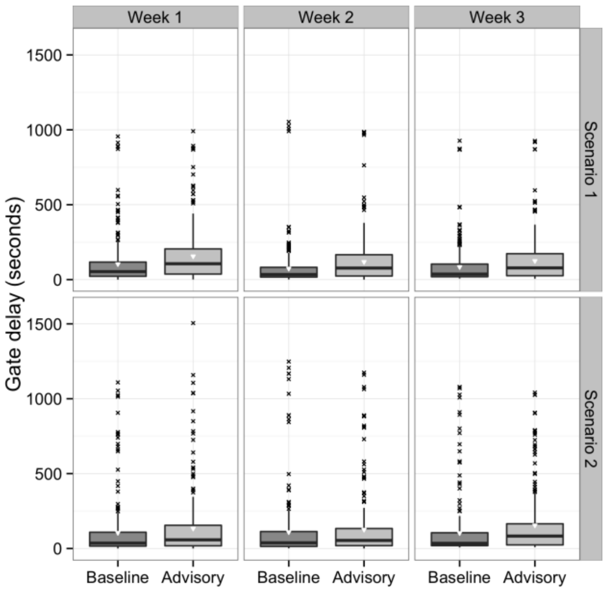

Figure 7. Gate delay for departures. (Horizontal bars show median, 25th, and 75th percentile; vertical whiskers show 1.5 IQR; triangles show the mean.)

some aircraft at the gate for a long time in Baseline runs as well, and the longest gate-hold times in Baseline and Advisory runs were roughly comparable.

4) Departure Queue Size: Fig. 8 shows the average count of departures in the movement area by simulation time. The number of departure aircraft (to both runways 18L and 18C) was lower in Advisory runs than in Baseline runs. The lower number of departures in the movement area was one of the expected benefits of SARDA metering.

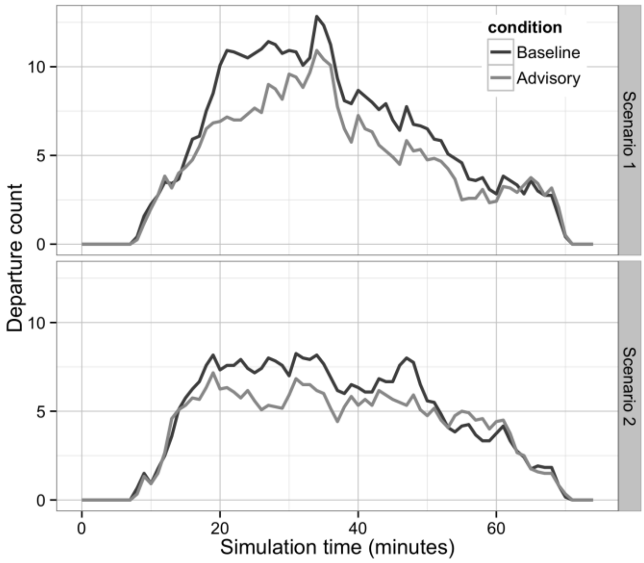

Figure 8. Number of departures in the movement area as a function of simulation time.

5) Total Delay: The total delay of departure is the overall delay experienced by the aircraft at the gate, the ramp, taxiways, and the runway queue. This delay is defined as the observed takeoff time minus the unimpeded takeoff time given the scheduled pushback time. In Baseline runs, the mean total delay was 500.2 seconds (SE = 5.8), and Advisory runs had a mean of 529.0 seconds (SE = 6.6). The total delay is about 30 seconds longer in Advisory runs than in Baseline runs, suggesting something did not work as intended.

The above results were derived taking all departure aircraft in the scenario into account, including the departures to the MERIL fix with the 15 MIT restrictions. In both scenarios, a few other-airlines (OA) flights were routed through MERIL. Since it was the American Airlines policy not to include the OA flights in the departure metering, these OA flights to MERIL were released as soon as they called. This interfered with the planning in the other sectors' MERIL departures and increased the total delay. If all the aircraft with MIT restrictions were removed from the calculations, Baseline runs resulted in an average total departure delay of 440.8 seconds (SE = 5.1), whereas the average in Advisory runs was 446.8 seconds (SE = 5.2). The results now appear comparable to each other.

6) Fuel Burn and Emissions: The amounts of fuel consumption and gas emissions were estimated by using the engine emission certification data from the International Civil Aviation Organization (ICAO) [20]. It was assumed that two engines were running at a standard thrust setting of 7% during the taxi phase of a flight, whereas they were turned off when the aircraft was being held at the gate. Table II lists the average fuel use and emissions per run and their reductions observed in Advisory runs. The reduction percentage was calculated relative to the Baseline average.

TABLE II. FUEL BURN AND EMISSIONS FOR DEPARTURES (KG/RUN)

Scenario	Advisory	Fuel	HC	CO	NOx
1	Baseline	11124.30	36.21	449.11	80.43
	Advisory	9789.58	31.89	395.52	70.80
	Reduction (%)	1334.72 (12.0%)	4.32 (11.9%)	53.59 (11.9%)	9.63 (12.0%)
2	Baseline	10113.50	31.50	399.95	75.05
	Advisory	9066.72	28.54	360.56	67.08
	Reduction (%)	1046.78 (10.4%)	2.96 (9.4%)	39.39 (9.9%)	7.97 (10.6%)

7) EDCT Conformance: Each scenario included five departures that had an assigned EDCT. To examine the conformance, the observed takeoff time (the time the aircraft started takeoff roll) was compared to the assigned EDCT. Fig. 9 shows the distribution of EDCT deviations aggregated over all Baseline runs (top) and all Advisory runs (bottom). The histograms show that Advisory runs resulted in a tighter distribution around the zero EDCT deviation than Baseline runs. The controllers were able to adhere to the EDCT constraints more precisely in Advisory runs. In Baseline runs, a few aircraft were delayed by up to five minutes. (Note that the Local controllers were asked to release EDCT departures within a ±1-minute window in this simulation, rather than the ±5-minute window used in the real operations.) In both

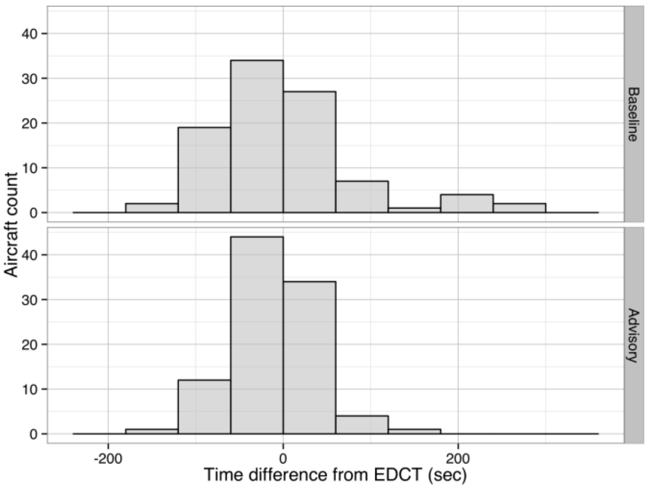

Figure 9. Histogram of take-off time deviation from EDCT in Baseline runs (top) and Advisory runs (bottom).

Baseline and Advisory runs, the controllers released some flights two minutes prior to the EDCT, though they did so more frequently in Baseline runs.

B. *Subjective Data Analysis Results*

The real-time workload ratings and numerical responses to the post-run questionnaire were subjected to linear mixed-models (LMMs) repeated-measures analysis [21]. Human participants' subjective ratings may be influenced by additional factors. To account for these influences in the model fitting, two new effects were generated. These are listed in Table III.

TABLE III. NEW EFFECTS FOR SUBJECTIVE-DATA ANALYSIS

New Effect	Descriptions
Run Block (1-4)	This effect represents the chronological order of the runs in each week. The effect may capture participants' learning or fatigue trends, if any. The first four runs in each week were labeled 1, the second four runs were 2, the third four runs were 3, and the last four runs were 4.
Phase (1-4)	Phase effect was relevant only to the real-time workload ratings. The effect mainly accounts for the influence from traffic volume changes within a single run. The ratings recorded in the first 15 minutes in a run were labeled 1, the second 15 minutes were 2, the third 15 minutes were 3, and the last 15 minutes were 4.

The data from the CLT ramp controllers, the confederate ramp controllers, and the tower controllers were analyzed separately, since their models were slightly different. Table IV lists the main effects included in the three models. In addition, two-way interaction effects that involved Advisory effect (e.g., *Advisory* × Scenario, *Advisory* × Sector) also were included in each model to assess the advisories' secondary effects on the other effects.

TABLE IV. MAIN EFFECTS FOR LINEAR MIXED-MODEL FORMULATION

Main Effects Common in the Three Models		
• Advisory (Advisory vs. Baseline) • Scenario (1 vs. 2) • Run Block (1-4) • Phase (1-4) – real-time workload rating models only		
Additional Main Effects		
CLT Ramp Controllers' Model	**Confederate Ramp Controllers' Model**	**Tower Controllers' Model**
• Sector (East vs. South) • Participant (1-6)	• Seat (1-6) • Participant (7-8)	• Seat (1-6) • Participant (9-12)

The statistical software used was *R* [22] and its *lme4* [23] and *lmerTest* [24] packages. Participant effect was treated as a random effect, and all other effects were treated as fixed effects. A likelihood-ratio test was performed to assess whether the Advisory × Participant term needed to be included in the model or not. Finally, using the derived model, statistical-significance levels for the fixed effects were calculated [24].

1) Real-Time Workload Ratings: The results found no statistically significant Advisory effect in the ramp controllers' workload ratings. However, the LMM regression coefficient indicated that the CLT ramp controllers' ratings were reduced by 0.17 (SE = 0.06, p = 0.008) in Advisory runs when they were in the South-sector position rather than in the East-sector position. Fig. 10 (left) plots the means to visualize the effect.

The tower controllers' ratings showed a statistically significant Advisory effect. In the seven-point scale, the tower controllers' ratings were reduced by 0.23 (SE = 0.10, p = 0.021) when advisories were provided in the ramp.

2) Post-Run Workload Ratings: No statistically significant Advisory effect was found in the CLT ramp controllers' Mental Demand, Time Pressure, Communication, and Coordination ratings; however, results showed that the CLT ramp controllers' Frustration rating (stress, annoyance, or irritation) was reduced by 0.58 (SE = 0.30, p = 0.054), on a 10-point scale, when they were in the South sector rather than in the East sector in Advisory runs. In other words, when they were in the East sector, the advisories did not reduce the CLT ramp controllers' frustration as much as when they were in the South sector. Fig. 10 (right) plots the means. The result is similar to the finding in the real-time workload ratings.

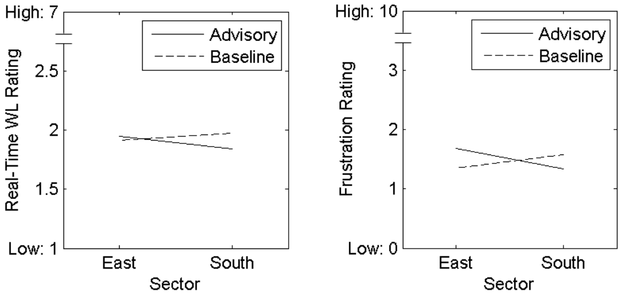

Figure 10. Means of CLT ramp controllers' real-time workload ratings (left) and post-run Frustration ratings (right).

3) Post-Run Usability Responses: Statistically significant Run-Block effects were observed in some of the responses, suggesting that the controllers were learning over the course of the week. For instance, the CLT ramp controllers felt that the gate-hold time advisories appeared in a reasonable range (i.e., the time was not abnormally long) more frequently toward the end of each week. On a scale of one to seven (1 being always, 7 never), the LMM analysis showed that the scores were reduced by 0.68 and 0.70 in Run Blocks 3 and 4, respectively, compared to those in Run Block 1 (SE = 0.33, 0.27; $p = 0.045, 0.014$, respectively). Fig. 11 (left) plots the means of the scores.

Toward the end of each week, the CLT ramp controllers also felt the MC advisories were stable more frequently (score differences compared to Run Block 1 = -0.77, -0.51, -0.60; SE = 0.22, 0.26, 0.22; $p = 0.002, 0.058, 0.009$, in Run Blocks 2, 3, and 4, respectively). Fig. 11 (right) shows the means. Note that the advisory algorithms were not changed in the course of the experiment. The results imply that some learning curves may be expected when the tool is brought to the field.

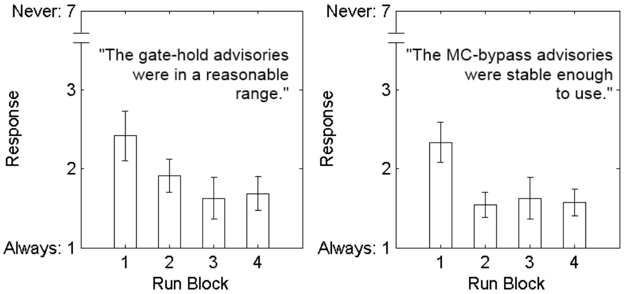

Figure 11. Means and standard errors of CLT ramp controllers' responses on how often the gate-hold advisories were perceived in a reasonable range (left) and how often the MC-bypass advisories were stable enough to use (right).

IV. DISCUSSION

The results showed that the SARDA-CLT gate-hold advisories did not impact the runway throughput or the total delay (when all MERIL departures were excluded). The taxi delay was, on the other hand, reduced by one minute per flight when the advisories were provided. This means that the tool successfully shifted a portion of the taxi delay to the gate, where aircraft could wait with their engines turned off and save fuel. Indeed the increased gate-hold time contributed to a 10-12% fuel burn reduction for overall departure flights per run.

The above fuel savings were achieved by using only the ramp tool (SARDA-CLT), rather than a full, airport-wide SARDA-CDM tool. Fast-time simulations of SARDA-CDM operation previously conducted estimated the achievable departure fuel savings to be 23-30% of the current-day fuel consumption levels [25]. Therefore, SARDA-CLT alone already achieved roughly 30-50% of the estimated fuel-saving benefit of SARDA-CDM without implementing the tower-controller advisories.

The results also demonstrated that the MERIL OA flights, which were not subject to departure metering and were allowed to push back right away, could cause additional delays for American Airlines' MERIL flights by assuming their takeoff slots. Therefore, it is recommended that OA flights be included in the metering if they have a TMI constraint.

The advisories reduced the runway queue lengths, as expected. The results also showed the tower controllers' self-reported workload was reduced, perhaps because of the presence of fewer departures in the movement area along with shorter runway queues. These results are consistent with the findings in the SARDA-DFW 2012 study [4]. The shorter queue lengths also can account for the improved EDCT conformance demonstrated in the current study.

The study found no significant Advisory effect to the ramp controllers' self-reported workload ratings. Thus, the tool's benefits were achieved at least without negatively impacting the ramp controllers' workload. The CLT controllers' real-time workload ratings and the Frustration ratings were lowered by the advisories only in the South sector, not in the East sector. The major difference between the East and South sectors was that the East-sector controller handled the MC-bypass operations. The results imply that the pushback advisories successfully reduced the South controller's workload and frustration, whereas the MC-bypass advisories increased those for the East-sector controller, canceling out the benefit of the pushback advisories. In Advisory runs, when the RTC was showing a provisional MC request, there were three possible cases: 1) the East controller requested it; 2) the SARDA's scheduler suggested the MC bypass, and the East controller liked it (thus, left it as is); or 3) SARDA's scheduler suggested the MC bypass, but the East controller had not had a chance to look at it due to high workload. Because of the ambiguity, the RM had to ask the East-sector controller about his/her intention each time before requesting permission from the Ground controller to use the MC taxiways. This additional coordination may have burdened the East-sector controller in Advisory runs. In Baseline runs, all MC-bypass requests sent to the RM had been initiated by the East-sector controller; thus, there was no ambiguity. The method used to communicate and coordinate the MC bypass requires improvement in the future—which could be as simple as a different color used on the RTC between the controller-initiated versus advisory-initiated MC-bypass requests.

V. CONCLUSION

This paper presented a new ramp controller DST (SARDA-CLT) that utilized tactical pushback advisories for the ramp controllers. The tool did not provide the tower-controller advisories, but ensured coordinated pushbacks through data exchange with the ATCT. A human-in-the-loop simulation experiment demonstrated that the SARDA-CLT advisories reduced the departure taxi delay by one minute per flight and reduced fuel consumption in departure flights by 10-12%. The tool successfully reduced the runway queue length, which likely also improved EDCT conformance and reduced the tower controllers' self-reported workload. The tool's benefits were achieved without negatively impacting the ramp controllers' self-reported workload. There were some indications that the tool's pushback advisories reduced the ramp controllers' workload, but that reduction may have been canceled out by the MC-bypass advisories' high workload and frustration in the East sector. Minor changes to the RTC may mitigate these issues in the MC-bypass operations. The results also indicate it would be beneficial to change the current policy for handling the OA flights and include the OA flights with MIT constraints in the departure metering. Lastly, the results demonstrated that the ramp DST alone already could achieve 30-50% of the fuel savings anticipated by an airport-wide full SARDA-CDM.

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