USING ENHANCED FLIGHT VISION SYSTEMS (EFVS) FOR LOW-VISIBILITY TAXI IN TRANSPORT CATEGORY AIRCRAFT

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Two studies (using Boeing 777 and 737 simulators) examined flight crews' use of an Enhanced Flight Vision System (EFVS) for low-visibility taxi operations. Twenty-five flight crews completed 21 short taxi scenarios under combinations of the following: Runway visual range (RVR: 300, 500, and 1000 ft); EFVS on head-up display (on/off); Airport infrastructure - 3 levels. The use of EFVS produced fewer route deviations, most at 300 feet RVR with edge lights and standard centerline or routes with LVO/SMGCS "enhancements" (without centerline lights). Larger turn angles and lower visibilities were associated with slower rates of travel. Crews detected the obstacle on the right-side most of the time and twice that of the left-side obstacle. Regardless of EFVS, crews had more route deviations on larger (>90 degrees) turns and right turns, possibly from loss of visual references in the turn. Recommendations are provided regarding benefits and limitations of EFVS for low-visibility taxi with suggestions for additional research.

The Federal Aviation Administration (FAA) Low-Visibility Operations/Surface Movement Guidance and Control System (LVO/SMGCS) voluntary program has supported safer taxi operations in low visibilities of less than 1200 feet runway visual range (RVR) since 1996. Approximately 70 U.S. airports have FAA-approved LVO/SMGCS plans, which comprise a combination of airport infrastructure and procedures as outlined in Advisory Circular (AC) 120-57A (FAA, 1996) and FAA Order 8000.94 (2012). The current LVO/SMGCS program has two levels: Level 1 is at visibilities from less than 1200 to 500 feet RVR and Level 2 is at visibilities from less than 500 to 300 feet RVR. A Level 3 (<300 feet RVR) is proposed once FAA/industry can jointly demonstrate that aircraft will operate safely with emerging technologies like an Enhanced Flight Vision System (EFVS), which displays a sensor image of the outside scene on a head-up display (HUD). EFVS technology combined with procedural mitigations could provide support for changing the existing low visibility taxi route program to include an EFVS low visibility taxi route at participating airports.

To gain a better understanding of how the proposed changes may be implemented, the FAA is interested in whether an EFVS can aid pilots in taxiing safely in low-visibility conditions when LVO/SMGCS infrastructure is reduced or not present. If so, it might increase access to airports that do not have an LVO/SMGCS plan because of current infrastructure costs. Although the FAA does not regulate taxi operations, the FAA is interested in understanding how to better support low visibility taxi operations without compromising safety with reduced airport infrastructure.

The focus of this examination was limited to a sensor-based display in light of (1) the fact that there have been numerous studies performed using database oriented (electronic map or synthetic vision) displays to facilitate low-visibility operations (maps: Lorenz & Biella, 2006; Battiste, Downs, & McCann, 1996; Yeh and Chandra, 2003, and perspective forward-looking displays: McCann, Andre, Begault, Foyle, & Wenzel, 1997; Beringer, Domino, and Kamienski, 2018), (2) a lesser number on use of EFVS (eg. Kramer, et al., 2013), and (3) some inherent limitations in displays generated from a database (accuracy of registration with the outside world, and obstacles or momentary obstructions unlikely to be in the database). The intent of this effort was to identify any potential safety decrements that might be encountered during the use of EFVS for taxiing in low-visibility conditions under likely airport infrastructure variations with less than that presently required for LVO/SMGCS. Data were collected for simulated wide-bodied aircraft (Boeing 777) and narrow-bodied aircraft (Boeing 737) to see if crews' anticipation of turns, being different in the two, might affect operations with the display.

Method

Participants

Twelve two-person B-777 flight crews from one carrier participated in Phase 1 and 13 two-person B-737 flight crews from various carriers participated in Phase 2. Both pilots in each crew were required to have at least 10 hours flight time within the past 30 days. The pilot flying was required to have at least 100 hours of head up display (HUD) experience. For the B-777 pilots, required HUD experience was as pilot-in-command in an aircraft equipped with an EFVS. At least one crewmember was required to be Category (CAT)-III ILS qualified for the previous five years. Each flight crew was comprised of pilots from the same company to minimize differences in standard operating procedures. On average, B-777 pilots had 17 years of CAT-III experience (SD = 10, Range = 0 to 35) and B-737 pilots had 12 years (SD = 9, Range = 0.5 to 30).

Simulation Environment

Phase 1 was conducted in a CAE B-777F level D full-flight simulator operated at the FedEx Flight Training Center in Memphis, TN, and Phase 2 was conducted in a CAE Boeing 737-800NG level D full-flight simulator operated by Flight Standards Flight Operations Simulation Branch at the Mike Monroney Aeronautical Center in Oklahoma City, OK. Both simulators used a version of the same Rockwell-Collins EP-8000 visual model for the EFVS image and airport simulation. The simulators were operated with the motion on to provide additional feedback (operational realism) to the pilots. The infrared (IR)-based EFVS was displayed on a Rockwell-Collins HUD in front of the left-seat pilot. The right-seat pilot did not have an EFVS. Pilots were able to control the pilot-adjustable settings (e.g., brightness) for the EFVS and HUD. All other EFVS settings were preset prior to the taxi scenarios. EFVS display features, characteristics, flight information, flight symbology, and sensor imagery were based on regulatory requirements (14 CFR §§ 91.176 and 25.773), minimum aviation system performance standards for EFVS (RTCA, 2011; FAA, 2016), guidance for EFVS operations (FAA, 2017), and/or as recommended by LVO/SMGCS subject matter experts (SMEs).

Design

Three independent variables were combined, as shown in Table 1, to form a 3x3x2 fully crossed within-subject factorial design: Runway Visual Range (RVR; 3 levels), Infrastructure (3 levels), and EFVS display (2 levels).

Table 1. *Experimental Conditions (taxiway edge lights were always present).*

RVR (ft)	**Infrastructure**	**EFVS**	
		On	**Off**
300	Standard centerline + edge lights Level 1 (L1)	**300-L1-on**	**300-L1-off**
	+centerline enhancement (L2)	**300-L2-on**	**300-L2-off**
	+ centerline lights (L3)	**300-L3-on**	**300-L3-off**
500	L1	**500-L1-on**	**500-L1-off**
	L2	**500-L2-on**	**500-L2-off**
	L3	**500-L3-on**	**500-L3-off**
1000	L1	**1000-L1-on**	**1000-L1-off**
	L2	**1000-L2-on**	**1000-L2-off**
	L3	**1000-L3-on**	**1000-L3-off**

Note. Heavily shaded cells with white text indicate the 18 cells of the 3x3x2 factorial design.

Task/Scenarios

Pilots performed taxi scenarios at a simulation of KSLC (Salt Lake) at night. Nighttime conditions were chosen based on SME input to represent the more commonly encountered difficult low-visibility condition, compared to worst-case dusk or dawn times. Because the study examined variable infrastructure, the KSLC simulator airport model was altered to remove LVO/SMGCS lights and markings along the taxi routes other than the specific LVO/SMGCS route used as a baseline reference. Twelve taxi scenarios were constructed such that (1) each contained at least one turn each of <90 degrees, 90 degrees, and >90 degrees (a sampling variable); (2) scenarios were balanced between left and right turns; (3) all began on a taxiway or runway. Some were repeated within an order, but those that were repeated were placed near the beginning and near the end of the counterbalanced orders. Three additional scenarios were included as supplemental conditions; two routes passed near a truck parked at the edge of the taxiway to examine crew obstruction detection/reactions, and a third used LVO/SMGCS centerline enhancements and designated route centerline lighting at 300 feet RVR, EFVS off, for a baseline.

Procedure

Upon arrival, crews completed the pre-experiment paperwork and briefing, including the Informed Consent Form, pilot experience questionnaire, and viewing of a PowerPoint briefing (Phase 2 only), along with a short briefing regarding the procedures to be followed. Pilots were told that they would be asked to traverse some non-standard routes (i.e. some that may be contrary to current SLC airport routings and requirements). These included some turns greater than 90 degrees. Additionally, pilots were also given paper route maps for each scenario that included printed copies of the ATC taxi instructions, EFVS setting (on or “hide”), and the aircraft’s starting position on the airport surface.

Pilots next entered the simulator and completed a practice taxi scenario, to familiarize themselves with the simulator and EFVS setting, with the EFVS on in 500 feet RVR with LVO/SMGCS centerline “enhancements” (12-in wide with a 6-in black border), centerline lights, and edge lights. This was followed by the 21 experimental scenarios. Each scenario took approximately 5 to 10 minutes to complete. A 15 to 20-minute break was provided halfway through the scenarios. Two researchers sat in the simulator cab during the sessions, one acting as a simulated ATC controller, and the other as observer. When the scenarios were completed, the pilots returned to the briefing room where each completed a post-experiment questionnaire. After completing the questionnaire the test team solicited general comments or questions from the crews and presented an overview of the purpose of the study. The entire session required between 4 and 5 hours. As the results of both phases were similar, they will be presented together by type of performance measure.

Results

Performance Metrics

Centerline tracking. Although the means for centerline tracking were consistent and all averages were within 3.5 to 5 feet of the centerline, slightly more variability was evident when RVR was 300 than in the other visibilities, with 1000 RVR showing the narrowest variability. There was also slightly more variation with EFVS off than there was with it on, but the means were essentially the same. A similar pattern was observed for infrastructure but was somewhat anomalous with slightly less variation in conditions with the least infrastructure (Level 1).

Route Deviations. The majority of route deviations occurred at 300 feet RVR (Figure 1A). This was expected as a function of the reduced visibility. The maximum percentage of scenarios on which uncorrected deviations occurred was just over 15% for 777 at 300 RVR. About half as many deviations were detected soon enough to correct them. The 737 crews had roughly an equal proportion of uncorrected and corrected deviations in same visibility conditions (9% and 11.5% respectively). There were no uncorrected errors with either aircraft when EFVS was on at 300 RVR. This may also be related to the fact that crews taxied slightly slower in the lowest visibility than in the two higher visibilites. Overall, the percentage of deviations roughly linearly decreased as visibility increased.

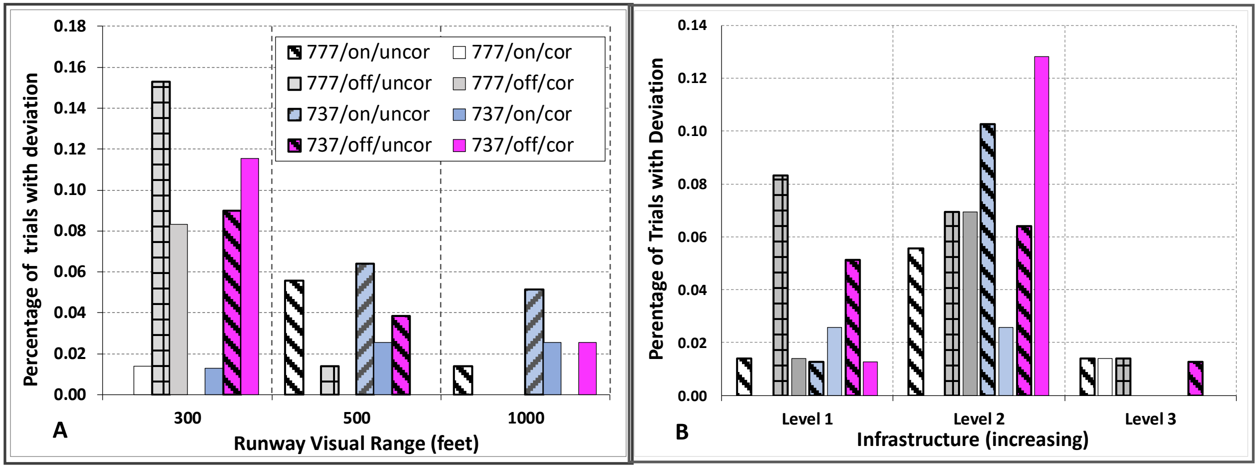

Figure 1. Percentage of route deviations by aircraft type, EFVS (on/off), and (A) RVR and (B) Infrastructure.

Interestingly, the pattern of deviations relative to increasing taxiway infrastructure was not entirely as anticipated. Level 3 did exhibit the lowest number of deviations (Figure 1B). The nonintuitive result was that Level 2 exhibited the most, with Level 1 having the middle frequency of deviations. One can also see across the two figures that the percentage of deviations with EFVS on (which averaged 2.2%) was smaller than when EFVS was off (4.3%).

Obstacle detection. Obstacle detection was defined as the pilot verbally indicating seeing the truck during the scenario. Flight crews in both studies detected the right-side truck the majority of the time, and about twice as often as they detected the left-side truck (Figure 2). In fact, the detection rate was approximately 90% for the 777 crews when the truck was on the right of the taxiway. If pilots did not verbally acknowledge seeing the truck, researchers asked the pilot about it during the post-test questionnaire and interview. However, for the purposes of analysis, only verbal indications of seeing the truck were included. The first officer frequently detected the obstacle, as the captain was often looking out the left-side window trying to keep the taxiway edge line in sight. The left-side truck was at a 90-degree turn to the left, and thus was not in the sensor field of view (30° x 15° in Study 1 and 32° x 15° in Study 2) during the turn, which possibly led to a lesser chance of being detected. This represented a situation where objects outside the sensor's field of view could potentially pose a hazard not immediately apparent in the EFVS. Descriptive statistics are presented here because the events were not independent due to the repeated-measures design.

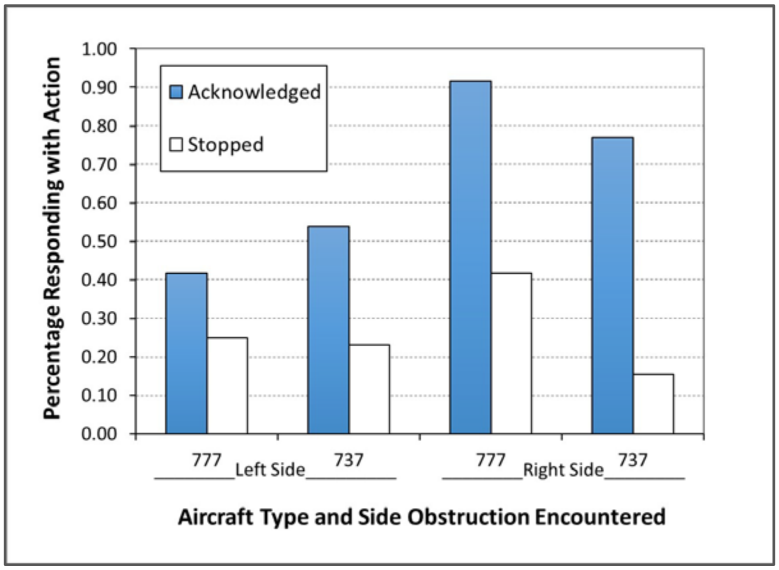

Figure 2. Pilot responses to an obstacle near the taxiway by aircraft type and object location.

Pilot Opinions

Boeing 737 pilots felt that reduced infrastructure contributed to increased workload. Moreover, Captains reported difficulty making right turns, particularly in the B-777, because they would lose visual reference to the centerline under the aircraft. Pilots did not feel that EFVS contributed to their position awareness above what their own direct observations provided. Although a moving map was not used in this study, pilots also felt that a moving map in addition to EFVS would provide improvements in position awareness. Some pilots had concerns about the use of EFVS in low-visibility operations, including the restricted EFVS FOV, limitations regarding EFVS visuals (e.g., parallax, blue lights showing up as green), and the limited effectiveness of EFVS under certain environmental conditions (e.g., precipitation or dense fog). Despite their concerns, both groups of pilots generally felt that an EFVS repeater should be made available to the First Officer.

Conclusions

EFVS provided a benefit to navigation performance at 300 feet RVR when there were no centerline lights. However, EFVS had no effect on navigation performance at 500 feet RVR and above. That is, with minimal taxiway infrastructure in visibilities of 500 feet RVR or greater, flight crews were generally able to navigate successfully with or without EFVS. Note that these results should not be taken to suggest that taxi operations are safe in these conditions without EFVS. Almost all of the wrong or missed turns observed in these studies were made on right turns. However, flight crews made very few wrong turns when centerline lights were available, suggesting that difficulties finding the centerline may be alleviated when the centerline is lit.

These studies also examined potential limitations on taxiing with reduced infrastructure. As mentioned previously, right turns were difficult and were observed to have more errors, notably without centerline lighting. It was also found that sharp turns greater than 90 degrees were associated with more route deviations and were described by pilots as being difficult, particularly without lights and markings. In wide-body aircraft, pilots may also find it difficult to oversteer on sharp turns. Additional research is needed to understand the impact of intersection complexity (using a more robust definition) during low-visibility taxiing. Taxi routes used in these studies were not designed to be complex. Although some complex intersections were noted, there were too few of them to make any conclusions about how effectively flight crews navigated them.

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