

NEXTGEN FLIGHT DECK SURFACE TRAJECTORY-BASED OPERATIONS (STBO):
SPEED-BASED TAXI CLEARANCES

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A pilot-in-the-loop simulation was conducted that required pilots to taxi following acceleration and speed profiles under two Speed-conformance conditions (Defined and Undefined). Pilots were given a commanded speed in both conditions, however, in the Defined Speed-conformance condition, air traffic control (ATC) issued alerts when the aircraft speed exceeded a +/- 1.5 kt speed range. A current-day, baseline trial with no required speed profile was also included. While pilots achieved required time of arrival (RTA) errors of less than 10 sec in each condition, both Speed-conformance conditions produced more visual fixation time on the speed tape, located head-down on the primary flight display (PFD), compared to the baseline condition. Fourteen out of eighteen pilots reported that the demand of maintaining the required speed conformance range in actual operations would compromise safety. These results indicate the need for advanced flight deck displays to enable pilots to safely comply with runway RTAs during taxi.

The present study investigated the taxi-out departure environment (from the ramp area to the runway) of the next generation (NextGen; JPDO, 2009) of the National Airspace System. Current research efforts are aimed toward the development of surface traffic management (STM) systems for air traffic control (ATC) to provide optimized taxi clearances that eliminate active runway crossing delays and enable more efficient use of runways. These taxi clearances would have a speed- or time-based component with which the pilot must comply. These NextGen taxi operations have been referred to as “4-D taxi” (with the fourth dimension referring to the time component), or surface trajectory-based operations (STBO). 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 (Cheng, Yeh, Diaz, & Foyle, 2004; Rathinam, Montoya, & Jung, 2008). To accomplish the required precision, the STM system provides speed/time commands to pilots throughout the taxi route, such that they 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 STBO command, or if traffic is unable to comply creating a reduction in separation, or to meet the needs of the dynamic airport surface.

Previous Research

Foyle, Hooley, Kunkle, Schwirzke, and Bakowski (2009) investigated the impact of speed commands on pilots’ ability to meet a required time of arrival (RTA) at traffic flow points between a ramp departure spot and the runway. The goal of the study was to drive aircraft to a specified location (runway end or traffic flow point) at a specific time by having ATC provide the pilot a taxi clearance with a commanded speed to be followed. (Note that speed is the parameter that pilots actually control via throttle inputs – arrival time derives from that speed control. If ATC provided clearances with a time requirement, pilots would have to transform that into speed, taking route distance into account.) In the ‘Limited’ NextGen condition¹, the Primary Flight Display (PFD) presented the commanded and current ground speeds. Trials consisted of 1, 3, or 5 segments, where each segment had a commanded speed of 10, 14, 18, or 22 kts. Because the total distance of all trials was similar, segment distance in one-segment trials was longer than in the three- or five-segment trials. Pilots were instructed to comply with the commanded speed on straight segments, accelerate/decelerate “aggressively”, and, for commanded speeds of 18 and 22 only, slow to 15 kts for turns. The RTA was originally calculated using the taxi route segment length and the ATC-commanded speed for the straight segments. The primary measure of performance was time of arrival (TOA) error, calculated by subtracting the RTA from the observed arrival time at each segment transition. The results indicated TOA errors of -24 sec (early) to 53 sec (late) for one-segment trials. However, it was noted that the RTA

¹ The study examined two conditions of speed commands, which varied according to the complexity of the flight deck avionics, however only the ‘Limited’ NextGen condition is discussed here.

calculation used in Foyle et al. did not account for turns or acceleration/deceleration, which may have exaggerated true TOA errors. To correct this, and provide a suitable comparison to the present study, the RTA for each segment was recalculated to account for the commanded speed in turns and an assumed underlying speed profile of 2 kts/sec acceleration/deceleration, commonly considered the maximum acceleration/deceleration limit (Cheng, Sharma, & Foyle, 2001). TOA scored against the recalculated RTA, is shown in Figure 1, and as can be seen, mean TOA errors ranged from -28 sec (early) to 27 sec (late) for one-segment trials. That is, even with a more precise RTA calculation method, there is still considerable TOA error.

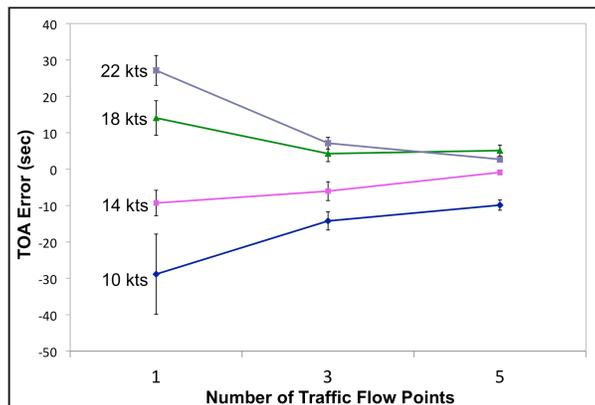


Figure 1. TOA Error in Limited NextGen Condition (Foyle et al., 2009) using adjusted RTA calculation. Negative TOA errors indicate that the pilot taxied too quickly and therefore arrived early. Positive TOA errors indicate that the pilot taxied too slowly and therefore arrived late. (Error bars are +/- 1 Standard Error).

The goal of the present study was to investigate the possibility of improving TOA performance beyond what was observed in the Limited NextGen condition through the manipulation of procedural instructions. Two flight deck procedures were implemented in the present study with the expectation of reducing TOA error: 1) Requiring pilots to follow a specified speed profile with acceleration/deceleration rate of 2 kts/sec, and specific speeds on straightaways and in turns; and, 2) Specifying a required speed conformance level (specifically +/- 1.5 kts) from the commanded speed. The purpose was to evaluate the impact of these procedural manipulations on pilots' ability to comply to taxi clearances with a speed requirement (resulting in an RTA).

Method

Participants

Eighteen commercial pilots (both current and recently retired) participated in the study. The mean pilot age was 45 years with a range of 25 to 65 years. Thirteen of the pilots were Captains and five were First Officers. The mean flight hours logged was 3,832 hours (range of 300 – 11,000 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 International 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. Participants wore an Applied Science Laboratory Mobile Eye with EyeHead Integration eyetracker.

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 by expanding (doubling) the speed scale (left) from 0-60 kts to support taxi operations. Current ground speed (14 kts in Figure 2 left) was shown as a white sliding indicator with a digital, whole number value inside. Commanded speed was issued verbally by ATC and was not displayed on the PFD. The PFD was identical in both conditions (Undefined and Defined).

Taxi Navigation Display (TND). To assist in navigation of the airport, the simulator flight deck included a TND that depicted the airport layout in a track-up perspective during taxi (see Figure 2 middle). The ownship aircraft's position, shown as a white chevron, and other aircraft traffic within the ownship's 1,250 ft declutter circle, shown as yellow aircraft icons, were updated in real time. The taxi clearance, presented graphically as a magenta route, indicated a positive cleared-to-cross runway clearance.

Navigation Display (ND). The ND was used to present a graphic view of the tailored departure path, representing what had been loaded into the Flight Management System (FMS). When the departure route was first datalinked to the cockpit, the pending departure path was shown as a white dashed route. The departure route of the lead aircraft was represented by a solid green line. Once accepted by the pilot, the ownship's route was shown as a solid magenta path (see Figure 2 right).



Figure 2. PFD (left), Taxi Navigation Display (middle), and Navigation Display (right).

Datalink Display. The datalink display was used to present a text description of the tailored departure path, representing what had been sent from ATC. An auditory chime accompanied the delivery of the datalink, which pilots viewed by alternating between the TND and the datalink text. Pilots were responsible for verifying that the 4-D departure path sent by ATC was the same as that received and loaded in the FMS.

Experimental Design

The taxi task portion of the experiment consisted of three within-participant factors: Speed-conformance condition (Undefined and Defined); Number of traffic flow points (1, 3, and 5); and, Commanded speed (14, 18, and 22 kts). These three factors were crossed factorially to create nine nominal trials in each of the two Speed-conformance conditions. For all participants, the Undefined Speed-conformance condition trials were tested first, followed by the Defined Speed-conformance trials. Testing was done in this order so that performance in the Undefined Speed-conformance condition represented the pilots' "natural", uninstructed speed conformance level. A single "current-day taxi" trial with no commanded speed was presented at the midpoint of the study. In addition, three off-nominal trials were tested, but they are not discussed here.

Procedure

Three familiarization trials were presented prior to the start of the Undefined condition and a fourth was presented prior to the start the Defined condition. In each of the experimental trials, pilots taxied from a ramp departure spot to the departure runway. Pilots received a speed-based taxi clearance during each trial. A verbal ATC command (e.g., "NASA227, taxi at 14 kts.") accompanied each taxi segment transition (14, 18, or 22 kts) at the traffic flow point location. Segment distances and speed changes were not depicted on the TND. Two specific speed profile instructions were given, and, with the exception of the baseline trial, applied to all trials in both implementations: Taxi all turns at 14 kts and accelerate/decelerate at a rate of 2 kts/sec (e.g., a 0 kt to 14 kt initial acceleration should take 7 sec, a 22 kt to 18 kt speed change should take 2 sec, etc.). In the baseline (current-day)

trial, pilots were not given a commanded speed and were instructed to taxi as they normally would in actual operations. With the exception of the absence of a speed command, all other requirements of this trial were the same as the other experimental trials (e.g., checklist task, departure clearance verification task, navigation, maintaining safe separation, etc.).

In the Undefined Speed-conformance condition, pilots were instructed to taxi as close to the commanded speed as was reasonable. No required speed conformance range or performance feedback was provided in this condition. However, in the Defined Speed-conformance condition, pilots were instructed to taxi within +/- 1.5 kts of the commanded speed. When ground speed exceeded the +/- 1.5 kt range for more than a continuous five-sec period, ATC delivered a verbal alert, "NASA227, check speed". The verbal alert repeated every 10 sec until the pilot's speed returned to within the +/- 1.5 kt range from the commanded speed. The computer-activated ATC "check speed" alert was disabled for 2-4 sec (depending on the size of the speed change for acceleration/deceleration to the new speed) after a new speed command was issued by ATC, and in the area around the turns.

In every trial, a departure clearance was datalinked to the cockpit and auto-loaded to the FMS and delivered at one of three possible times: 1) prior to the start of taxi; 2) in the first half of the taxi route; or, 3) in the second half of the taxi route. Pilots were required to crosscheck the altitude, heading, and speed in the departure datalink text message against the route displayed graphically on the ND (Figure 2 right). As a secondary task to emulate pilot workload, pilots were required to monitor a simplified electronic 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. A paired departure task was also presented following the completion of the taxi task in each trial. This departure task was examined independently of the taxi task and is not discussed here.

Following each taxi trial, pilots supplied subjective ratings of situation awareness, workload, and impact of the departure clearance on taxi performance. At the completion of each block of Speed-conformance (Undefined and Defined) trials, pilots also completed questionnaires that pertained to display usage, safety, and acceptability of the speed conformance condition.

Results

The taxi TOA error analyses included nine nominal trials in each condition, Undefined Speed-conformance condition and Defined Speed-conformance condition. The primary measure of pilot performance on the taxi task was TOA error, which was calculated by subtracting the RTA from the observed arrival time. The RTA for each segment was calculated using the taxi route segment length, the ATC-commanded speed for the straight segments, 2 kts/sec acceleration/deceleration, and a turn speed of 14 kts.

As seen in Figure 3, TOA error is quite good, and is much better than found in Foyle et al. (2009, see Figure 1) where no specific speed profiles or speed conformance requirements were placed on the pilots. A 2 (speed-conformance condition) by 3 (number of traffic flow points) by 3 (commanded taxi speeds) within-participants ANOVA showed that there was an interaction between number of traffic flow points and commanded taxi speed, $F(4,68)=3.44, p=.013$. A trend analysis revealed a significant Linear by Linear interaction, $F(1,17)=8.15, p=.011$. This suggests that TOA error increased linearly as commanded speed increased from 14 kts to 22 kts, and decreased as the number of traffic flow points increased from one to five.

There was also an interaction between Speed-conformance condition and number of traffic flow points, $F(2,34)=4.44, p=.019$. Post hoc tests showed a simple main effect of number of traffic flow points in the Defined Speed-conformance condition, $F(2,34)=7.75, p=.002$. TOA error for one-segment trials ($M=2.28, SD=3.12$) was significantly higher than for three-segment trials ($M=.71, SD=1.75$), $t(17)=2.70, p=.015$, and five-segment trials ($M=.39, SD=1.15$), $t(17)=3.21, p=.005$. This was consistent with the Foyle et al. (2009) results (see Figure 1), in which pilots exhibited more difficulty maintaining a commanded taxi speed for a long distance (as in the one-segment trials), than for shorter distances (three- or five-segment trials). The simple main effect of number of traffic flow points in the Undefined condition was not significant.

A main effect of speed was also found, $F(2,34)=21.83, p<.001$. A significant Linear effect, $F(1,17)=39.57, p<.001$ suggests that TOA error increased as the commanded speed increased.

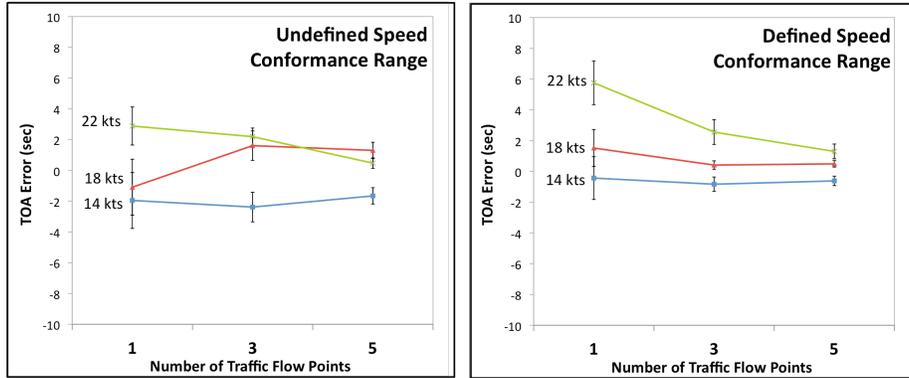


Figure 3. Mean TOA Error as a function of commanded speed and number of traffic flow points for the Undefined and Defined Speed-conformance conditions. Negative TOA errors indicate that the pilot taxied too quickly and therefore arrived early. Positive TOA errors indicate that the pilot taxied too slowly and therefore arrived late. (Error bars are +/- 1 Standard Error).

Percent Dwell Time on PFD Speed

The percentage of the taxi trial during which the pilots' eyes fixated (termed percent dwell time, PDT) on the current speed read-out displayed on the PFD is shown in Figure 4 (left). The Undefined and Defined conditions respectively produced 2.4 and 3.3 times more visual fixation time on the PFD speed display when compared to that of the current-day baseline trial ($M=7.55$ PDT) where pilots taxied with no commanded speed, $F(2,20)=41.29$, $p<.001$. Pilots spent 17.89 and 24.39 percent of the trial looking at the speed display, in the Undefined and Defined conditions respectively. In absolute as well as relative terms, this is a large percentage of the trial to be looking head-down at the speed display when the main duties of the Captain are to navigate and control the aircraft, and maintain awareness and separation from other aircraft taxiing on the airport surface.

Questionnaire Data

On a post-study questionnaire, using a 5-point scale, where 1 = Rarely and 5 = Most of the Time, participants were asked, 'How often did you find yourself focusing on the PFD speed tape when you would have preferred to have been paying attention to the external taxiway environment?' As shown in Figure 4 (right), the results showed a significant effect of Speed-conformance condition, $F(2,34)=69.19$, $p<.001$. Participants reported focusing on the speed tape more than they would have preferred in the Defined Speed-conformance condition ($M=3.69$, $SD=.79$) than in either the Undefined ($M=3.20$, $SD=.79$), $t(17)=3.35$, $p=.004$, or baseline conditions ($M=1.67$, $SD=.77$), $t(17)=9.71$, $p<.001$. Pilots also reported focusing on the speed tape more than they would have preferred in the Undefined than in the baseline condition, $t(17)=8.59$, $p<.001$.

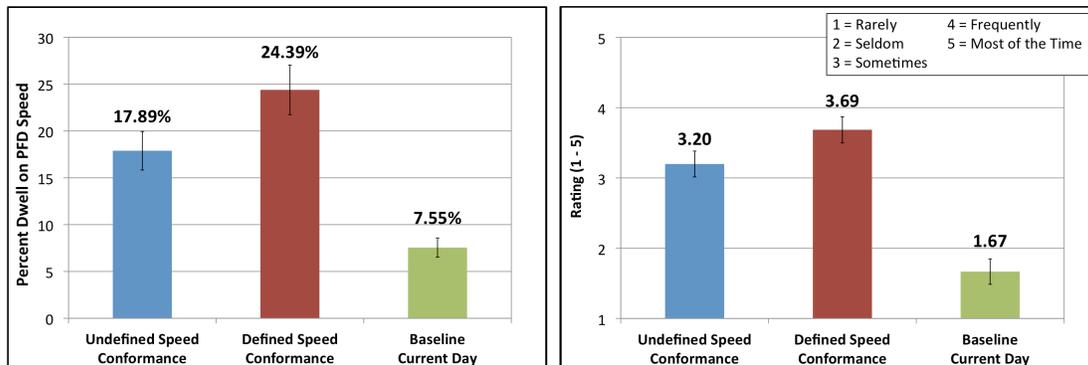


Figure 4. Mean percent dwell time on PFD speed (left). Mean post-trial rating of question: How often did you find yourself focusing on the PFD speed tape when you would have preferred to have been paying attention to the external taxiway environment? (right). Error bars represent +/- 1 standard error.

Participants were asked, 'Would the demand of having to maintain the required speed conformance range compromise safety in the real world?' A chi-square goodness-of-fit test revealed that more pilots (n=14) responded that the demand of having to maintain the required speed conformance range in the real world would compromise safety than responded that it would not (n=4), $X^2(1, N=18)=5.56, p=.018$.

Participants were also asked, under the simulated future airport concept, in which all aircraft are similarly equipped and conducting time-based taxi operations, 'Is it a reasonable requirement to stay within +/- 1 kt of a commanded speed?' A chi-square goodness-of-fit test revealed that more pilots (n=15) responded that staying within +/- 1 kt of a commanded speed was not a reasonable requirement than responded that it was reasonable (n=3), $X^2(1, N=18)=8.00, p=.005$. On average, participants reported that a +/- 3.7 kt range would be reasonable. It should be noted that this would likely result in very poor TOA errors – a simple calculation indicates that depending on the speed, each 1 kt error bias over a 12,000 ft taxi results in 20-40 sec error.

Discussion

A previous NextGen taxi simulation study (Foyle et al., 2009) showed that pilots were not able to achieve accurate RTAs when issued speed-based taxi clearances (unless provided with an enabling flight deck algorithm and display). However, in the Foyle et al. study, pilots were not given explicit speed profiles (acceleration/deceleration) or explicit speed-conformance requirements, so as to require aircraft taxi handling that would be comparable to current-day operations. The current simulation was conducted to expand on this result. The present simulation experiment required explicit speed profiles and manipulated speed conformance. Both factors may have caused the poor RTA performance in the previous (Foyle et al.) simulation.

The present simulation demonstrated that pilots were able to taxi their aircraft according to specified speed profiles, resulting in quite good RTA performance. Unfortunately, however, this required the pilot to view the head-down speed display 2.4 to 3.3 times more than in a current-day baseline condition. Pilots overwhelmingly (14 of 18) felt that this would have a negative impact on safety, interfering with the primary taxi tasks to navigate the aircraft and maintain visual separation from other aircraft and obstacles. Thus, although pilots are able to follow a specified speed profile in response to a taxi clearance incorporating a commanded speed, resulting in good RTA performance, it also likely results in unsafe surface operations. As suggested by Foyle et al. (2009), a flight deck display aid may support pilot taxi RTA performance with reasonable and safe workload.

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