Flight Deck Crew Experiences Flying Profile Descents During Metering Operations

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ABSTRACT

NASA's Air Traffic Management Technology Demonstration #1 Project has a goal of improving airport capacity by developing and testing ground and flight deck tools for the terminal airspace. The Controller Managed Spacing (CMS) suite of tools has been developed to maintain high traffic density for aircraft on optimal profile descents on area navigation routes. Several studies have examined the controllers' interaction with CMS, but there has only been one study that explored the impact of this toolset on pilots. This human-in-the-loop simulation is the second to focus on the impact of CMS on the flight deck. Twelve Boeing 737-800 qualified flight crews flew a glass cockpit simulator with the flight management system and flight dynamics of a B737-800 aircraft. Crews flew four scenarios in the Phoenix Terminal Airspace that included clearances to descend on a profile, which was adjusted almost exclusively with speed changes. Two variables were manipulated: speed changes and ATC phraseology. Workload and questionnaire data indicate that scenarios with clearance speeds faster than the route restrictions were more challenging. The phraseology of the speed clearances had an impact upon pilot workload and the efficiency of the profile descent, as determined by the number and duration of flight level-offs. Finally, the time variation to fly the descent illustrated the potential for disrupting ground scheduling tools in the terminal area.

Keywords: Continuous descents, speed management, controller phraseology, flight efficiency

INTRODUCTION

One of the major problems in the current air traffic control (ATC) system is the inability to efficiently manage the movement of aircraft as they get closer to the airport. In busy terminal areas, a large number of aircraft are required to transition into a compressed amount of airspace that is constrained by the number and position of the landing runways. This can result in inefficiencies, particularly when there is high traffic volume, and these inefficiencies can effect traffic that are a large distance from the airport. In addition, greater fuel consumption (Abbott, 2002) often occurs as aircraft are required to absorb delays to account for the terminal area traffic volume. There are a number of airports that have tested or operated more efficient descents such as optimized profile descents (OPDs) including Los Angeles International Airport, Hartsfield-Jackson Atlanta International Airport, and a few airports within Sweden (see Stibor & Nyberg, 2009).

The Air Traffic Management Technology Demonstration #1 (ATD-1) concept developed by NASA (Robinson, 2011) aims to safely sustain high runway throughput while also enabling fuel-efficient operations. Research is being undertaken in advanced scheduling capabilities that create schedules at the runway to enable aircraft to fly OPDs along area navigation (RNAV) routes (Swenson, Thipphavong, Sadovsky, Chen, Sullivan & Martin, 2011). Aircraft on these descents will be able to maintain 4D trajectories as they move into the terminal area. Assuming en route controllers deliver the aircraft close to their scheduled times of arrival (STAs) at the meter fix, Terminal Radar Approach Control (TRACON) controllers would rely primarily on speed adjustments to bring aircraft through the terminal area (Isaacson, Robinson, Swenson & Denery, 2010). The benefit to aircraft is a continuous, low energy descent that is fuel efficient and faster than traditional step-down descents.

One of the controller toolsets being developed and evaluated by the ATD-1 research team is the Controller-Managed Spacing (CMS) tools. The CMS tools assist/ enable TRACON controllers to meet tight schedules by displaying key schedule information on controller stations. Researchers at NASA Ames (Prevot, Lee, Callantine, Mercer, Homola, Smith & Palmer, 2010) have conducted a series of real-time human-in-the-loop simulations to investigate the CMS tools during terminal area operations. The controller participants were able to effectively adjust aircraft positions relative to a schedule primarily using speed changes. The research on the CMS controller tools has indicated that they allow for meeting runway schedule times in dense terminal airspace with no increase in controller workload. (See Kupfer, Callantine, Martin, Mercer & Palmer, 2011, and Callantine, Palmer & Kupfer, 2010, for accounts of this research.)

In the first few years of development of the CMS concept, there was an assumption that the use of these new controller tools would be transparent to the pilots. The use of the CMS tools requires pilot to fly efficient descents and meet the necessary speed constraints provided in the ATC clearance, a task that pilots conduct on a routine basis. Another assumption was that no new technology is required for an aircraft equipped with a flight management system (FMS). Since there is no requirement for additional flight deck tools, there is also an assumption that no new training is required for pilots.

As the CMS tools matured, more consideration was given to the assumption that there would be no impact upon flight crews receiving CMS clearances. CMS shifts much of the air traffic management technique to a broader use of speed control, which may result in larger speed modifications than those typically issued in today's terminal environment. Additionally, speed changes may be given to the pilot at a more frequent rate. These potential changes in air traffic control strategy led to initial exploratory investigations of the use of CMS clearances with flight crews.

In 2012, an exploratory human-in-the loop simulation was undertaken to explore crews' ability to fly to schedule-based OPDs with no prior training and to examine their workload level and aircraft management strategies (Martin, Sharma, Lozito, Kaneshige, Dulchinos, & Hayashi, 2012). The study examined the effect of the variation and range of acceptable descent speeds upon pilot workload. Some of the speed changes differed by 20% from the routes' specified speed restrictions to intentionally create a dramatic airspeed shift from one clearance to the next. In addition, the degree to which the speed clearances might impact the pilots' use of automation was explored, as well as the phraseology of the clearances.

Although the simulation was exploratory, there were some interesting findings that warranted further investigation. The results from the initial study indicated that there were some difficulties with understanding and implementing speed clearances, particularly those with larger magnitudes. In addition, there was some increase in workload for pilot participants associated with speed clearances. Previous research examining schedule-based terminal tools found that pilots and controllers reported difficulties using speed clearances (Kupfer, et al., 2011). The pilot participants also reported some confusion associated with aspects of the clearance phraseology. The confusion was most prominent when using long, conditional clearances with temporal constraints related to aircraft changes. Controllers had difficulty interpreting the content of speed clearances when they were used to help crews manage and refine flying OPD clearance types in an earlier simulation (Callantine, Kupfer & Martin, 2013).

This study is a follow-on human-in-the loop investigation to the one conducted in 2012 (Martin, et al., 2012). The objectives of this study are to further test the impact of CMS speed clearances and their associated phraseology that were explored in the initial simulation on flight deck crews and the way profile descents were flown as a result. Clearances with smaller magnitudes of speed modification were used (deviating by 15% from the published speed restriction rather than 20%) to represent more realistic schedule-based CMS clearances. Two variations of phraseology were presented to the pilots to systematically test the clarity of conditional clearance content. Finally, to obtain data that could be more broadly generalized to today's operations, a flight deck simulator representing the Boeing 737-800 was used, along with qualified flight crews.

METHODS

The Simulation Facility

The study scenarios were flown in the Advanced Concept Flight Simulator (ACFS) (Davis, 2008) at the NASA Ames Research Center. The simulator offers a full visual field and is on a motion platform. This is a generic cockpit simulator that has the performance characteristics of a Boeing 737-800, and includes a GE Aviation Boeing 737-800 flight management computer (FMC). This FMC features a full geometric descent path calculation (FULL setting) in which the vertical flight path is computed waypoint to waypoint after the top of descent, based on the given altitude constraints. This results in a fixed flight path angle between two successive waypoints, which differentiates it from an idle or continuous descent, as a constant flight path angle is not computed from top of descent to the runway. The full geometric descent path option allows the FMC to stay in vertical navigation (VNAV PTH) mode when using the mode control panel (MCP) to override the FMC commanded speed (i.e., MCP Speed Intervention) throughout most of the descent, or rather after passing the first altitude constraint. This allows flight crews to avoid flying the vertical navigation speed (VNAV SPD) mode, which can often result in mode confusion and energy management issues that were illustrated in previous research (Kaneshige, Sharma, Martin, Lozito & Dulchinos, 2012). While this option provides tighter altitude control by allowing the aircraft to stay on the vertical descent path, it reduces the speed control accuracy and will take the aircraft significantly longer to slow down. Most US carriers with this same aircraft type have purchased (and use) a modified option in which the geometric path descent is active in approach only (APP setting). Thus, with this APP setting, a continuous descent can be flown down a standard terminal arrival route (STAR).

In addition, landing performance was not included in the data collection of the experimental runs due to lack of simulator fidelity in that flight phase.

Participants

Participants were twenty-four active pilots (twelve crews), all currently flying for one of five US air carriers operating under CFR 14 Part 121 (commercial). All were certified to fly a Boeing 737-800. The participants had a mean of 14510 hours of commercial flying experience but not all of this time was flying glass-cockpit aircraft. Crew members were paired from the same air carrier to ensure consistent procedures within each crew.

Routes and Airspace

Each crew flew six approaches through Phoenix Terminal Airspace towards the Phoenix Sky Harbor International Airport (PHX). Two of the six experimental scenarios were intended to test larger speed variances and were not considered in this data analysis. The remaining four scenarios were assessed and will be discussed in this paper.

The EAGUL5 arrival route transitioning to the instrument landing system (ILS) 26 was used for the experimental runs. The published EAGUL5 STAR that was current in March 2012 was used. The EAGUL5 has a number of window altitude constraints with speed constraints (Figure 1). Participants were given a set of Jeppesen reference charts (Terpstra, 2001), in both paper and electronic format, that showed the speed and altitude profiles for the study and the distances between waypoints.

The simulator was initialized about 140 nautical miles (nm) from the runway, putting it a few miles before the top-of-descent; it was always initialized at 36,000ft and at 280 knots. The scenario began with the crew receiving a descent clearance that cleared them to descend via the EAGUL5 route to the runway. For each run, the speed scenario that was presented and the phraseology used were varied. The data collection for the simulated flights stopped at the end of the STAR (at DERVL). Landings were not included in the data collection, although crews were given the option to continue to land.

The same forecast winds were used for all runs. It was initialized out of 253°, a headwind aligned with the landing runways that began at approximately 80 knots at cruise and gradually decreased to an eight knot headwind on landing. The forecast wind profile was entered into the FMS, in order to compute the aircraft's idle descent profile. The wind data were obtained from analysis of actual wind data in the Phoenix Terminal Airspace (Robinson, III, unpublished). For consistency in the evaluation of ATD-1 studies, the wind data have been used across a series of evaluations.

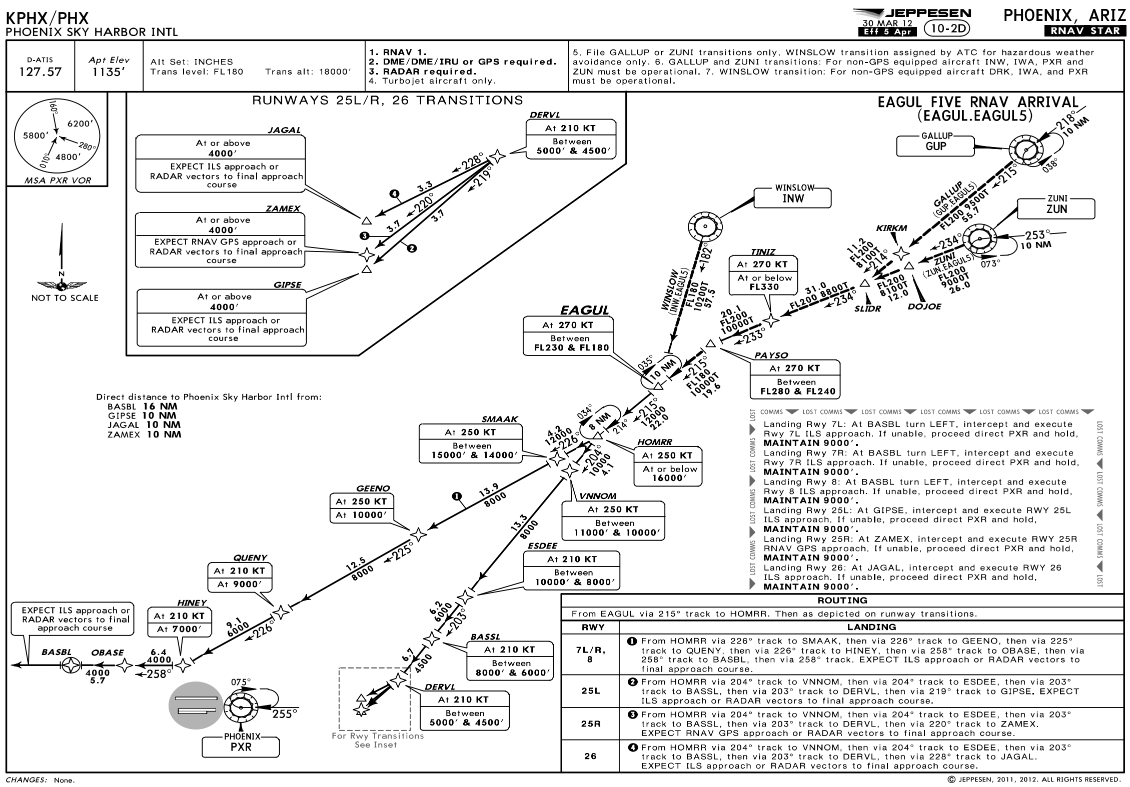

Figure 1: The Jeppesen EAGUL5 STAR as published on 30th March 2012

Study Design

The variables for the study were the speed scheme used and the phraseology type used to convey the clearances. Each variable had two conditions. This generated a 2x2 matrix (2 phraseology x 2 speed scheme) that translated to four scenarios representing each cell of this study design matrix. These four scenarios were each presented once to each crew in a random order.

To increase scenario realism, additional traffic was generated by the Multi Aircraft Control System (MACS) software (Prevôt, Lee, Callantine, Mercer, Homola, Smith & Palmer, 2010) which also emulated an air traffic controller's display and schedule. The confederate controller issued clearances from the scripts provided and used the ATC display to issue clearances at the same points for every crew and to separate the surrounding traffic.

Crews participated in the study for one day. They were briefed in the morning and given time to review the charts and discuss their procedures. The crews also received training on the ACFS, including a training run to insure their comfort with flying generic glass cockpit simulator. The training run was conducted using the GEELA6 arrival route into PHX. Crews flew six data collection runs on the EAGUL5 route, with each run taking approximately 30 minutes.

Speed Schemes

To test the effects of speed variations that are within the ten to fifteen percent boundaries that have been deemed an acceptable range based on the body of work in ATD-1 (e.g., Callantine, Kupfer, Martin & Prevot, 2013), the nominal conditions explored up to a fifteen percent speed deviation around the profile speeds that had been created for the controller automation studies. Video and audio recordings from a previous controller study were reviewed (Callantine, et al., 2013). The controller study used the TMA (Traffic Management Advisor, Swenson, et al., 1997), a scheduling tool that provided an order and spacing for the arrival traffic in its test runs. Clearances issued to flights (from the controller study, Callantine, et al., 2013) that fell within the criteria for the present flight deck study were transcribed, i.e., where the controller had issued speed clearances consistently below or consistently above the published restrictions (in an effort to meet the schedule). Clearance segments from each of the three descent controllers working on the EAGUL route were compiled to create two speed schemes. For the first scheme, the clearances issued were consistently slower than the published speed restrictions by ten to fifteen percent and for the second scheme the clearances issued were consistently faster than the restrictions by approximately the same amount.

Phraseology

Within each script, several strategic clearances were provided to the flight crews. One strategic component of the clearance phraseology was manipulated in an attempt to further explore the phraseology from the previous flight deck study and other CMS research (Martin, et al., 2012). Both forms of the clearance instructed crews to increase or decrease their speed away from the profile speed. Each of the phraseology types contained a temporal constraint suggesting a speed change at a future location. However, the content of the clearances differed in the wording of the instruction. One of the clearance types used the combination of "until….then" to convey future speed constraints (e.g., "Maintain 300 knots *until* EAGUL, *then* resume published speeds"). The other option included the use of "cross….at" clearances ("e.g., *Cross* EAGUL *at* 270 knots and resume published speeds") being more specific about the speed the aircraft should be flying across the waypoint. There were either 12 or 16 clearances provided in a scenario, and two of these strategic clearances were included in each of those runs. Although the two conditions differed in their phrasing of the speed clearances, exactly the same increases and reductions were given in both conditions.

Data Collection

Data were recorded for each run through a variety of media. The ACFS's data collection logs recorded all flight parameters and cab flight-panel button states. A voice-over-internet-protocol system recorded the crew-controller communications, and in-cab video equipment recorded six views of the general cab environment and the flight displays. Participants were asked to respond to a real-time workload prompt, using an ATWIT-based procedure (Stein, 1985), that was recorded on a digital pad and observers recorded flight crew actions using a pencil-and-paper scheme. MACS' data collection logs recorded an ATC view of each run. Following each run, the participants completed a one-page questionnaire that included questions about their workload and problem solving. At the end of the study, participants completed a longer questionnaire asking more generic questions about the concept, and took part in a short debriefing discussion.

The data considered below are focused on the portion of the descent on the STAR, landing performance was not included due to lack of simulator fidelity in that flight phase. Not having to land during the scenarios, particularly during the runs with faster than normal speeds, may have affected crews' acceptance and handling of speed clearances. Pilots were not required to manage the aircraft stability in the landing, or consider the consequences of a missed approach.

The aims of the study were to look at the effects of speed changes and phraseology differences on the ways crews flew an arrival. These effects are potentially numerous and could have a wide range of impacts on both aircraft behavior and crew performance. As the concern is how aircraft fly within schedule-based airspace, the time it takes to fly a descent under identical conditions is a key element, along with whether aircraft were able to stay on their 4D path or diverged from it. An indication of divergence is where aircraft leveled off or where crews had to use speedbrakes. Having to react to speed clearances that may affect the aircraft's flight profile will also impact crew experience, and changes in crew workload are a concern. The following section describes results from a sample of the analyses conducted thus far.

RESULTS

Descent Profiles

Crew descents from SLIDR to DERVL, on the EAGUL5 arrival into Phoenix, took between 20 and 26 minutes. On average, scenarios where crews were given fast speeds (speeds faster than the restrictions) were completed three minutes more quickly (in 22mins 18sec) than scenarios where crews were given slow speeds (speeds slower than the restrictions)(in 25mins 14sec). Even with the manipulations that take communication exchanges from different flights, these times are comparable with the earlier ATC study (Callantine, et al., 2013) as the 104 flights that flew from SLIDR to DERVL in the ATC study took an average time of 24 minutes, 5 sec and ranged in flight time from 21 minutes to 26 minutes.

When the combined speeds issued in the scenarios vary by twenty to thirty percent, differences in flight times are a "given" but it must also be noted that the top of descent point varied with the scenario. For the slow-scenarios, aircraft began their descents at 32sec (on average) into the scenario, which is about 5nmi *before* SLIDR on the STAR, i.e., the aircraft was already in descent as it crossed SLIDR. For the fast-speeds, aircraft began their descents at 262sec on average (4min, 22sec) into the scenario, which is about 20nm after SLIDR (and approximately 25nm further along the STAR than when the aircraft was flying the slow-scenario).

What is notable about these flight times is the variation within one speed condition, that is, within the two sets of speed scenarios there was a surprising amount of variation between crew runs in time but not in distance. For example, it took crew2 24min, 44sec to fly the slow-scenario but it took crew5 71 seconds longer. When apportioned out, the descent-time differences by scenario and phraseology are between 43sec and 66sec across the four nominal study scenarios. The standard deviation in the arrival times at waypoints along the route) are depicted in Figure 2. In general, the slow-speed descents (green and purple lines in Fig. 2) had more time variations than the fast-speed descents (red and blue), and the "until" clearances (green and blue) had more time variations than the "cross at" clearances (purple and red). However, a closer look reveals that a significant portion of these time variations are due to the scenarios, when speed changes occur (relative to the clearances), and how these speed changes are implemented by the full-geometric descent path setting, i.e., the FMS configuration that was used in this study.

As noted, the Full setting provides tighter altitude control by allowing the aircraft to stay on the vertical descent path but reduces speed control accuracy, and it will take the aircraft significantly longer to slow down. This slow deceleration was the primary cause of the significant time variations since the use of speed brakes to increase the deceleration rate varied among crews.

The effects of faster- and slower-speed scenarios resulted also in differences in crew opinion that reflected these objective performance differences. In their post run questionnaires, participants agreed that fast-speed descents were slightly more efficient (ns, m-fast=5.1, m-slow=4.9 out of 7) but reported that they were more challenging (Z=2.966, n=45, p=.003) and that the fast speed requests were less reasonable (Z=-2.269, n=47, p=.023).

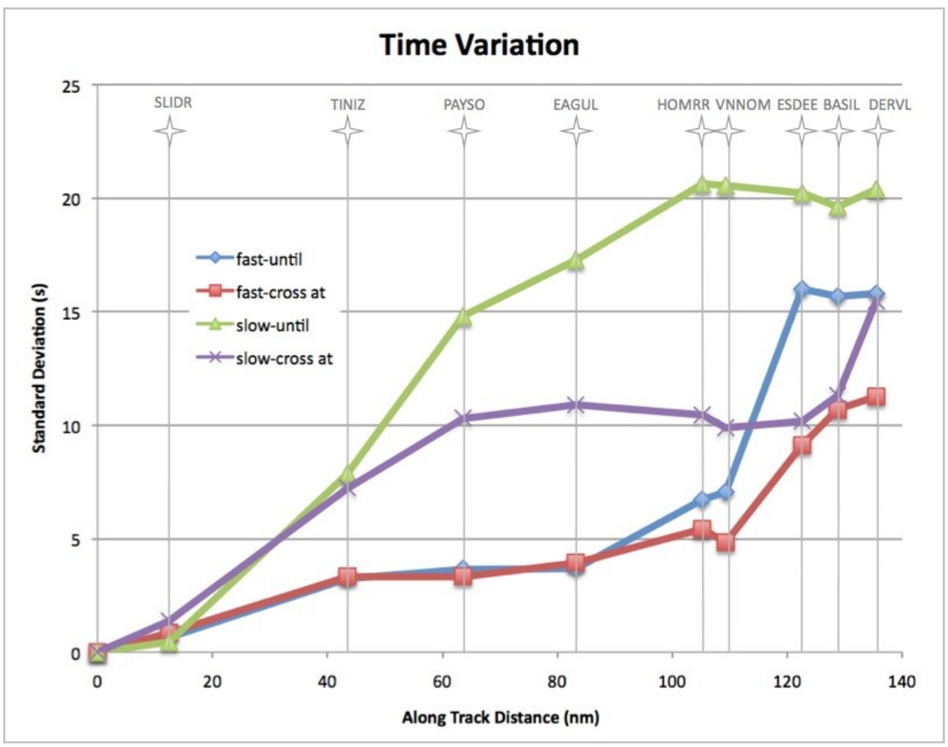

Figure 2. Flight time deviation on the EAGUL5 STAR by speed and phraseology study conditions

Workload

Every four minutes, both crew-members were prompted to assess their current level of workload on a seven-point scale from ‘very low’ (1) to ‘very high’ (7) (Stein, 1985). On average across a run, crews rated their workload at around 3 ‘some’ (m=2.85). Reported workload varied across a run, showing a slight upward trend from the beginning of the run to the end, although the last two points shown on the x-axis (28 and 32 minutes) of Figure 3 were collected on the approach (after the end of the STAR) and are not included in the analysis.

On average, pilots’ ratings for fast-speed runs were slightly higher than those for the slow-speed runs. However, the perceived loads are not clearly different in the chart. The biggest differences in mean workload ratings occur at 12 mins into the run, close to the EAGUL waypoint, where workload increases to just above 3, on average, for fast-speed scenarios, and dips below 2.5 for the slow speed scenarios. When just the first 24 minutes of the run are considered (the first 6 ratings), the differences are not significant. There are also no significant differences between runs based on the phraseology the controller used.

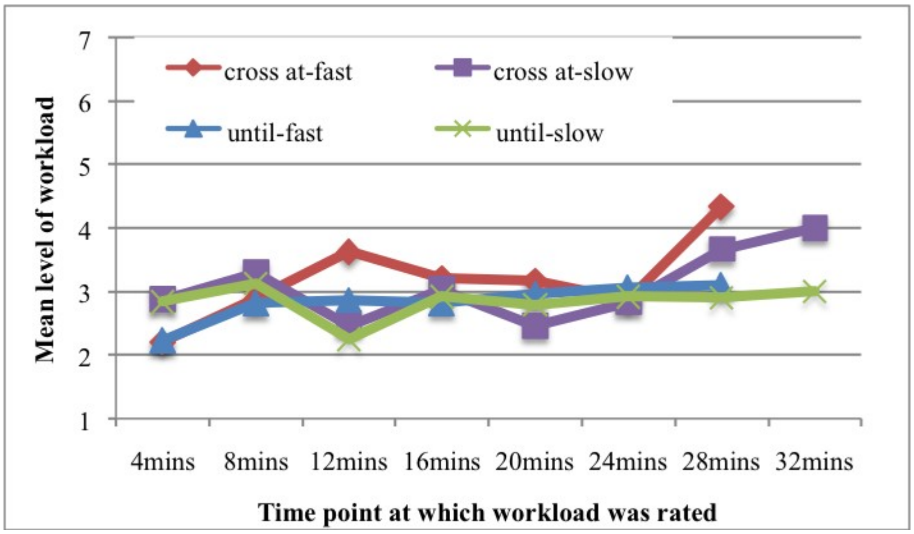

Figure 3: Mean level of workload for the four study conditions

Post-hoc/ Retrospective Views of Workload

Workload was also investigated through four questions in the post run questionnaire that asked four of the six task load index (TLX) questions (Hart & Staveland, 1988). Participants rated these four aspects of their workload on a 1 to 7 (‘very low’ to ‘very high’) scale. Figure 4 illustrates that all the mean ratings for these four aspects of workload fall below the midpoint of the scale, between ‘low’ and ‘moderate’, indicating that participants felt the workload of the scenarios they flew were manageable and reflecting their real-time workload ratings (above).

Between the two speed scenarios, slow-speed runs were consistently rated as having slightly less load than fast-speed scenarios. The largest difference between the two conditions is in reported frustration, with a .7 difference in mean scores, but even time pressure ratings show a small difference, suggesting that participants found the fast scenarios slightly harder to fly. This difference between the frustration ratings is significant (Z=2.57, n=47, p=.01) and between effort ratings (Z=2.33, n=47, p=.02) suggesting that faster-than-restriction clearances were more effort and more frustrating to implement than slower-than-restriction clearances.

There are also differences in participant load responses when they are re-categorized by the phraseology that was used. As expected, means for the four workload questions, when categorized by run phraseology, fell below the midpoint of the scale, between ‘low’ and ‘moderate’ indicating that participants felt both phraseology scenarios generated workload that was manageable. The cross at-phraseology was always rated by participants to require slightly more work and to be less successful on average than the until-phraseology, but not an unacceptable amount and all of the TLX scale comparisons show significant differences (Z_{effort} = -1.965, n=47, p=.049; $Z_{time\ pressure}$ = -2.046, n=47, p=.041; $Z_{frustration}$= -3.279, n=47, p=.001; $Z_{success}$= 3.625, n=45, p=.000) suggesting that crews found the ‘cross at’ phraseology was harder to work with in terms of both effort and affect.

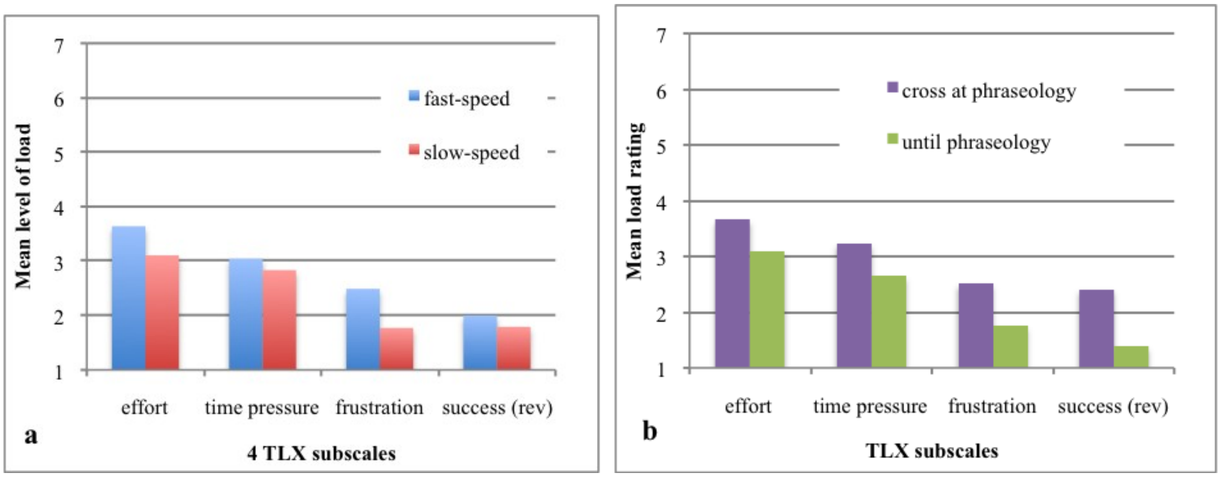

Figure 4: Mean level of four aspects of self-reported workload sorted by clearance study conditions (a, left) and phraseology study conditions ((b, right)

Note: that the ratings for 'success' were reversed so that a lower mean reflects a higher success rating.

Other Questionnaire Responses

Although it seems a generalization to say the participants found the 'cross at' phraseology harder to work with, differences between the mean ratings on all the other post-run rating scales, of which there were seven, show less favorable ratings (albeit by a small amount sometimes) for the 'cross at' phraseology. Three of these rating differences are not significant but the rest are (four). For example, one question asked participants whether they were confused about the actions of the automation during the descent. Participants' mean ratings reflected that they thought they were 'not confused' when they were using the 'until' phraseology and were 'rarely confused' when using 'cross at' phraseology. This seems only a small difference in opinion, but the higher (more often confused) rating for the 'cross at' condition is significantly higher (Z=-3.897, N=48, p=.000, Figure 5) suggesting a consistent difference in participants' views. Likewise, participants rated the speeds given in the 'until' runs as 'fairly reasonable' on average (m=5.12) but a little less reasonable in 'cross at' runs (m=4.36) (Z=2.668, n=47, p=.008) and that it was 'not difficult' to interpret the 'until' speed change requests (m=2.02) but a little less easy to interpret the 'cross at' speed change requests (m=2.89) (Z=-3.106, n=46, p=.002). They also reported that the 'cross at' phraseology placed 'moderate demand' on their attention, which is significantly different from the 'occasional demand' they reported for the 'until' phraseology (Z= -2.406, n=46, p=.016).

Participants' opinions were not the only data from the study that suggest they found the runs using 'cross at' phraseology as more challenging. Some of the data collected by the simulator suggest the descents may have been more difficult to achieve.

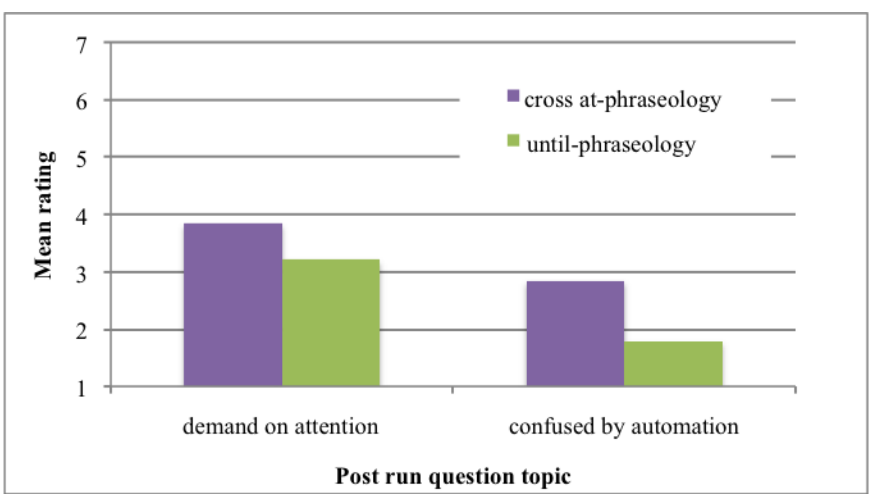

Figure 5: Mean rating of attention and confusion questions under phraseology study conditions

Note: for these ratings, a lower mean reflects less confusion and demand

Level Offs

The number of seconds that aircraft spent in level (or climbing) flight between SLIDR and DERVL were obtained from the simulation data. Figure 6 is an example of the slow-speed runs that used the 'cross at' phraseology, showing that some crews leveled (on purpose or by accident) at approximately four altitudes – FL290, FL230, 16000ft and around 11000ft. These level offs reflect that the speed clearances given meant the flight crew had to manage their descent strategy and the effect of this is a less efficient descent.

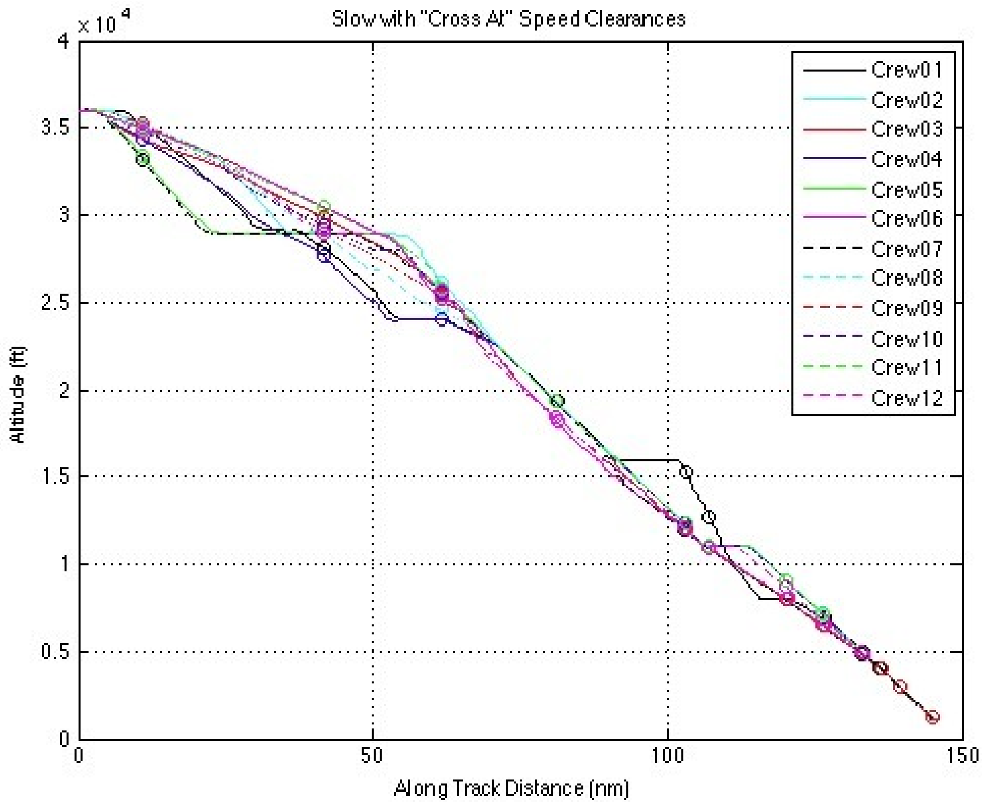

Figure 6: The profile of 12 crew descents under the slower speed than restrictions-cross at study condition

The amount of time crews spent in level flight for runs that used the 'until' phraseology was compared to those that used the 'cross at' phraseology. Figure 7a shows the number of seconds in level flight for the slow-speed runs. On average, crews spent 143.8sec in level flight in slow-'cross at' runs and 116.4sec during slow-'until' runs. This difference lies with seven crews flying their descents differently, as five crews were level for nearly the same amount of time under both phraseology conditions. In all cases but one (crew12), crews spent less time in level flight in the 'until' phraseology condition. Three crews (3, 6, and 9) spent no time in level flight, managing a continuous descent from SLIDR to the bottom of the STAR (DERVL). These differences are not significant when all twelve crews are considered. However, if crew12 is removed from the data, there is a significant difference ($t=2.807$, $df=10$, $p=.019$), with crews spending longer in level flight when the controller was using 'cross at' phraseology than when he was using 'until' phraseology for slow scenarios.

Figure 7b shows the number of seconds in level flight for the fast-speed runs. On average, crews spent 42.9sec in level flight in fast-'until' runs and 52.8sec during fast-'cross at' runs – a much shorter time than for slower-speed runs. This difference lies with ten crews flying their descents differently, as two crews were level for nearly the same amount of time under both phraseology conditions. Six crews spent less time in level flight in the 'until' phraseology condition and four crews spent less time in level flight in the 'cross at' phraseology condition. All crews spent some time in level flight, although the least time (12sec) is very short. These differences are not significant when all 12 crews are considered.

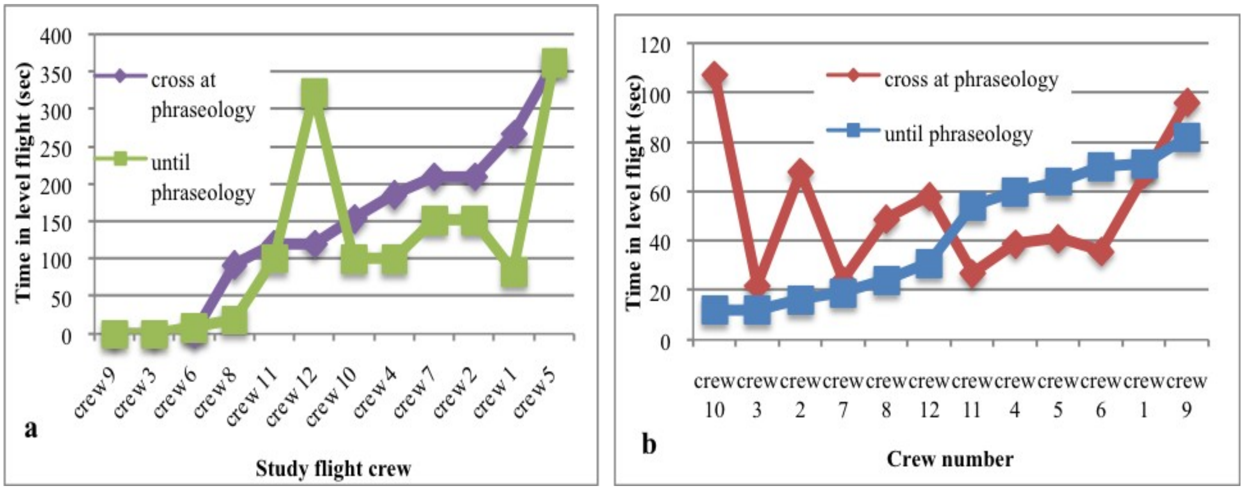

Figure 7: Number of seconds in level flight per slow-speed run (left, a) and fast-speed run (right, b).
Note the difference in scale on the y-axis between the two charts.

Speedbrake Usage

Where level offs indicate when the aircraft is trying to rejoin its path from below, use of speed brakes can sometimes indicate the opposite situation – where the aircraft has flown above its path and the crew is trying to catch it from above. As a preliminary analysis, the number of seconds that the speedbrakes were deployed between SLIDR and DERVL were obtained from the simulation data. Figures 8a and b show the amount of time crews spent with the speedbrake deployed over the study. On average, crews spent the least time with their speedbrakes out in the fast-

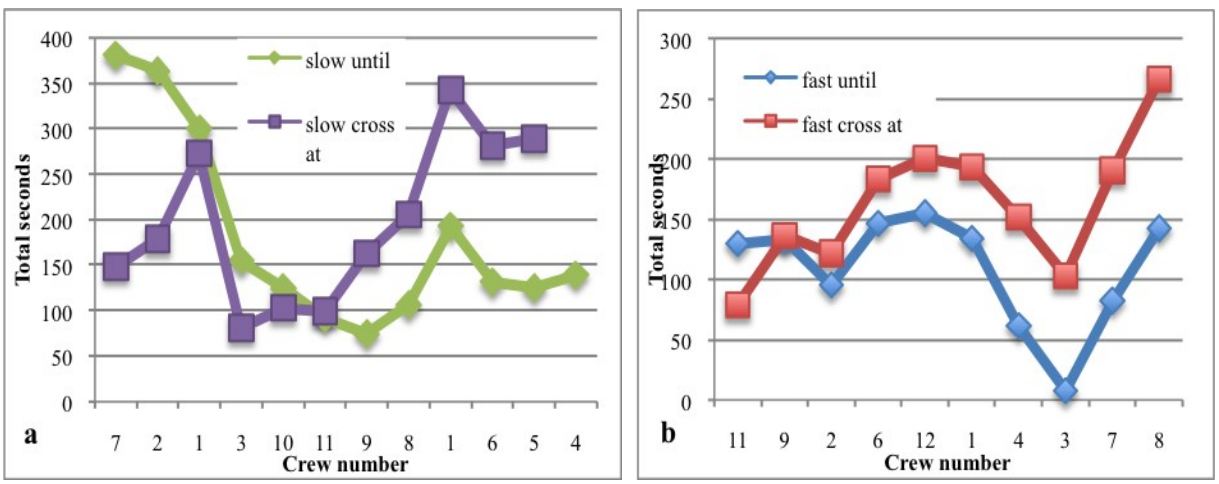

Figure 8: Number of seconds speedbrakes were deployed per slow-speed (left, a) and fast-speed run (right, b).
Note the difference in scale on the y-axis between the two charts.

until condition (m=106.13sec) and the most time, over three minutes, in the slow-cross at condition (m=196.89sec[1]). This difference is significant for scenario speed ($F(47,1) = 5.6$, $p = .022$) but not for the phraseology used. However, speedbrakes were not used one-time only but usually deployed several times, on average four times in a run.

Notable about these data are the sizes of the ranges both for number of uses and for time deployed. In the fast-until scenario, two crews only used their speedbrakes once and for less than 10sec in both cases. While during the cross-at phraseology scenarios two crews deployed their speedbrakes eight times[1] and the longest single time[1] the speedbrake was deployed was for 202sec (over three minutes).

[1] These data do not include the slow-cross at run data from crew 4, where the speedbrakes were deployed early and only partially retracted, which meant they were slightly extended for nearly the whole run.

DISCUSSION

New technologies are being developed and evaluated as part of NASA's ATD-1 Project that are intended to increase capacity and efficiency in the terminal area. These include near-OPDs to insure fuel efficiency, and tools for managing aircraft in descent, such as the Controller-Managed Spacing toolset. Much of the existing research on these concepts has focused upon ground tools and their impact upon controllers, with the assumption that their implementation (which results in speed advisories) will be transparent to pilots. In 2012 an initial evaluation was conducted to explore the use of CMS clearances by commercial airline flight crews. That exploratory study indicated difficulties for pilots when managing speed clearances and in understanding some of the phraseology. The present flight deck study further assessed the impact of speed clearances and the way they are phrased on pilot behavior and workload in a more systematic way, with a simulator representative of a short-haul aircraft type in the today's airspace (Boeing 737-800).

There were some compelling findings related to the use of phraseology. Two forms of phraseology were used in this simulation to evaluate clearance understanding: The use of "until….then" terms to convey future speed constraints (e.g., "Maintain 300 knots *until* EAGUL, *then* resume published speeds"), and "cross….at" clearances ("e.g., *Cross* EAGUL *at* 270 knots and resume published speeds"). The data suggest the use of clearances that used "cross….at" may be more problematic for pilots. The NASA TLX workload subscales for frustration, effort, time pressure, and success revealed significant differences reflecting more workload reported with the "cross…at" clearances when compared to "until….then" clearances. It is important to note, however, that the average workload ratings across all conditions are still at or below the mid-range for the NASA TLX scale we presented, of seven. Some of the questions regarding confusion and reasonableness on the post-simulation questionnaire also indicated preference for the "until…then" phraseology. Finally, when examining the descent profiles for the experimental runs, more seconds in level flight and more seconds with speedbrakes extended were found in the cases where the "cross….at" clearances were used, rather than "until….then" clearances, which may indicate confusion about altitude constraints that resulted in a hesitation to continue the near-optimum descent. These findings seem to point to an overall increase in confusion for the pilots when receiving clearances with the constraints expressed as "cross….at". The use of "cross…at" provides clarity about aircraft performance at the specific point, but less clarity exists for the timing of the instruction related to the second part of the clearance (e.g., "cross EAGUL at 270 *and* resume published speed"). With the clearances using a combination of "until…then", the second part of the clearance provides more guidance about the temporal nature of implementing that part of the instruction, allowing for a sequential indication of clearance enactment. That is, in the clearance "Maintain 300 knots *until* EAGUL, *then* resume published speeds", there is clear guidance that 300 knots until EAGUL should be achieved first, followed by a resumption of published speeds. In fact, a few comments from the pilot participants stated that they felt that the "until…then" clearance phrase was more precise. The enhanced clarity about timing and sequence may provide the benefit of a better understanding about clearance implementation, particularly in a busy descent phase of flight. Pilots may experience a reduction in perceived frustration and workload, and confidence to continue a smooth descent profile.

As it is an implicit assumption of the ATD-1 work that no flight deck training will be required, the pilot participants were asked about whether there was a requirement for specific training or new aircraft equipment when receiving CMS clearances. The crews in this simulation noted they received speed changes, which they perceived to be unnecessary and inefficient, and sometimes not achievable. Due to these concerns, participants had varying opinions about whether any additional training or briefing materials might be required for pilots operating with these new tools. Twelve of the 24 participants felt that a segment of their recurrent training should include consideration of these types of speed clearances, and seven felt that there could be a flight bulletin – notifying potential pilots flying in relevant airspace that they may be provided these new clearance types. Three of the 24 pilots stated that no new training was required, or had no opinion. All pilot participants said that no new equipment is necessary on the aircraft.

An interesting result from this study suggests a fair amount of variability in the descent profiles flown in this simulation. This variability may disrupt the scheduling scheme provided by the ground automation tools, which could create instability and reduce efficiency, and suggests further research should be focused on this issue. The times to fly the faster-than-the-restriction speed descents and, separately, the slower-than-the-restriction speed descents varied by approximately a minute each, despite the fact that the actual speeds issued in the clearances were the same. Although there does appear to be an impact on the descent profile by the types of speed clearances and the phraseology, the variation may be more directly related to the timing and implementation of the speed clearances, i.e., when clearances were issued relative to waypoints. Slow deceleration seems to be the primary cause of the descent profile variation. It may also be a by-product of the full-geometric descent path setting in the FMS, a setting that is not commonly used in most of the B737 aircraft operated by US carriers. One difference created by this setting is the FMC mode when a pilot is using speed intervention. When flying a full-geometric path leg using the MCP for speed control, VNAV remains in VNAV PTH thus resulting in possible differences in energy management techniques compared with FMCs that are in the APP setting, where VNAV transitions to VNAV SPD if the MCP is used. The time variation may also be a result of the manner in which the clearances were executed. If a crew flies using MCP speed intervention and flies the descent in VNAV SPD, a faster commanded speed results and the aircraft increases its decent rate (and departs below the vertical path) in order to accelerate to the new commanded speed. Unless additional thrust is added to decrease the descent rate, the aircraft eventually levels off at the next altitude constraint until it crosses the corresponding waypoint. However, if a slower commanded speed is entered, the aircraft decreases its rate of descent (and departs above the vertical path) in order to decelerate to the new commanded speed. Unless additional drag is added (by deploying speed brakes or flaps), the aircraft could violate subsequent altitude constraints.

It should be noted that simulation effects may account for the results that were uncovered, and may impact the ability to generalize the data to broader operations. As previously noted, the differences in the VNAV mode switching in this simulator may have led to confusion regarding autoflight modes. In addition, landing performance was not included in the data collection, and that may have affected the crews' acceptance and handling of speed clearances. Pilots were not required to manage the aircraft stability in the landing, or consider the consequences of a missed approach. Further research in these descent tools and procedures should include landings as part of the experimental scenarios, and should also allow for varying FMS capabilities.

The present study aimed to build on the findings of a previous flight deck study (Martin, et al., 2012) to further investigate assumptions about training and transparency of controller tools to the flight deck, and to look more deeply into issues with phraseology and pilots' use of automation. The participants generally did not think that training was required to fly OPDs; however, there was some evidence that knowing more about the operational goals of OPDs might assist pilots to work towards meeting their STAs. Parameters such as level offs and use of speedbrakes were used in different amounts and locations, providing data that reflected variations in how crews flew the descents. Crews' approaches to flying the descents were impacted, as expected, by the speed of the clearances but also by the phraseology that was used to deliver them. The results suggest that these clearances can be used operationally, but some refinement of clearance phraseology and a general awareness of the goals of the controller tools would be beneficial. Further research should examine a broader use of flight deck automation tools when enacting OPD clearances, as well as exploring additional aircraft types for operational performance.

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