Flight Deck Robustness/Conformance Testing with a Surface Management System: An Integrated Pilot-Controller Human-in-the-Loop Surface Operations Simulation

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ABSTRACT

An integrated flight deck and controller human-in-the-loop simulation was conducted with a total of 120 Dallas-Ft. Worth (DFW) taxi-out operations. In this first integrated Pilot-Controller Spot and Runway Departure Advisor (SARDA) simulation, ATC Ground and Local Controllers used the SARDA decision support tool to plan and issue spot release clearances and departure clearances. The Airport and Terminal Area Simulator (ATAS), a simulated B737NG piloted, in turn, by 10 commercial transport participant pilots, was integrated into the realistic simulation traffic environment. In the simulation, controllers used SARDA advisories to issue spot release, taxi route, and runway/departure radio voice clearances to all aircraft on the airport surface. Simulation results indicated that under a variety of observed pilot/aircraft performance variations, SARDA yielded controller advisories that were: Supportive of current-day time-based operations; Compatible with controllers' expectations; Predictive of actual take-off times; and, Adaptable to off-nominal events. An Information Sharing Display, that presented SARDA sequence and timing information on the flight deck, was considered useful for both NextGen operations and current-day time-based Traffic Management Initiative (TMI) operations.

SIMULATION OVERVIEW

Study Goals

The primary objective of the ASIDE simulation was to evaluate SARDA's taxi conformance monitoring capabilities and robustness with actual pilot performance; specifically, assessing the effect of pilot/aircraft performance variability on SARDA's ability to produce stable and usable traffic sequencing and scheduling advisories for controllers -- a necessary condition for successful future field deployment. Pilot/aircraft taxi performance varies widely under actual operations; and, these variations were also observed during the course of the simulation. Some of the pilot/aircraft-based sources of uncertainty observed included: Taxi speed variation; Taxi navigation errors (one missed turn due to verifying that a crossing aircraft was stopping); Communication errors requiring repeated clearances; Taxi stops on the taxiway; and, Pilot's slow initiation of aircraft movement after: 1) Pushback; 2) Spot release clearances; 3) 'Line-up-and-wait' runway clearances; and, 4) Take-off clearances. Specific parameters associated with these pilot/aircraft performance variations will be used to inform the future development and "tuning" of the SARDA system and other traffic sequencing and scheduling ATC decision support tools.

METHOD

Participants

Ten commercial transport Captains, all male, with a mean age of 54.2 years (range of 38 – 66 years) participated in the study, acting as Captains in the flight deck simulator. The mean number of flight hours logged as Captain was 9,470 (range of 2,300 – 20,000 hrs). Pilots' current type-ratings included: B737 (1 pilot), B757 (1 pilot), and B747 (8 pilots). Captains were paired with an experimenter who acted as First Officer. Two Air Traffic Controllers subject matter experts participated in this study. The Local Controller retired from SFO Tower in 2004. The Ground Controller was also retired from SFO tower with over 20 years of experience in ATC operations at SFO and OAK.

Flight Deck Simulator

The study was conducted in NASA Ames Research Center's Airport and Terminal Area Simulator (ATAS), see Figure 1. The airport environment was the Dallas-Fort Worth International Airport (DFW), with high visibility and distant fog/haze conditions. The forward, out-the-window scene was depicted on four LCD displays, with a total horizontal viewing angle of 140 deg. The modified-B737NG cockpit included a Primary Flight Display (PFD), Navigation Display (ND), and Flight Management System (FMS) Control Display Unit (CDU) on both crew members' sides, a shared Electronic Moving Map (EMM), a digital clock showing simulation time, and a touch screen interface for loading taxi clearances and take-off times into the avionics. Aircraft controls included a tiller on the Captain's side, toe brakes, throttles, and parking brake. The physical and taxi handling characteristics of the aircraft were that of a mid-size, narrow-body aircraft. Each participant Captain, on successive days, sat in the left seat of the ATAS flight deck.

The participant Captain operated the aircraft in the simulation environment with the nose wheel tiller (with left hand) and the throttles (with right hand). An experimenter sat in the right seat and acted as First Officer. The Captain could hear all tower and flight deck voice communication, but the First Officer operated the digital radios and handled all communications, coordinating with the Captain as appropriate.

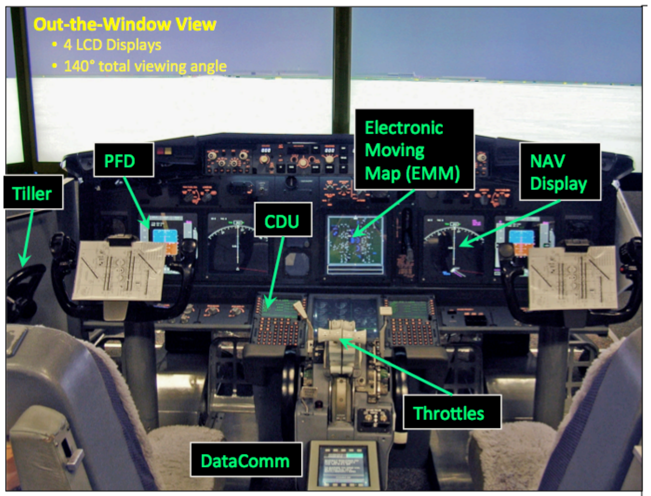

Figure 1. Airport and Terminal Area Simulator (ATAS)

Flight Deck NextGen Displays

In the NextGen conditions tested the flight deck displays included:

• A modification to the PFD speed tape display to enable STBO, specifically reaching the departure queue and runway at the scheduled times; and,

• An Information Sharing Display (ISD) that displayed departure sequence and estimated timing information received from the SARDA controller system.

These two NextGen displays were not available in the current-day conditions.

STBO PFD modifications

In the NextGen condition, pilots were given a Scheduled Takeoff time. To aid them in arriving at the runway on time, the flight deck was equipped with an error-nulling speed algorithm that computed the straightaway speed required to precisely meet the Scheduled Takeoff time. The algorithm dynamically computed the recommended straightaway speed by accounting for remaining distance to the runway, remaining time to the Scheduled Takeoff time, and number of turns, with an assumed acceleration/ deceleration rate of 1 kt/sec and turn speed of 10 kts (per standard operating procedures, SOPs). The algorithm was dynamic and compensated for the pilot slowing down or speeding up by appropriately increasing or decreasing the recommended straightaway speed. For more information, the reader is referred to Foyle et al ATM 2011.

The PFD was modified for taxi operations by expanding (doubling) the speed scale from 0-60 kts. Once the Scheduled Takeoff time was loaded by the flight deck, the PFD populated with speed and time information, as shown in Figure 4 (left panel). Recommended speed, as calculated by the Error-Nulling algorithm, was displayed as a magenta analog pointer ("speed bug") on the speed tape and digitally in magenta directly above the speed tape (15 kts in Figure 4). Scheduled Takeoff time (15:24:08 Z) and time remaining to the Scheduled Takeoff time (4 min 28 sec) were displayed below the speed tape. The PFD also included current ground speed, shown as a sliding indicator with digital value inside (14 kts). Upon entering a turn, the magenta speed bug dropped to 10 kts (per taxi SOPs), while the white, inner speed bug continued to dynamically indicate the recommended straightaway speed required to meet the Scheduled Takeoff time.

Information Sharing Display (ISD)

In the Current-Day condition, the ISD displayed current UTC time only. In the NextGen condition, the ISD also included information received from SARDA: Scheduled Spot Release time, Scheduled Takeoff time, and Departure Sequence number, as shown in Figure 4 (right panel).

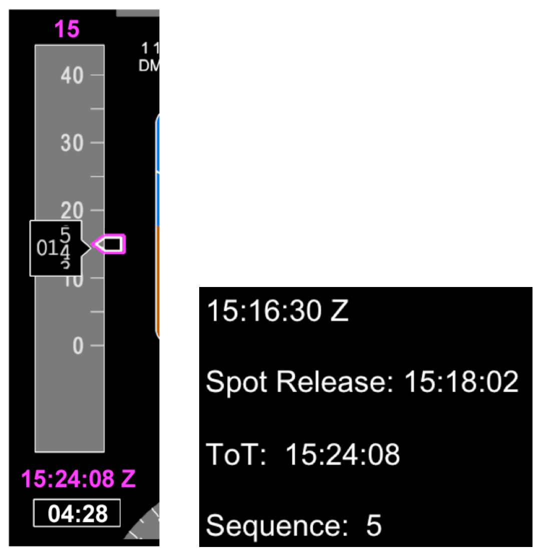

Figure 2. Modified PFD speed tape for STBO (left panel) and Information Sharing Display (right panel)

A touch screen interface was used by the crew to load the standardized taxi route and Scheduled Takeoff time into the flight deck avionics. Upon receiving the taxi clearance from the Ground Controller, the crew loaded the taxi route. After receiving the Scheduled Takeoff time and after receiving any subsequent changes to that time, the crew used the touch screen interface to load the Takeoff time. The error-nulling algorithm used route information, such as distance and number of turns, as well as, Scheduled Takeoff time to calculate the recommended straightaway speed.

Spot and Runway Departure Advisor (SARDA)

NASA's Spot and Runway Departure Advisor (SARDA) prototype tool (Jung et al 2010) is a surface management system (SMS) decision support tool (DST) that helps tower controllers manage airport flow to improve taxi operations efficiency through the integration of spot release and runway scheduling functions. SARDA's Spot Release Planner component provides the ground controller sequence and timing advisories for releasing departure aircraft into the aircraft movement area to minimize delay. SARDA's Runway Scheduler component provides the local controller aircraft take-off sequence and arrival runway crossing sequence in order to maximize runway usage.

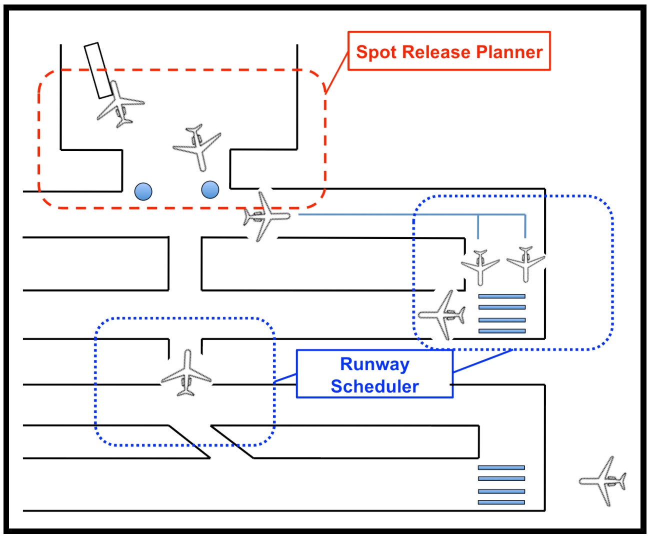

Figure 3. From Jung et al ATIO 2010

The SARDA software, displays, tower controllers and pseudo-pilots were located in NASA Ames Research Center's Future Flight Central (FFC). The ATAS flight deck was integrated with the Spot and Runway Departure Advisor (SARDA) tool via the HLA communication protocol. Thus, the ATAS aircraft was scheduled for spot release and departure by the SARDA software and appeared as a scenario aircraft on the SARDA controller displays. Similarly, all other scenario aircraft were visible out-the-window in the ATAS.

Aircraft other than the ATAS aircraft were controlled by two pseudo-pilots: One pseudo-pilot handled arrival, departure, and runway crossing aircraft, and one pseudo-pilot handled taxiing aircraft. Another team member monitored traffic alongside of the pseudo-pilots to ensure the other aircraft maintained safe separation from the ATAS aircraft at all times. Clearances and readbacks among the tower controllers, the ATAS Captain and First Officer and the aircraft pseudo-pilots were given via voice using a digital radio application, with a ground frequency and a local frequency.

The Ground Controller used the SARDA spot release scheduler to deliver taxi clearances to aircraft at the SARDA-suggested time. The Ground Controller also had an updating ground surveillance display with datatags (not shown). Figure x shows the SARDA Ground Controller touchscreen "flight strips" display. Columns (from left to right) show: Flight identifier; Aircraft type; Spot Release sequence number; Spot Release time (secs to go); Spot/taxi route; Departure runway/Fix/Destination; Traffic Management Initiative (TMI) take-off roll time (if appropriate); and, a Taxi-Departure button.

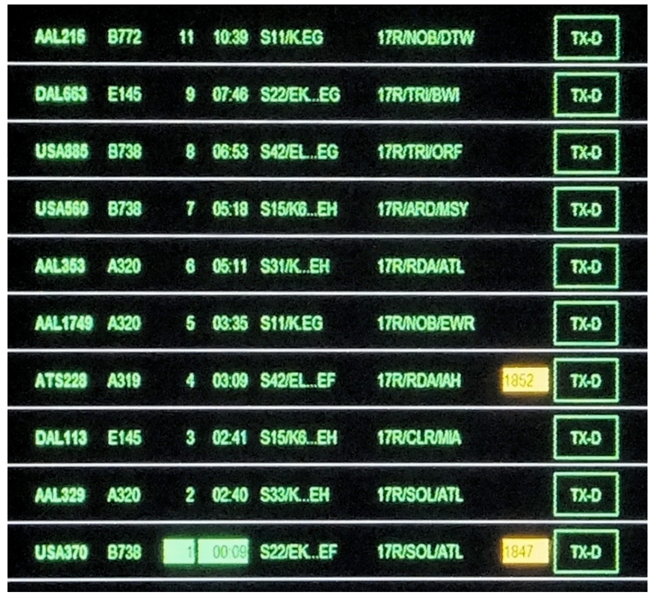

Figure 4. Ground Controller SARDA spot release display

The Local Controller used the SARDA runway departure sequencer for Line Up and Wait Clearances, Takeoff Clearances, and for crossing arrivals on an active runway. Figure x shows the SARDA Local Controller touchscreen "flight strips" display. Columns (from left to right) show: Flight identifier; Aircraft type; Sequence number for controller clearance; Destination (Taxi Queue); Departure fix/Destination; TMI time (if appropriate); and, Line up and Wait (LUAW) and Cleared for Take-off (CFTO) buttons. The format is slightly different for arrival/crossing aircraft: The third row in the figure ("AAL974") shows an arrival aircraft that is to be crossed as the fifth action ("5") heading to Spot 36 ("S36") and then handed off to the East Ground Controller ("E GND"), as shown in columns 3 to 5 respectively.

Figure 5. Local Controller SARDA departure queue (top) and runway crossing (bottom) touchscreen sections

SARDA used standardized taxi routes from the spot to the runway depending on departure fix. All departures for the ATAS aircraft were from Terminal E to Runway 17R. Non-ATAS aircraft departed from Terminals A, C, or E to Runway 17R. Arrival aircraft landed on Runway 17C, crossed Runway 17R, and proceeded to the gate. Controllers were instructed to follow the SARDA suggested timing and sequence in issuing clearances.

In addition to the displays above, the controllers also had an updating ground surveillance display with datatags (not shown). For more detail on SARDA and the controller displays, the reader is referred to Hayashi (2013).

Experimental Design

Prior to the 10 experimental test days with participant pilots, a full day of familiarization with procedures and scenarios was conducted for the experimenters, confederate First Officer, Tower Controller, Ground Controller, and two pseudo-pilots and traffic monitor. All parties, with the exception of the Ground Controller, had previous simulation experience with the facility, displays and systems.

Each flight crew completed a total of 12 taxi out/departures, comprised of two familiarization trials and four experimental trials in each of two conditions, current-day and NextGen. In the current-day condition, the flight deck was not provided with SARDA scheduling information or recommended speed. In the NextGen condition, Scheduled Spot Release time, Scheduled Takeoff time, and Departure Sequence number, as well as, the error-nulling speed display, were presented on the flight deck.

During the second familiarization trial in each condition, an off-nominal event was created when the crew was required to request a stop for 60 sec on the taxiway. In half of the trials, a Traffic Management Initiative (TMI) departure time was implemented in SARDA. Each trial started at the gate, prior to pushback and ended after the aircraft reached 120 kts on the runway. Order of testing of the experimental scenarios was counterbalanced, however, the current-day operations condition was tested first for all participants.

Procedure

Each trial began with the ownship parked at the gate. The crew was provided with pre-departure information approximately 5 min prior to pushback (spot, expected taxi route, and departure clearance). The experimenter First Officer was responsible for programming the FMS and for managing the radio, switching between the ground and local frequencies, as needed. Pilots were told that the Controllers would be using a new automation tool (i.e., SARDA) that meters aircraft from the spot, to improve efficiency of surface operations and reduce delay.

The trial began with an indication that the ATAS aircraft was ready for pushback. The Captain initiated pushback, and the crew received an audio notification when pushback was complete, instructing them to begin taxiing to the spot.

Pilots held at the spot until the Ground Controller delivered the Taxi Clearance, by voice (e.g., “ATS227, taxi to Runway 17R, via K, EG.”). After entering the queue area, the Local Controller delivered the Line Up and Wait and Takeoff Clearances, by voice.

Traffic Management Initiative (TMI) Departure Times

While half of the trials in each condition (current-day and NextGen) included a SARDA TMI, the takeoff time requirement was presented to the pilot participants differently, depending on the context of the condition.

In current-day trials that included a SARDA TMI, pilots were told they had an Expect Departure Clearance Time (EDCT) with a +/- 5 min window, which is consistent with current-day operations. The EDCT was provided to flight deck, by voice, before crossing the spot.

In *all* NextGen trials, pilots were presented with a Scheduled Takeoff time with a +/- 1 min window. The Scheduled Takeoff time represented SARDA’s prediction of takeoff time based on aircraft speed and location. In trials that did *not* include a SARDA TMI, the flight crew was notified any time the Scheduled Takeoff time changed by more than +/- 60 sec. In trials that included a SARDA TMI, however, the flight deck was not notified of any changes to Scheduled Takeoff time.

Upon receiving the Pushback Clearance in the NextGen condition, the Information Sharing Display (ISD) populated with the SARDA Scheduled Spot Release and Scheduled Takeoff times. Pilots were told that this information was intended to give them an awareness of the scheduled times that ATC was working toward, and be an aid to help them meet the smaller takeoff time window of +/- 1 min in

NextGen. If the Scheduled Spot Time changed by more than +/- 60 sec, prior to reaching the spot, the ISD updated with the new time and the magnitude of the change.

As the ATAS aircraft crossed the spot, the ISD blanked the Scheduled Spot Release time, updated the Scheduled Takeoff time, and populated the Departure Sequence Number, which continued to update in real time as the aircraft neared the runway. The pilots then loaded the Scheduled Takeoff time into the flight deck avionics, for the purpose of calculating the recommended straightaway speed. The error-nulling speed algorithm displayed the recommended speed on the PFD to aid the pilot in meeting the +/- 1 min takeoff window.

RESULTS AND DISCUSSION

Pilot-based Sources of Uncertainty

One goal of this simulation was to observe the effects of pilot/aircraft performance variation in the SARDA environment, and to observe the effects of that variation on SARDA scheduling. Table 1 below shows the variation observed in the ATAS pilot/aircraft performance across the simulation.

Table 1. Observed Sources of Pilot/Aircraft Uncertainty

Source	Mean	Range
Time to initiate taxi (sec)	12.5	0.2 - 32.5
Taxi Speed Straightaway (Mean, kts)	15.4	11.6 - 19.5
Time to initiate Line-up and Wait (sec)	7.1	0.1 - 16.5
Time to initiate take-off (sec)	9.2	0.0 - 37.0
Off-nominal Event: 1 missed taxi turn (traffic distraction)	--	--
Off-nominal Event: 1 minute delay on taxiway (induced)	--	--

To be adopted, SARDA advisories for traffic sequencing and scheduling must be robust to the pilot/aircraft performance variations delineated in Table 1. Simulation results indicated that with these observed pilot/aircraft performance variations, SARDA yielded controller advisories that were: Supportive of current-day time-based operations; Compatible with controllers' expectations; Predictive of actual take-off times; and, Adaptable to off-nominal events. These are addressed, in turn, in the following sections.

SARDA Estimates Supported Current-day Time-based Operations (TMI)

During trials with flow control Traffic Management Initiative, TMI scheduled take-off times (half of all trials), 100% of the pilots met their required take-off times within 1 min).

SARDA Sequences were Compatible with Controllers' Expectations

For the ATAS aircraft, the Ground Controller concurred with SARDA's recommendations of the spot release sequence on 94% of trials, and the Local Controller concurred with the take-off sequence on 96% of the trials. The Local Controller considered that the piloted aircraft arrived "just in time" (i.e., not early or late) at the runway hold line on 93% of the trials.

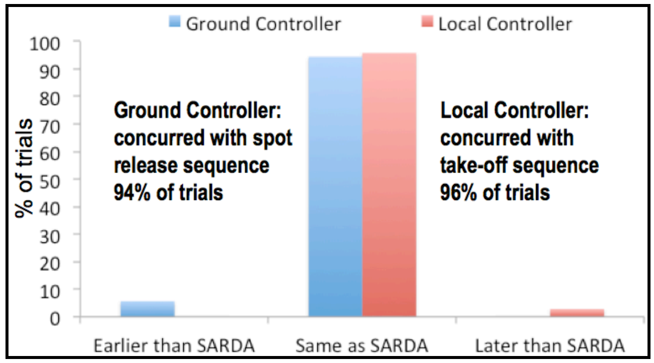

Figure 6. Controller concurrence with SARDA sequence recommendations

SARDA Estimates were Predictive of Actual Take-off Times

On average, the ATAS aircraft took approximately 8 min to taxi from the Terminal E spot to Runway 17R. As aircraft taxi, every 10 secs, the SARDA algorithms internally (not presented to the pilot or controller) predicted take-off times, which are then used as the basis to determine the take-off sequence. Figure x shows the mean absolute value error of SARDA's predicted take-off time from that actually observed for the ATAS aircraft. As can be seen, stable and accurate SARDA predictions of take-off times are seen throughout the departure taxi profile with average prediction errors of less than 45 sec error, which converge to about 10 sec at the time of the actual take-off clearance. To put these values in perspective, given actual departure and runway crossing operations timing, these observed take-off prediction errors would likely map to an adjustment in departure sequence of a single departure slot.

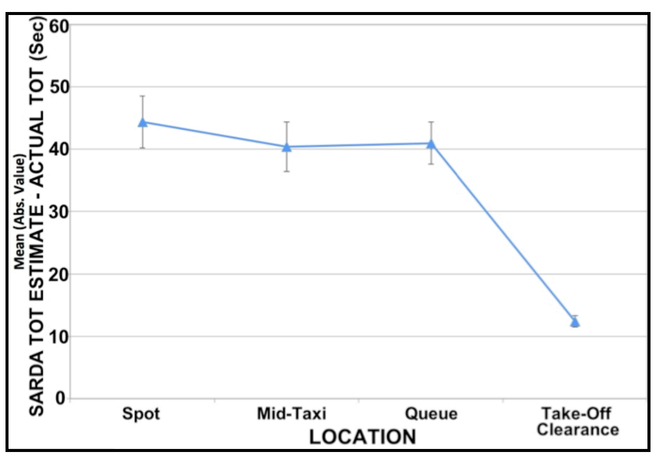

Figure 7. Mean absolute value error (sec) of SARDA's

take-off time (TOT) prediction at various taxi locations

SARDA Estimates were Adaptable to Off-nominal Events

At the mid-point of two taxi out operation trials, the experimenter asked the crew to contact the Ground Controller and request a 60-sec stop. This 60-sec stop simulated an off-nominal event in which the aircraft needed to stop because there was a standing passenger. Figure x shows that SARDA take-off time prediction error closely matched that of aircraft that did not have an unplanned stop.

A 2 (Nominal vs. Off-nominal 60-sec delay) by 3 (Taxi Location) within-participants ANOVA revealed a main effect of taxi location, only $F(2,18)=33.2$, $p<.05$. The interaction was not significant, suggesting the same pattern of take-off time prediction error for both nominal and off-nominal (60-sec delay) conditions. Thus, SARDA detected the pilot non-conformance (i.e., the 60-sec delay), adapted and successfully updated its internally computed predicted takeoff time in response to the 60-sec taxi delay. In this manner, SARDA detected aircraft non-conformance and was able to adapt and reschedule take-off times accurately.

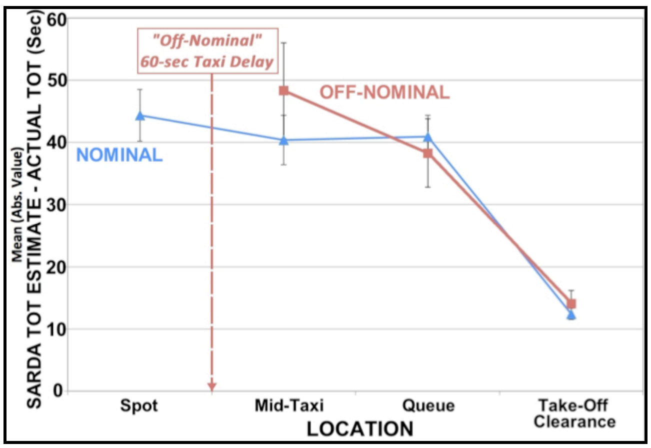

Figure 8. Effect of 60-sec off-nominal taxi delay on mean absolute value error (sec) of SARDA's take-off time (TOT) prediction

Information Sharing Display Usefulness

At the end of the experiment, each of the 10 Captains completed questionnaire regarding the usefulness of the Information Sharing Display. For all questions, Captains used the following ratings: 1="Not at all"; 3= "Borderline"; 5="Very Much"

NextGen Operations

Table 2. Mean and Standard Error of usefulness ratings for question, "For NextGen time-based operations, how useful were the following pieces of information in supporting time-based taxi (your ability to meet your take off time?)"

Information Sharing Display Source	Mean	SE
Assigned Pushback time	4.40	0.22
Spot Release Time	3.90	0.38
Take off Time	4.30	0.15
Departure Sequence	4.20	0.39
Speed Advisory on PFD	3.70	0.33
Time Remaining to Take off Time	3.80	0.25

Note: 1="Not at all"; 3= "Borderline"; 5="Very Much"

Table 3. Mean and Standard Error of usefulness ratings for question, "How useful were the following pieces of information in supporting taxi flow and procedures?"

Information Sharing Display Source	Mean	SE
Assigned Pushback time	4.40	0.22
Spot Release Time	3.90	0.38
Take off Time	4.30	0.15
Departure Sequence	4.20	0.39
Speed Advisory on PFD	3.70	0.33
Time Remaining to Take off Time	3.80	0.25

Note: 1="Not at all"; 3= "Borderline"; 5="Very Much"

Table 4. Mean and Standard Error of question, "Please rate the degree to which the Schedule Display information (spot release, take off time, departure sequence) might change the time at which you perform cockpit tasks such as checklists, taxi flow items, etc."

Information Sharing Display Source	Mean	SE
All information	4.00	0.33

Note: 1="Not at all"; 3= "Borderline"; 5="Very Much"

Current-Day TMI/EDCT Operations (+/- 5 minute window)

Table 5. Mean and Standard Error of usefulness ratings for question, "In current-day operations, when an EDCT is in place, how useful would it be to have the following pieces of information?"

Information Sharing Display Source	Mean	SE
Assigned Pushback time	3.80	0.44
Spot Release Time	3.30	0.40
Departure Sequence	4.00	0.39
Speed Advisory on PFD	3.30	0.45
Time Remaining to Take off Time	3.50	0.40

Note: 1="Not at all"; 3= "Borderline"; 5="Very Much"

Table 6. Mean and Standard Error of usefulness ratings for question, "Current EDCT operations have a time window of +/- 5 minutes. To what extent could that time window be reduced if the following pieces of information were available in your cockpit today?"

Information Sharing Display Source	Mean	SE
Assigned Pushback time	3.50	0.40
Spot Release Time	3.70	0.37
Departure Sequence	3.60	0.34
Speed Advisory on PFD	3.40	0.54
Time Remaining to Take off Time	3.50	0.48

Note: 1="Not at all"; 3= "Borderline"; 5="Very Much"

Additionally, as a follow-on to the question regarding reducing EDCT window times, (shown in Table 6), Captains were asked to estimate the window size for EDCT operations if they had the information sources present in the Information Sharing Display. On average, Captains estimated that the window could be reduced from +/- 5 min to +/- 3.05 min (on average), with standard error of 0.47 min; Median value was +/- 3.0 min.

Taken as a whole, these questionnaire data suggest that pilots generally rate positively the usefulness of having the various information sources available on the flight deck in an Information Sharing Display. The data also suggest that having such an Information Sharing Display available could allow for tighter EDCT/TMI time windows (reduced from +/- 5 min to approx. +/- 3 min), which would allow for improved future efficiency.

CONCLUSIONS AND SUMMARY

The results of this integrated Controller- and Pilot-in-the-loop simulation demonstrated that the SARDA algorithms were able to accurately monitor aircraft taxi conformance and adapt to the range of typical pilot/aircraft taxi performance as well as off-nominal taxi operation scenarios.

To be adopted, SARDA advisories for traffic sequencing and scheduling must be robust to the pilot/aircraft performance variations similar to those observed in this simulation (i.e., Variation in taxi speeds; and, Delays in initiating taxi, line-up-and-wait movement, and to effect take off after receiving clearance). Simulation results indicated that with these observed pilot/aircraft performance variations, the SARDA system yielded controller advisories that were: Supportive of current-day time-based operations; Compatible with controllers' expectations; Predictive of actual take-off times; and, Adaptable to off-nominal events.

Having a controller advisory system such as SARDA, allows for that information to be shared with the flight deck, possibly via a solution akin to a secure internet site connection (given that the information is for information only). Since, one NextGen goal is to expand information sharing among operating partners, displays and concepts similar to the Information Sharing Display will become more likely as we move forward. Questionnaire results indicated that pilots generally had positive attitudes toward the usefulness of such information, and, in fact, that it coud be useful for supporting current-day time-based (i.e., EDCT/TMI) operations.

The results of this integrated ATAS flight deck and SARDA simulation suggest that the SARDA system is in position for expansion to other airport environments and field testing. It also suggests the value in developing integrated flight deck and air traffic controller STBO solutions in the NextGen environment.

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