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NextGen Surface Trajectory-Based Operations (STBO): Evaluating Conformance to a Four-Dimensional Trajectory (4DT)

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Abstract

A pilot-in-the-loop simulation was conducted to assess the feasibility of a Surface Trajectory-Based Operations (STBO) concept [1]. The STBO concept was investigated from the pilot perspective by evaluating pilot conformance to a four-dimensional trajectory (4DT) while taxiing under manual control. Simulation conditions included a Current-Day Equipage condition; a verbal Speed-Advisory condition, which represented a near-term condition in which pilots were provided with verbal speed guidance from ATC, but not provided with any additional flight-deck tools by which to support schedule conformance; and two NextGen 4DT conditions in which the pilots were provided with flight deck displays to support conformance to the 4DT at two different levels, +/- 30 sec ($4DT_{30}$) and +/- 15 sec ($4DT_{15}$). In the NextGen 4DT conditions, pilots were presented with a graphical representation of the 4DT on an Airport Moving Map (AMM). Results showed that both the $4DT_{30}$ and $4DT_{15}$ conditions afforded more than 99% conformance to the 4DT across the entire route. An evaluation of the time of arrival (TOA) at the end-point revealed significantly less TOA error in the $4DT_{30}$ and $4DT_{15}$ conditions as compared to the Speed-Advisory condition. Although eye-tracking data revealed an increase in eyes-in time in the 4DT-display conditions, pilots rated this increase as acceptable. The results of this pilot-in-the-loop simulation demonstrated that the NextGen 4DT displays afforded high conformance with a substantial increase in predictability throughout the entire taxi route and at the runway queue. Pilots also rated that conforming to a speed profile, during taxi, was acceptable and safe.

Keywords: NextGen; STBO; 4D Trajectory (4DT); surface operations; taxi; displays.

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1. NextGen Surface Trajectory-Based Operations (STBO)

Research and development efforts are currently underway to design the next generation (NextGen; [2]) of the National Airspace System to increase capacity and efficiency. Surface Trajectory-Based Operations (STBO) is a NextGen concept for managing traffic on the airport surface. It envisions coordinating surface operations so that aircraft can be delivered to specific locations on the airport surface at specific times, in the most efficient manner possible [3]. STBO can be defined along a continuum of schedule certainty. For example, operations in which only a pushback time is scheduled offer the least amount of certainty about when an aircraft will reach the runway. Future operations, where a pushback time, a runway queue arrival time, and possibly intermediate points, are scheduled, offer an increasing degree of timing precision. Finally, four-dimensional trajectory (4DT) operations, in which pushback, runway queue, and all intermediate points in-between are scheduled, offer the highest level of timing precision for surface operations. This study explores 4DT operations [4].

In contrast to current-day operations, where aircraft can experience delays in the departure queue or at active runway crossings, the 4DT operations concept enables coordination of all surface traffic to improve efficiency and reduce fuel burn. The concept assumes the existence of an ATC surface traffic management (STM) system that schedules and sequences surface traffic, and generates a 4DT with an expected x,y location (with fixed altitude), *at all times*, t, along the taxi route for each aircraft [1]. Each 4DT also specifies the allowable positional error for each aircraft while ensuring conflict-free trajectories. Conformance to 4DTs on the surface is expected to enable higher temporal precision, which is necessary to support trajectory-based operations in all other phases of flight [1].

2. Present Study

The purpose of the present study was to investigate pilots' ability to safely conform to a 4DT, while taxiing under manual control. The study included four flight-deck equipage conditions: Current-Day Equipage, Verbal Speed Advisory, and two NextGen 4DT-display conditions. The Current-Day Equipage condition represented potential near-term operations in which ATC may be equipped with sequencing and scheduling tools but the flight deck is not augmented to support schedule conformance. The Speed-Advisory condition represents the same near-term condition, with the exception that pilots are provided with verbal speed guidance by ATC. In the two 4DT-display conditions, the flight deck Airport Moving Map (AMM) is augmented to include a graphical representation of the 4DT and associated allowable deviation. Two allowable deviations were evaluated in this study, +/- 30 sec and +/- 15 sec. This study explored whether pilots can safely conform to a 4DT (the expected x,y position) at all times along the route and at the end-point of the taxi route.

3. Method

3.1. Participants

Thirteen commercial/cargo Captains (10 current, 3 recently retired) participated in the study. The mean pilot age was 57.7 years (range: 44 to 66 years). The mean flight hours logged as a Captain was 7,985 hours (range: 800 to 13,000 hours). Captains were paired with an experimenter who served as the First Officer.

3.2. Flight Deck Simulator

The study was conducted in the Airport and Terminal Area Simulator (ATAS) in the Human-Centered Systems Laboratory (HCSL) at NASA Ames Research Center. The ATAS is a modified B737-NG cockpit equipped with an unobtrusive four-camera eye tracking system (Smart Eye Pro; Smart Eye AB, Goteborg) to measure pilot gaze.

The airport environment was the Dallas/Fort Worth 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 physical and taxi handling characteristics of the aircraft were that of a mid-size, narrow-body aircraft. The modified-B737NG cockpit included all current-day controls and flight instruments. An AMM in place of the traditional Navigation Display depicted the airport layout, in track-up perspective, to aid pilots in airport navigation (see Figure 1). In all trials, the ownship position, depicted as a white chevron, and airport traffic within 1,250 ft of the ownship were updated in real time. Current ground speed (16 kts in Figure 1, left) and heading (000 deg in Figure 1) were also shown on the AMM.

3.3. NextGen 4DT Displays

In the two 4DT-display conditions, the AMM was augmented to include a 4DT display, and DataComm was used for taxi clearance delivery. Each is described below.

4DT Displays. The AMM was augmented to display the cleared-to-taxi route from the ramp departure spot to the departure runway in dark magenta (Figure 1, right). The two horizontal reference markers (shown just behind the ownship, Figure 1, right) move along the route according to the assigned 4DT and show the expected ownship position at all times. The light pink segment that overlays the magenta route (Figure 1, right), represents the allowable deviation from the expected aircraft position per the ATC-issued 4DT. This study used two allowable deviations: 1) +/- 15 sec ($4DT_{15}$) and 2) +/- 30 sec ($4DT_{30}$). These allowable deviations were converted to distance based on the assigned speed (e.g., at 15 kts, +/- 380 ft and +/- 760 ft respectively) and shown graphically on the AMM. As long as the ownship icon was on the light pink band, it was assured that the aircraft would arrive at any location on the airport surface within 15 sec of the expected time in the $4DT_{15}$ condition, or within 30 sec of the expected time in the $4DT_{30}$ condition. The AMM also displayed text of the taxi clearance and speed profile information, including: the taxi Start Time (23:08:06, as shown in Figure 1, right), the advised Straightaway Speed (14 kts), and the Queue-entry time (23:13:36).

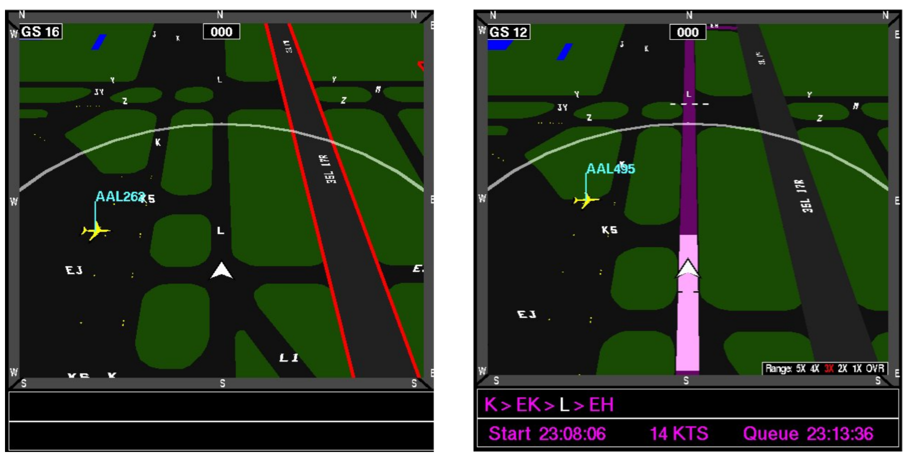

Fig. 1. Airport Moving Map (AMM) in the Speed-Advisory condition (left) and in the NextGen 4DT conditions (right) ($4DT_{15}$ is shown).

DataComm. In the 4DT conditions, taxi clearances were delivered via DataComm instead of by voice. The DataComm touchscreen interface was located aft of the throttles between the two pilots. After reaching the ramp departure spot, pilots received the taxi clearance via the DataComm. All DataComm messages were indicated by an auditory chime and were read aloud by the First Officer.

3.4. Experimental Design

Four conditions were tested: Current-Day Flight Deck Equipage, Verbal Speed Advisory, $4DT_{30}$, and $4DT_{15}$. In all conditions, even Current-Day Equipage, taxi routes, start times, and queue times were generated by the Spot and Runway Departure Advisor (SARDA), an STM tool developed at NASA Ames Research Center [5]. The conditions differed in the taxi clearance delivery method; voice for Current-Day Equipage and Verbal Speed Advisory, and DataComm for the $4DT_{30}$ and $4DT_{15}$ conditions. They also differed in the nature of the speed component of their clearance. In the Current-Day Equipage condition, there was no speed requirement. In the Speed-Advisory condition, an advised straightaway speed was issued verbally by ATC along with the taxi clearance, and in the NextGen $4DT_{30}$ and $4DT_{15}$ conditions, the 4DT was shown graphically on the AMM.

The four equipage conditions were factorially crossed with three unique route/speed conditions (East/14kts, West1/15kts, and West2/16kts) resulting in 12 experimental trials. From the ramp departure spot to queue entry, the East route was 7,336 ft and both the West1 and West2 routes were 12,502 ft in length. The two west-side routes were also matched in terms of the number and type of turns. The three speeds (14, 15, and 16 kts) were chosen as typical taxi speeds normally observed in actual operations. The four equipage conditions were blocked so that Current-Day Equipage was always presented first and Speed Advisory second so as to avoid influencing pilot speed and speed variability in these conditions with the speed requirements imposed by the 4DTs. The two 4DT-display conditions were presented last, with the order of the $4DT_{15}$ and $4DT_{30}$ being counterbalanced. A Latin square was used to assign the order of the three route/speed conditions within each block. Each trial started with the aircraft parked at the gate and ended just before reaching the hold-short line at the departure runway. In all trials, the pushback clearance was triggered by SARDA and the taxi clearance was sent by either voice or DataComm, at the SARDA-generated spot-release time.

3.5. Procedure

All pilots received an introductory briefing and completed two simulator familiarization trials before training on the specific experimental conditions. Pilots were instructed that their first priority was to maintain safety, never taxi faster than they would in an actual aircraft full of passengers, and remain eyes out and taxi with the same regard for passenger safety and comfort as in actual operations. In the Current-Day Equipage condition, pilots were not provided with any speed profile information. In the Speed-Advisory condition, crews were told that following the advised speed would improve overall airport efficiency, improve traffic coordination, and reduce runway delays. They were instructed that their first priority was always to maintain safe, eyes-out taxi and that their second priority was to comply with the advised speed the best they could. This was emphasized because previous studies showed that requiring pilots to prioritize speed conformance with high precision resulted in unacceptable levels of head-down time [6]. In the two 4DT conditions, pilots were again instructed that their first priority was to maintain safe, eyes-out taxi, and their second priority was to comply with the 4DT as best they could. They were instructed that it was acceptable to be anywhere within the allowable deviation (i.e., light pink band on the AMM) and they were not required to track the center reference markers precisely. If they found themselves outside of the allowable deviation, they were instructed to recapture it as quickly, but as safely, as possible. In the Speed-Advisory and 4DT conditions, pilots were told that the standard operating procedure was 10 kts in turns and 1 kt/sec for acceleration and deceleration.

Prior to the start of each trial, the crew was provided with expected routing information, including spot number and departure runway. After completing pushback, pilots taxied to the spot. Once there, pilots received the taxi clearance via voice in the Current-Day Equipage and Speed-Advisory conditions. The taxi clearance included: Departure Runway (e.g., 36R), Taxi Route (e.g., K, K8, L, B, F, WP), Advised Taxi Speed (e.g., "Taxi at 15 kts"; in the Speed-Advisory condition only), and verbal instruction to "wait for the Proceed Instruction" before crossing the spot and beginning their taxi. The clearance to proceed was issued 30 sec after the taxi clearance was issued.

In the two 4DT conditions, taxi clearances were issued by DataComm and included: Departure Runway (e.g., 36R), Taxi Route (e.g., K, K8, L, B, F, WP), Start Time (the time when the aircraft may initiate taxi), and Queue Time (the time when the aircraft was expected to enter the runway queue). The clearance information was automatically loaded into the flight deck avionics and appeared in cyan to indicate that the clearance was pending. This information changed from cyan to magenta at start time, which occurred 30 sec after the taxi clearance was issued and was accompanied by an auditory tone. The start time matched the proceed clearance in the Current-Day Equipage and Speed-Advisory conditions to ensure that pilots crossed the spot at the same time (i.e., 30 sec after the taxi clearance) in all conditions, in order to allow for comparisons across conditions.

In the 4DT conditions, the queue entry location was marked on the AMM with a white dashed line (as shown in Figure 1, right). As the ownship crossed that queue entry point, the speed guidance was blanked, and pilots were instructed to continue taxiing safely into the queue area and follow ATC instructions. In all conditions, the experimental trial ended just before reaching the runway hold line.

4. Results

The main objectives of this study were to assess the degree to which pilots can conform to a 4DT while taxiing under manual control and to evaluate the safety of the concept. Conformance was evaluated by measuring the aircraft's conformance to the expected position along the taxi route and the arrival time at the end-point (runway queue entrance). Safety was evaluated by measuring the percentage of 'eyes-out' time using eyetracker data and the pilots' subjective ratings.

4.1. Along-Route Conformance

Pilot conformance to the expected position along the route was examined using four conformance tolerance bands (+/- 15 sec, +/- 30 sec, +/- 45 sec, +/- 60 sec). Each band was converted to distance based on the assigned speed of each trial. The percent of time that the aircraft position was within the tolerance band was recorded. Through pre-testing, +/- 15 sec was deemed to be the smallest tolerance band that could be possible from a safety standpoint, whereas +/- 60 sec was deemed to be the largest tolerance band to still provide optimization benefits on the airport surface.

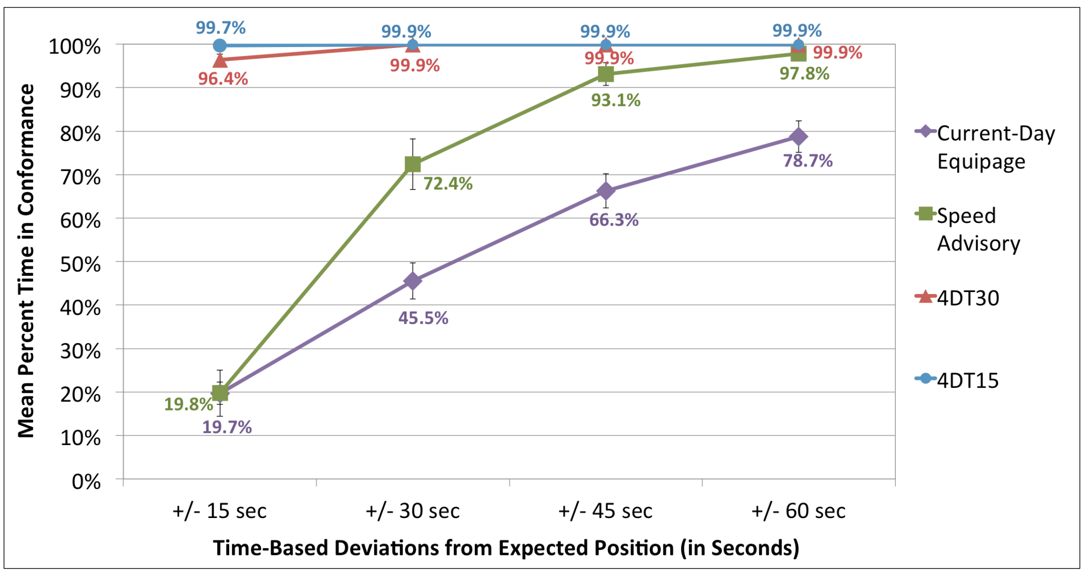

Fig. 2. Percent time in conformance with each conformance tolerance band (+/- 15, +/- 30, +/- 45, and +/- 60 sec). Error bars=+/- 1 standard error.

Figure 2 shows the percent of time the aircraft was within each conformance tolerance band. Pilot conformance was exceptionally high with the 4DT display. The $4DT_{15}$ condition resulted in greater than 99% conformance across all tolerance band levels, and conformance with the $4DT_{30}$ display was more than 99% for the +/- 30 sec, +/- 45 sec, and +/- 60 sec bands. However, the Speed-Advisory condition resulted in much lower conformance with 19.8% in the +/- 15 sec band and 72.4% in the +/- 30 sec band. These results suggest that depending on the required level of precision, the verbal speed command, alone, may not support adequate conformance. With the Current-Day Equipage condition, in which pilots were not provided with tools to support 4DT conformance, percent time in conformance ranged from 19.7% for the +/- 15 sec band to 78.7% for the +/- 60 sec band. This means that the aircraft was at any given position on the airport surface (e.g., a taxiway intersection) within +/- 60 sec (+/- 1,519 ft at 15 kts) of the position expected by the STM only 78.7% of the time. Because scheduling and sequence decisions will be made based on where the STM expects aircraft to be, this level of non-conformance may yield inefficient operations with large time buffers for each aircraft movement or the need for frequent re-planning of the airport surface schedule.

4.2. End-Point Time of Arrival (TOA) Conformance

TOA conformance at the end-point, located at the entrance to the departure runway queue area, was measured by subtracting the expected TOA from the ownship's actual TOA. Although pilots were not given an advised speed or an expected TOA in the Current-Day Equipage condition, a predicted TOA was computed based on the issued spot-release time and straightaway speeds used in the other three conditions. TOA error (absolute value) for each of the four experimental conditions and each of the three route/speed conditions is shown in Figure 3. A 4 (condition) by 3 (route/speed) repeated-measures ANOVA revealed a condition by route/speed interaction, $F(6,72)=4.97$, $p<.05$. Post-hoc pairwise comparison tests with Bonferroni adjustments revealed that TOA error was highest in the Current-Day Equipage condition, with TOA error higher than the Speed-Advisory, $4DT_{30}$, and $4DT_{15}$ conditions for all three scenarios ($p<.05$ for all pairwise comparisons). TOA error was higher in the Speed-Advisory condition than the $4DT_{15}$ conditions for all three scenarios ($p<.05$ for all pairwise comparisons) and than the $4DT_{30}$ condition for two of the three scenarios ($p<.05$ for the two longer scenarios West1/15kts and West2/16kts; $p=.059$ for the shorter East/14kts scenario). TOA error was not significantly different between $4DT_{30}$ and $4DT_{15}$ for any of the three scenarios presumably due to a floor effect. As can be seen in Figure 3, the TOA error was approximately 15 sec or less, even when the allowable deviation was +/- 30 sec ($4DT_{30}$).

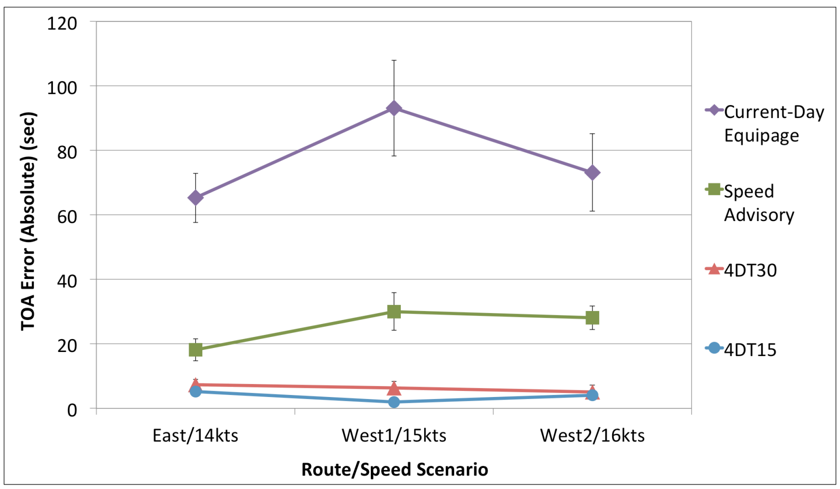

Fig. 3. Mean TOA error (absolute value) (sec) at queue entry by condition and route/speed. Error bars = +/- 1 standard error.

4.3. End-Point TOA Variability

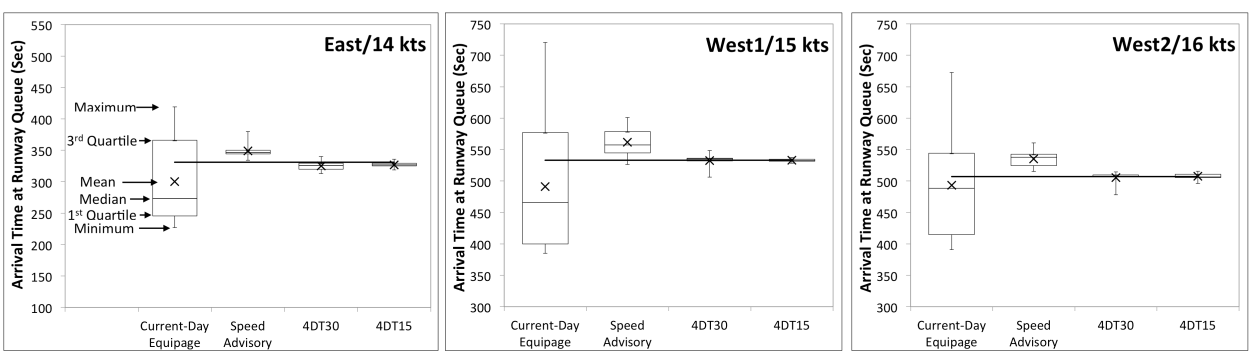

Fig. 4. Time of arrival (TOA) variability at the runway queue in each of the four experimental conditions and each of the three route/speed conditions. The black line represents the expected TOA at the runway queue, according to the speed profile.

Figure 4 shows the variability in the TOA at the runway queue. The box plots show that when pilots did not receive any speed or time guidance (Current-Day Equipage condition), variability was very large (TOA ranges were 192 sec, 335 sec, and 282 sec, respectively, for the East/14kts West1/15kts, and West2/16kts scenarios). Providing a verbal speed in the Speed-Advisory condition reduced those TOA ranges to 46 sec, 75 sec, and 45 sec. When pilots were provided with the 4DT display on the flight deck, the TOA ranges were further reduced to 27 sec, 42 sec, and 36 sec for the $4DT_{30}$ condition, and 17 sec, 9 sec, and 19 sec for the $4DT_{15}$ condition.

4.4. Eyes-Out Time

One safety concern of 4DT taxi is that high levels of conformance could come at a cost of increased eyes-in time. Figure 5 shows the time spent scanning out-the-window (eyes-out) and the flight deck instrument panel (eyes-in) between spot release and queue entry. Pilots who had undefined data (e.g., looking at something other than a defined display such as throttles, tiller, or paper chart) or unreliable data (e.g., eyes closed, blinks) for 20% or more of a trial were excluded from these analyses, yielding a subset of eight pilots. As would be expected, eyes-out time was highest in the Current-Day Equipage condition (M=81.3%, $S.E.$=1.3%), followed by the Speed-Advisory (M=70.9%, $S.E.$=1.3%), $4DT_{30}$ (M=65.6%, $S.E.$=1.4%), and $4DT_{15}$ conditions (M=62.1%, $S.E.$=1.5%). A 4 (condition) by 3 (route/speed) repeated-measures ANOVA revealed a condition by route/speed interaction, $F(6,42)=4.56$, $p<.05$. Post-hoc tests with Bonferroni adjustments revealed that pilots' eyes-out time was higher in the Current-Day Equipage condition than in the Speed-Advisory condition for the two longer scenarios (West1/15kts and West2/16kts, $p<.05$) but not for the shorter East/14kts scenario. Pilots were eyes-out significantly more in the Current-Day Equipage condition than the $4DT_{30}$, and $4DT_{15}$ conditions in all three scenarios ($p<.05$ for all pairwise comparisons). The eyes-out time in the Speed-Advisory condition was higher than in the $4DT_{15}$ condition for all three scenarios ($p<.05$ for all pairwise comparisons) and for two of the three $4DT_{30}$ scenarios (East/14kts and West2/16kts, $p<.05$; West1/15kts, $p>.05$). Eyes-out time was not significantly different between the $4DT_{30}$ and $4DT_{15}$ conditions.

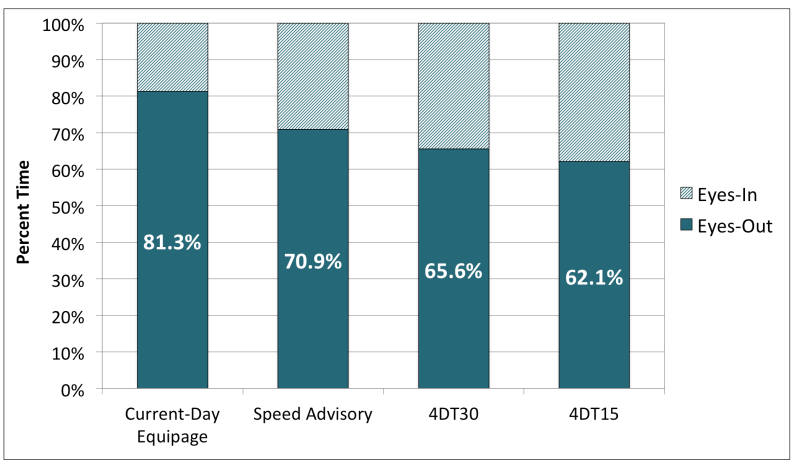

Figure 5. Percent time spent scanning out the window (eyes-out time) vs. flight deck displays (eyes-in time).

It was expected that the 4DT concept ($4DT_{30}$ and $4DT_{15}$) would result in higher eyes-in time, relative to the Current-Day Equipage, condition because pilots do not typically monitor their speed read out in current-day operations and because the 4DT conditions provided richer navigation information (e.g., graphical and text taxi route). It is not known, empirically, what level of eyes-out time is required for taxi operations, however, in a post-study questionnaire, pilots were asked to assess the degree to which the additional eyes-in time required to conform to the advised speed or 4DT was acceptable on a scale from 1 (very unacceptable) to 5 (very acceptable). The effect of condition approached significance, $F(2,24)=3.20$, $p=.059$. Results revealed a higher acceptability of eyes-in time in the $4DT_{30}$ condition (M=4.38, $S.E.$=0.18) than in either the $4DT_{15}$ condition (M=3.92, $S.E.$=0.21), $p<.05$, or the

Speed-Advisory condition (*M*=3.77, *S.E.*=0.23), *p*=.055. There was no difference in rated acceptability between the $4DT_{15}$ and Speed-Advisory conditions.

4.5. Subjective Ratings of Safety and Ease-of-Use

On a post-study questionnaire, pilots rated the *safety* of each condition using a 5-point scale (1= Very Unsafe, 5= Very Safe). Mean pilot safety ratings were high (above 4) in all conditions (Speed Advisory: *M*=4.08, *S.E.*=0.18; $4DT_{30}$: *M*=4.62, *S.E.*=0.18; $4DT_{15}$: *M*=4.38, *S.E.*=0.24) but there were differences among the conditions, $F(2,24)=3.73$, $p<.05$. Post-hoc tests revealed that the $4DT_{30}$ condition was rated as safer than the Speed-Advisory condition $t(12)=2.5$, $p<.05$. No other comparisons were significant.

On a post-trial questionnaire, pilots were asked to rate how easy/difficult it was to maintain the ATC-issued taxi speed (Speed-Advisory condition) and maintain the aircraft within the $4DT_{30}$ and $4DT_{15}$ bounds (4DT conditions). A 3 (condition) by 3 (route/speed) repeated-measures ANOVA revealed a main effect of condition, $F(2,24)=32.11$, $p<.05$ (and a main effect of route/speed scenario, $F(2,24)=4.78$, $p<.05$, not discussed here). Pilots rated that keeping the aircraft within both the $4DT_{30}$ (*M*=4.72, *S.E.*=0.07) and $4DT_{15}$ (*M*=4.58, *S.E.*=0.09) bounds was easier than maintaining speed in the Speed-Advisory condition (*M*=3.72, *S.E.*=0.10), $t(12)=7.71$, $p<.05$ and $t(12)=7.29$, $p<.05$.

5. Conclusion

The results demonstrated that when pilots are not provided with speed or 4DT information, predictability of position along the taxi route and arrival time at the runway queue may not be adequate for NextGen surface operations which will require greater precision. Although providing pilots with a speed advisory improved end-point conformance, the NextGen 4DT displays afforded both high end-point conformance and substantial increases in predictability throughout the entire taxi route. While along-route conformance could have been increased in the Speed-Advisory condition by requiring pilots to prioritize the speed-tracking task, this has previously been determined to result in unsafe taxi operations [6]. Still, eyes-in time during taxi did increase with the Speed-Advisory and 4DT-display conditions, relative to current-day operations, however pilots rated this increase as acceptable. Future research is needed to determine acceptable levels of eyes-in time under various taxi scenarios (including off-nominal events) and to continue to evaluate 4DT flight deck displays formats that minimize eyes-in time such as the use of head-up displays, high-mounted displays, and auditory cues.

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