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Piloted Simulation of NextGen Time-based Taxi Clearances and Tailored Departures

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Abstract

This paper describes the results of a medium-fidelity piloted flight deck simulation of future surface operations. Sixteen commercial transport pilots conducted time-based taxi-out operations at DFW airport under two Next Generation Airspace (NextGen) implementations. In the Limited NextGen implementation, time-based operations were defined by providing a taxi clearance with a commanded average speed to the pilot. In the Advanced NextGen implementation, advanced avionics allowed for time-based taxi operations to be conducted with speed error-nulling algorithms and arrival time information. Results indicated that the Advanced NextGen implementation substantially improved pilots' ability to arrive at airport traffic flow points at the required time. An additional "tailored departure" (i.e., NextGen 4-D departure) clearance verification task assessed the impact of time-based taxi on the departure phase of flight. Results indicated that time-based taxi operations in general, and specifically the Advanced NextGen implementation, might add to pilot workload during taxi out. Future research regarding the assessment and the impact of time-based taxi operations is required.

Introduction

The present study investigated the taxi-out departure environment (from the ramp area to the runway) of the next generation of the National Airspace System, NextGen[1]. Current-day taxi-out departure has been referred to by pilot Subject Matter Experts (SMEs) as being the busiest phase of flight for the crew (R.L. Newman, 2008, personal communication). During taxi-out, crew taxi operations include communicating with air traffic control (ATC) regarding the clearance, maneuvering the aircraft, navigating the clearance by referring to airport signage and the airport taxi chart, and maintaining separation from other aircraft. In addition to these taxiing duties, the pilots also conduct duties associated with departure, including, verifying the flight plan and departure clearance information in the Flight Management System (FMS), confirming final passenger and baggage weight loads, and completing pre-departure briefings related to the normal departure and potential safety backup procedures in the case of such off-nominal events as an engine-out on take-off.

Surface Traffic Management Systems

Current NASA research efforts are aimed toward the development of surface traffic management (STM) systems for ATC to provide optimized taxi clearances that eliminate active runway crossing delays and enable more efficient use of runways. STM systems are envisioned to use dynamic algorithms to generate speed- or time-based taxi clearances for aircraft to calculate the most efficient movement of all surface traffic and enable precise surface coordination[2 3]. To accomplish the required precision, the STM system provides speed/time commands to pilots throughout the taxi route, such that they would arrive at certain airport "traffic flow points" (e.g., traffic merge points, active runway crossings, etc.) at specific times. The aircraft's speed may need to be adjusted if the pilot is unable to conform to the speed command, or if traffic is unable to comply creating a reduction in separation, or to meet the needs of the dynamic airport surface. One specific goal of this study was to characterize the distribution of pilots' Time of Arrival (TOA) performance to inform the development of STM algorithms with regards to the allowable time constraints of the STM system. Since the time-based taxi concept is in its infancy, current efforts aim to impact the design of the STM algorithms so that the resulting STM system does not exceed pilot/aircraft performance capabilities[4].

Tailored Departures

Current datalink capabilities coupled with avionics capabilities in advanced air transport flight decks allow for ATC to send oceanic routes to the flight deck via datalink. Research is underway investigating datalink uploading of arrival trajectories and crossing restrictions directly into the Flight Management System (FMS)[5]. In the NextGen concept of Tailored Departures (TD), fixed Standard Instrument Departure (SIDs) routes will be replaced with more flexible 4-D trajectory departure paths tailored to each aircraft to ensure maximum system efficiency. These future departure paths will be specified in four-dimensions (4-D) comprised of latitude, longitude, altitude, and speed/time. The TD concept raises new issues for pilots, including the need to crosscheck and verify these non-standard departure routes during taxi. The impact of this new requirement on pilot attention and workload during taxi remains unknown.

Integration of STM and TD Concepts

An important aspect of NextGen concept design is the impact on pilot attention and workload. It is imperative that STMs are designed so they do not draw visual or attentional resources away from critical tasks such as monitoring the environment for traffic, completing in-cockpit tasks and checklists, or cross-checking and verifying the departure clearance. To address these attention and workload issues, this human-in-the-loop study measured pilots' performance on secondary tasks and off-nominal events to determine the amount of available attentional resources, and evaluate the interaction between NextGen STM and TD concepts[6].

A pilot-in-the-loop simulation at NASA Ames Research Center was conducted to characterize pilot taxi-out performance under task loads representative of NextGen STM system and TD concepts. Specific goals include determining pilot/aircraft conformance parameters, defining the workload and procedural impacts of these NextGen concepts on future flight crews, and characterizing the distribution of TOA performance at airport traffic flow points to inform the development of STM algorithms with regards to the allowable time constraints of the STM system. The simulation compared two NextGen implementations, which varied in avionics and information complexity -- a Limited NextGen implementation, and an Advanced NextGen implementation. In the Limited NextGen implementation, the STM controlled timed arrivals to specific airport locations by providing aircraft with a commanded taxi speed. Only minor changes were made to the flight deck displays including a modified primary flight display (PFD) that provided an accurate speed read-out for taxi operations. The STM in the Advanced NextGen implementation provided both a commanded speed and a Required Time of Arrival (RTA) for each taxi segment. The flight deck incorporated more sophisticated avionics including a PFD that displayed dynamically adjusting speed commands based on an error-nulling algorithm that incorporated pilots' speed and the remaining distance to drive the pilots toward on-time RTAs, and thus, zero TOA error.

Method

Participants

Sixteen commercial pilots (both current and recently retired) participated in the study. The mean pilot age was 45.5 years with a range of 25 to 63 years. Thirteen of the pilots were Captains and three were First Officers. The mean flight hours logged was 5,586 hours (range of 1,000-20,000 hours).

Flight Simulation

The study was conducted in a medium-fidelity part-task simulator in the Human-Centered Systems Laboratory (HCSL) at the NASA Ames Research Center. The airport environment was the Dallas/Fort Worth Airport (DFW) with high visibility and distant fog/haze conditions. Aircraft controls included a tiller side-stick control with left/right rotation for nose-wheel control, non-differential throttle, and toe brakes. A B737 aircraft simulation control model was used. The forward out-the-window scene was rear-projected on a 2.44 m horizontal (53.13 deg visual angle) by 1.83 m vertical (41.11 deg) screen located 2.44 m in front of the pilot's eye point. The side window scenes were presented on two 48.26 cm (19-in diagonal) monitors, one on each side of the pilot, at a viewing distance of 0.91 m (29.57 deg visual angle). The simulator flight deck included a Primary Flight Display (PFD), Navigation Display (ND), Taxi Navigation Display (TND), Datalink Display, and an Electronic Checklist.

Primary Flight Display (PFD)

The PFD was modified for taxi operations for both NextGen implementations (see Figure 1). The speed scale (left) from 0-60 kts was expanded (doubled) to support taxi operations. The commanded ground speed (10 kts in Figure 1, top left) was displayed both digitally in magenta directly above the speed tape and as a magenta analog pointer "speed bug". Current speed (11 kts in Figure 1) was shown as a white sliding indicator with digital value inside.

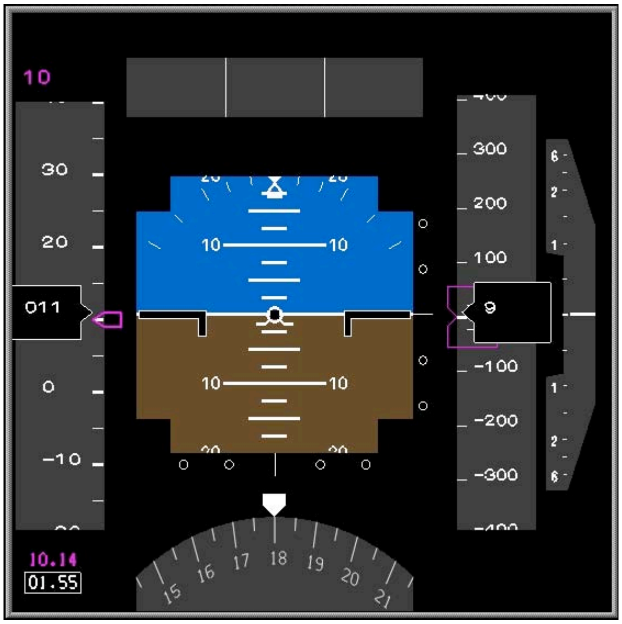

Figure 1. Advanced NextGen PFD

In the Advanced NextGen implementation only, the PFD also presented Elapsed Time in a white box (in min:sec), counting upwards from zero, and the RTA in magenta (in min:sec), both shown in the lower left corner of the PFD. The error-nulling algorithm, in the Advanced NextGen Implementation, dynamically compensated for speed-maintenance errors by adjusting the current commanded speed according to the remaining RTA and remaining distance to the traffic flow point (according to the formula: current commanded speed = remaining distance / remaining time). Thus, by following the currently commanded speed, the aircraft would arrive at the traffic flow point at the RTA. In the Advanced NextGen implementation with the error-nulling algorithm, pilots received implicit performance feedback relative to the RTA. For example, if they were too slow, the algorithm would push the commanded speed higher, and vice versa, attempting to drive the pilots toward on-time RTAs, and thus, zero TOA error. This is in contrast to the Limited NextGen implementation, where pilots received only a commanded taxi speed, and had to estimate their average taxi speed based on their ability to maintain that speed.

Taxi Navigation Display (TND)

Figure 2. Advanced NextGen TND

To assist in navigation of the airport, the simulator flight deck included a TND that depicted the airport layout. At the start of each trial the map was shown in the north-up "airport layout" view to support route planning. It changed to the track-up perspective taxi mode when the pilot started taxiing (see Figure 2). The ownship aircraft's position, shown as a white chevron, and other aircraft traffic, shown as yellow aircraft icons (only within the ownship's 800-meter declutter circle) were updated in real time. The taxi clearance, presented graphically as a magenta route, indicated a positive cleared-to-cross runway clearance. Clearance text was presented below the TND. In the Advanced NextGen implementation only, the traffic flow point location was shown graphically on the TND as a yellow bar across the cleared route.

Datalink Display

The aircraft was equipped with a datalink display for text-based communications with ATC regarding the tailored departure clearance. An auditory chime accompanied all datalink messages. These departure clearances differed from what pilots receive in current-day operations (i.e., SIDs) and included only the departing runway number and the direction of the last route segment shown on the Navigation Display (ND). Each datalink departure clearance was identified by the aircraft's call sign (NA227) followed by a six-digit ID number (e.g., 534803) specifying the departure clearance. This ID number appeared on the ND and in the datalink text clearance display, allowing pilots' to confirm that the 4-D departure path sent by ATC was the same as that received and loaded in the FMS. For example, the datalink text clearance for the pending clearance shown in Figure 3 read, "NA227-534803, DEPART RWY 36R to NE".

Navigation Display (ND)

Figure 3. ND with Accepted Departure Route

The ND was used to present a graphic preview of the departure path described in text in the datalink display. When a departure route was first datalinked to the cockpit, the pending (but not yet accepted) departure path was shown as a white dashed route. Once accepted by the pilot, the route was shown as a solid magenta path (see Figure 3). The aircraft call sign and six-digit route identifier of the route were shown on the bottom left of the ND in yellow.

Experimental Design

The experiment was a mixed-participants design with one between-participants factor, NextGen Implementation (Limited and Advanced), and two within-participant factors, Number of traffic flow points (1, 3, or 5) and Commanded speed (10, 14, 18, or 22 kts).

The two within-participants factors, Number of traffic flow points (3) and Commanded speed (4), were crossed factorially and assigned randomly to 12 unique taxi routes, as follows. Four routes had one traffic flow point located at the destination runway creating routes that consisted of a single segment with a commanded speed of 10, 14, 18, or 22 kts. Four routes with three traffic flow points were comprised of three taxi segments, with commanded speeds that were randomly drawn without replacement from the 4 speeds. Similarly, the remaining 4 routes with 5 traffic flow points were comprised of five individual segments with speeds randomly drawn without replacement from the set of 4 speeds. However, the fifth segment's speed was randomly selected such that it was not the same as the fourth segment's speed. These 12 taxi clearance routes were repeated twice during the testing day such that traffic flow point locations were identical across the two repetitions but each route had a unique configuration of airport traffic. Thus, there were a total of 24 identical taxi trial configurations (3 flow point values x 4 speeds x 2 repetitions) comprising each of the (between-participants) NextGen implementations.

In order to allow a comparison between NextGen time-based operations and current-day taxi operations (not time- or speed-based), a single "current-day taxi" trial was presented at the mid-point of the study (after the first 12 experimental trials were completed). In this trial, the pilot was instructed to taxi-out at a "normal" taxi speed, as if taxiing at a present-day DFW. All other aspects of this trial were identical to the 24 nominal data trials.

Procedure

Pilots completed departure taxi scenarios from a ramp departure spot to a departure runway in a medium-fidelity simulator with B737 aircraft dynamics at Dallas/Fort Worth (DFW) airport. On average, taxi routes with the assigned speeds took 9.5 min to taxi. At the beginning of each trial, pilots were issued a taxi clearance (verbally from ATC, in text and graphically on the TND, initially in plan-view whole airport mode) to a runway. The ND indicated that a pre-departure clearance was loaded into the FMS. When the pilot had studied the taxi clearance and was oriented to the departing location and taxi clearance, an acknowledgement was given to the experimenter and the trial began. At this point, the TND switched automatically to a track-up perspective view (see Figure 2), and the pilot was to begin taxiing immediately. Data were collected after the pilot had completed 4 similar taxi departure trials of simulator familiarization.

An auditory chime and verbal cue (Limited NextGen: "change speed"; Advanced NextGen: "checkpoint") accompanied each taxi segment transition at the traffic flow point location. Pilots received a time-based taxi clearance and, while taxiing, a departure clearance was datalinked to the cockpit and auto-loaded to the FMS. Pilots were required to crosscheck that the six-digit route identifier in the departure datalink text message matched the route loaded into the FMS, as displayed on the ND. As a secondary task to emulate pilot workload, pilots were required to monitor a pseudo-checklist on the instrument panel to ensure that all items were checked; a specified button press on the tiller was required when an item became unchecked according to a randomly-timed schedule.

Tailored Departure (TD) Clearance Task

With the addition of a time or speed requirement under NextGen surface operations, the potential exists for workload to become too high with negative impacts. Specifically, in order to examine the interaction between the STM and TD concepts, we evaluated the pilots' ability to accurately and quickly verify and crosscheck the departure clearance when taxiing with speed-based taxi commands. At a predetermined location (random between 25% and 75% of the route, and unknown to the subject), the datalink chime and message appeared, indicating that the departure clearance had been sent. "ACCEPT" and "REJECT" were displayed flashing immediately below the datalink text clearance message. After pressing one of two buttons on the tiller denoted "Accept" and "Reject", the flashing stopped and the responded value stayed on. Pilots were instructed to accept clearances in which the text clearance information and the ND information matched, otherwise, to reject. If an incorrect response was made, the clearance was re-sent until accepted. On the 24 nominal data trials described previously, the ID number shown in the datalink text clearance and the ID number of the FMS-loaded route shown on the ND correctly matched.

In addition to the 24 nominal trials, two off-nominal trials were included in which the departure route ID number shown in the datalink text clearance did not match the ID number of the departure route loaded into the FMS and shown on the ND. (In fact, for the first off-nominal trial, the heading direction of the route on the ND also did not match the heading stated in the datalink text). Pilots experienced these additional two off-nominal trials at approximately 25% and 75% of the way through the test day, and were not cued in advance to their nature. The off-nominal mismatch between the route specified in the datalink text clearance and that which was loaded in the FMS emulated the result of two potential operational problems. The route shown in the FMS may not have been correctly loaded into the FMS, and could represent a previously loaded route, (an FMS load or freeze error) or, an ATC operator may have incorrectly sent a route to the aircraft different than what was specified in the datalink text clearance (an ATC "drag-and-drop" operational error).

After each taxi trial, on a 1-page form, pilots supplied subjective ratings of situation awareness (SA), workload, and information usage regarding the completed trial. At the completion of the study, pilots completed a 1-page form of ratings of display usage, taxi speed compliance, the number of speed changes, and the departure clearance task. After completing the post-study questionnaire, structured interviews were conducted by the first author in a 1.5-hr session. Topics included usage of the specific displays, feedback about the display features, and views about implementation of the displays tested.

These structured interviews also allowed for discussion of NextGen issues outside of the bounds of the specific simulation's conditions. The structured interview documented the insights of these now "NextGen-experienced" pilots regarding the impact of the NextGen concepts on flight deck procedures, communications, safety, efficiency, and other factors associated with actual operations.

Results And Discussion

Taxi TOA Error

The primary measure of pilot performance on the taxi task was TOA error, which was calculated by subtracting the RTA from the arrival time. In the Limited NextGen implementation, pilots did not receive an explicit commanded RTA (they received a commanded speed). In this condition, RTA was calculated using the taxi route segment length and the ATC-commanded speed for the segment.

It is important to note that for the analysis below, factors such as engine spool-up time or time to change from one commanded speed to the next, can be expected to affect pilots' TOA performance because display support was not available to help pilots factor this information into their taxi speed. Also note that the procedure required that pilots take turns no faster than 15 kts, consistent with aircraft structural ratings, and operational and simulation data. These factors are important operational issues that must be considered in STM algorithm development, and future piloted studies. The baseline trial and the off-nominal trials (i.e., the two departure clearance mismatch trials) were excluded from the TOA error data analyses. There were 11 nominal trials (4 in the Limited NextGen implementation and 7 in the Advanced NextGen implementation) in which the pilot committed a navigation error and taxied off of the cleared taxi route. These trials were re-tested, such that only the trials without navigation errors were included in the TOA error analyses.

TOA average error provides an indication of the presence of an 'early' or 'late' bias. Positive TOA errors indicate that the pilot taxied too slowly and therefore arrived late. Negative TOA errors indicated that the pilot taxied too quickly and therefore arrived early. There was an interaction among implementation, number of traffic flow points, and commanded taxi speeds, $F(6,84)=7.21$, $p<.01$. The number of traffic flow points by speed interactions were significant for both the Limited NextGen, $F(6,42)=12.53$, $p<.001$, and the Advanced NextGen implementation, $F(6,42)=3.67$, $p=.01$, but the nature of the interaction was very different (see Figure 4).

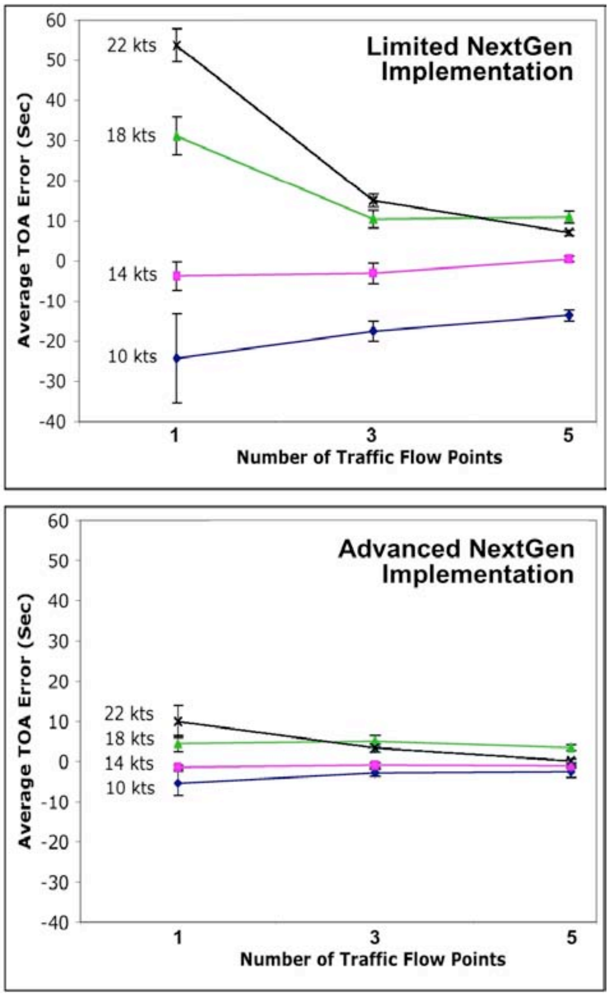

Figure 4. Mean TOA Error (+/-1 S.E.)

Limited NextGen Implementation

In this condition, pilots were issued an average speed command and did not have error-nulling avionics. A trend analysis revealed a significant Quadratic by Linear interaction, $F(1,7)=14.32$, $p<.01$, which can be seen in Figure 4 (top panel). The difference in TOA error as a function of speed grew exponentially larger as the number of traffic flow points decreased from 5 to 3 to 1. Without the assistance of error-nulling avionics, pilots exhibited more difficulty maintaining a relatively fast taxi speed (18 or 22 kts) for a long distance, as in the 1 traffic flow point condition, but TOA error was reduced for these speeds by adding 3 or 5 traffic flow points. Pilots performed best at a taxi speed of 14 kts, with negligible TOA error regardless of the number of traffic flow points. It was easier for pilots to maintain an average taxi speed of 14 kts, because they did not need to slow down for turns and then resultantly correct for the slower speed. With a commanded speed of 10 kts, there was some reduction in TOA error with the addition of multiple (3 or 5) traffic flow points, which served to decrease the distance of each segment.

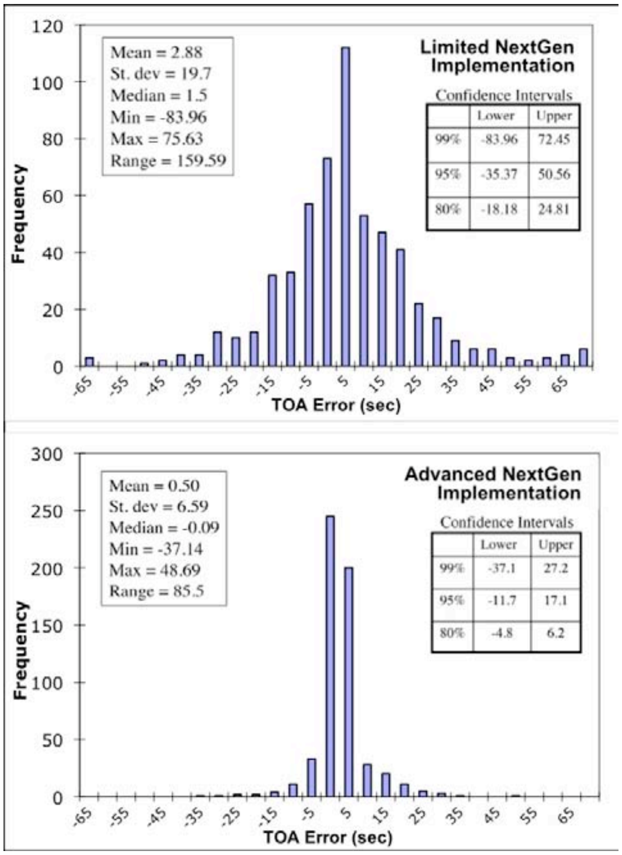

Figure 5. TOA Error Distributions

Advanced NextGen Implementation

In Advanced NextGen condition, pilots taxied with error-nulling avionics and explicit time information. The Linear by Linear trend approached significance, $F(1,7)=5.128$, $p=.058$. As can be seen in Figure 4, pilots' TOA error was negligible in all conditions. The negative effects of faster commanded taxi speeds and one traffic flow point seen in the Limited NextGen implementation, were substantially mitigated by the presence of the error-nulling avionics in the Advanced NextGen implementation condition.

TOA Error Distributions

TOA error distributions revealed positively-skewed distributions with marked difference in spread for the two implementations (Figure 5). In the Limited NextGen implementation, TOA errors were quite variable with standard deviation of 19.7. As seen by the confidence intervals, 80% of the arrival times were within approximately 20 sec (plus and minus) of the RTA. In contrast, TOA error was much less variable for the Advanced NextGen implementation, with standard deviation 6.59. This results in 80% of the cases being within approximately 5 secs (plus and minus) of the RTA.

Departure Clearance Verification

Recall that during taxi, the departure clearance was datalinked to the flight deck and shown as a pending (white dashed) route on the ND. Pilots were required to verify that the six-digit route identification (ID) number and departure heading presented in the datalink matched that on the ND. If the information matched, pilots were to respond by accepting the departure clearance using a button on the tiller. Upon acceptance, the departure clearance was loaded into the FMS and was shown as a magenta route on the ND. Each subject received two 'clearance mismatch' trials. On the first of these trials, the 6-digit ID number and heading of the departure path in the text datalink clearance did not match that shown on the ND. On the second trial, the 6-digit ID numbers alone did not match.

Departure Clearance Errors

Of the 400 nominal trials, in which the clearance was consistent between the datalink and the ND, 3 clearances were incorrectly rejected when they should have been accepted, $p(\text{error})=.008$. These likely occurred because of a discrepancy in interpretation of the heading of the departure path (shown graphically) on the ND and the heading stated in text in the datalink clearance (i.e., N, NW, etc.). Of the 32 off-nominal clearance mismatch trials, 2 of the mismatched departure clearance trials of the departure clearances were incorrectly accepted when they should have been rejected, $p(\text{error})=.06$. Both of the incorrect clearance acceptances occurred on the second clearance mismatch trial, with one in each of the NextGen implementation conditions. In general, most pilots were able to correctly detect departure clearance errors despite increased taxi-out workload. However, the fact that there were missed departure clearance mismatches may indicate potential pilot complacency regarding cross-checking the automated clearance uploading, or may be indicate increased workload during time-based taxi.

Departure Clearance Latency

Departure Clearance Latency was measured as the duration of time between the datalink chime, which announced the presence of the departure clearance on both the datalink and ND, and the pilot's response (accept or reject button press). The data presented here are for correct first responses only. The analysis compared three Departure Clearance Conditions that differed in the taxi task demands and the accuracy of the departure clearance:

- Baseline Taxi – Nominal Clearance. This refers to the single baseline trial in which no speed command was issued and pilots were instructed to taxi as they would in current-day operations. The correct clearance was datalinked to the cockpit and the correct response was to accept the datalinked departure clearance.
- NextGen Taxi – Nominal Clearance. For the two NextGen implementations, the mean clearance latency was calculated for the 24 trials with a nominal (accurate) departure clearance. Accept was the correct response on these trials.
- NextGen Taxi – Off-Nominal Clearance. For the two NextGen implementations, the mean clearance latency was calculated for the two off-nominal trials in which the datalinked departure clearance did not match the departure path presented on the ND. Reject was the correct response on these trials.

The analysis revealed a 2x3 NextGen implementation by Departure Clearance Condition interaction, $F(2,28)=6.42$, $p=.005$ (see Figure 6). A significant difference was revealed in the Limited NextGen implementation condition in which pilots were issued an average speed, but without error-nulling avionics, $F(2,14)=4.45$, $p=.032$. In this condition, clearance latencies for the NextGen-Off-nominal trials were longer than for the NextGen-Nominal trials, $t(7)=2.87$, $p<.05$. Latencies for the Baseline-Nominal condition were not significantly different than the NextGen-Nominal or the NextGen-Off-nominal trials.

In the Advanced NextGen implementation (where pilots taxied with error-nulling avionics), there was a significant difference among the three departure clearance conditions, $F(2,14)=27.31$, $p<.001$. The mean clearance latency of the NextGen Nominal trials was significantly longer than the Baseline-Nominal trial, $t(7)=2.48$, $p<.05$. In addition, the clearance latency for the NextGen Off-nominal condition was longer than both the Baseline-Nominal, $t(7)=5.61$, $p<.001$, and the NextGen-Nominal trials, $t(7)=5.10$, $p<.01$. That is, when pilots were engaged in the speed maintenance task using the error-nulling avionics, response time to correctly accept, or correctly reject, a departure clearance was significantly longer than when no speed requirement was provided.

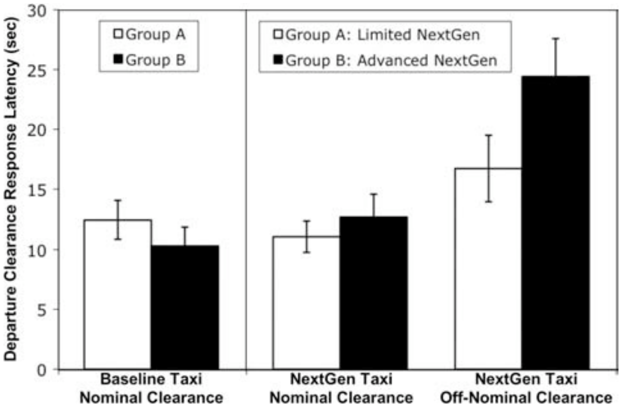

Figure 6. Mean Departure Clearance Latency (+/- 1 S.E.)

There was also a significant difference between the two NextGen implementations for the off-nominal trials, $t(14)=2.17$, $p<.05$. When pilots were engaged in the error-nulling speed maintenance task in the Advanced NextGen implementation, response time to correctly 'reject' a mismatched departure clearance was significantly longer than in the Limited NextGen implementation without error-nulling.

Questionnaire Data

Post-trial Questionnaires

Generally, no significant effects were found regarding the SA and workload ratings. However, for the Advanced NextGen implementation (with the error-nulling algorithm), there was some indication, from the stress and effort post-trial workload scale ratings, that pilots were more impacted by scenario characteristics (e.g., route complexity, and speed), lending further evidence that the Advanced NextGen error-nulling algorithm requires more pilot workload.

Post-study Questionnaires

Discussion of the post-study questionnaire results is limited in this paper to the two questions that referred to the number of speed changes/traffic flow points in the study.

Question 1: "If deemed appropriate for airport efficiency, how many taxi 'checkpoints' or speed commands would be acceptable in a single taxi route?" Possible responses included: None; Only 1; 2-3; 4-5; 6 or more. All 14 pilots completing the post-trial questionnaire responded "2-3". (Due to an experimenter error, two of the eight subjects in the Limited NextGen implementation condition did not complete the post-trial questionnaire.)

Question 2: "Were the number of speed change commands in any of the trials too many for actual taxi operations?", with possible responses of yes or no. In the Limited NextGen implementation, 0% (0 out of 6) of the pilots responded "yes"; while in the Advanced NextGen implementation, 88% (7 out of 8) of the pilots responded "yes", Chi-squared(1) =10.50, p=.001. That is, five traffic flow point updates were acceptable in the Limited NextGen implementation, but not in the Advanced NextGen implementation. This likely is a result of the "closed-loop" control nature of the Advanced NextGen implementation (i.e., error-nulling algorithm), and the "open-loop" control nature of the Limited NextGen implementation. In the Advanced NextGen implementation with the error-nulling algorithm, if pilots went slower, the algorithm would push the commanded speed higher, and vice versa, attempting to drive the pilots towards on-time RTAs, and thus, zero TOA error. Although not borne out by the subjective workload ratings, compared to the Limited NextGen implementation, the Advanced NextGen implementation likely required more workload and effort due to increased throttle (speed) inputs. In the Limited NextGen implementation, pilots only received a single speed command for the taxi segment, and did not receive any indication regarding their RTA or TOA error (other than that as inferred from their indicated error between current speed and commanded speed on the PFD). Without this explicit feedback, the pilots were likely less "coupled" to the task, and likely made fewer speed adjustments within a segment. Thus, it may be the case that in the lower workload Limited NextGen implementation, pilots found five speed updates spread across the taxi route as acceptable, whereas this larger number of traffic flow points in the Advanced NextGen implementation was not acceptable because of the higher control workload.

Post-Study Structured Interviews

For the concept of time-based taxi clearances, pilots generally felt that airport efficiency would improve, since the goal is to eliminate long departure queues. Because of the increased efficiency, pilots felt that the pilot community would easily accept the concept. Some concerns were expressed about safety, since the pilot taxiing does need to monitor speed, which could result in the pilot taxiing "eyes in", away from the out-the-window view of the airport and traffic. Generally, the implementation of the ground speed information on the PFD, where air speed is typically presented, was deemed appropriate and consistent with the pilots' training. Pilots suggested that the TND show nearby traffic and taxi hold instructions. Some pilots suggested that increased crew coordination may be necessary (i.e., flight deck "callouts" for speed conformance and traffic) because of the increased speed monitoring required.

For the concept of tailored departures, since the in-air departure route would be tailored to their destination (accounting for weather, winds, and traffic), the concept was clearly seen to be an improvement to system level and individual aircraft efficiency (e.g., time and fuel savings). Pilots felt that direct upload of departure routes into the FMS would decrease the workload of the flight crew, and did not see a problem with it conceptually (some pilots had similar experience with flight plans being loaded via datalink). This was somewhat surprising because it is a dramatic change from current-day operations where each airport has a small number of fixed, defined SIDs at an airport, to the NextGen environment where there are a huge number of 4-D departure trajectories that can be supplied as a TD. Pilots voiced that they expected that ATC would have the responsibility of ensuring that the TD clearances would be clear of terrain and traffic, and were not especially concerned that it may be a new departure clearance every time. In fact, some pilots commented that it might be good to receive unique departures -- stating that under current-day SIDs operations, because they receive the same SIDs departure every time, they occasionally find themselves complacent and may not conduct a sufficiently thorough pre-departure briefing. Pilots generally agreed with the requirement to be able to verify that the departure route sent by ATC and loaded into the FMS was, indeed, intended for their flight. They felt that the implementation in the simulation (i.e., a datalink text clearance that contained the aircraft call sign, route ID number, departing runway, and departure path compass direction, coupled with the call sign and route ID number on the ND) provided sufficient confidence of this. Consistently, pilots reported the value of current-day SIDs operations that include hardcopy (printed) procedures to refer to for the pre-departure briefing, during manual flight control if there is an FMS problem, and during emergency procedures in the case of an off-nominal event (e.g., catastrophic equipment failure, engine out, etc.) on departure. In contrast, it was voiced that completely unconstrained unique 4-D departure routes present a challenge to the flight crew who generally communicate the normal and off-nominal departure procedures to each other in the pre-departure briefing. Possible solutions may include standardized emergency routes and procedures, and may include some restriction of the generation of tailored departure routes (although still more flexible than SIDs), so that the routes can be printed and described procedurally if the pilots need to fly them manually. Future development and procedural efforts will need to address these concerns.

General Discussion

The results of this study confirmed and extended the findings in our previously conducted time-based taxi study, even though the time and speed displays presented in that earlier study were extremely rudimentary (by design)[7]. As in that previous study, pilots tended to be most accurate with moderate taxi speeds (e.g., 14 kts), which represents the mid-range of typical taxi speeds[8]. Furthermore, pilots tended to arrive at traffic flow points early for slower commanded speeds, and late for faster commanded speeds. In the present study, TOA error was largest when only a single (and thus, long taxi segment) was used, improving as more traffic flow points were added. This is consistent with our previous study in which longer distance routes led to larger TOA error[7].

This study indicated that in order to arrive on time at airport traffic flow points, pilots will need some form of advanced flight deck displays, as opposed to receiving simple ATC speed commands. The large spread of TOA error around the traffic flow point in the Limited NextGen implementation compared to that of the Advanced NextGen implementation allows for much less predictability of aircraft location, and would likely limit attempts to optimize traffic flow with STM algorithms.

The error-nulling algorithm used in the Advanced NextGen implementation significantly reduced TOA error. There was some indication (i.e., increased TD clearance acceptance times), however, that it may increase overall workload, possibly even more so with more frequent (and hence shorter) routes (indicated by the post-study question related to the acceptable number of traffic flow points). The challenge, then, is to implement these algorithms in such a way as to improve taxi RTA performance (minimizing TOA error), without adverse effects on pilot workload, situation awareness and the completion of other flight deck duties. These challenges will be addressed by future research including: Refinements in the error-nulling algorithm that account for taxi turn speed limits; and, Procedures or display aids that communicate the required conformance of speed and the size of a RTA "time window" for the traffic flow points.

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