Use of an Enhanced Flight Vision System (EFVS) for Taxiing in Low-Visibility Environments

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Abstract. Two studies (Boeing 777 and 737 simulators) examined flight crews' use of an Enhanced Flight Vision System (EFVS) for taxiing in low-visibility conditions in lieu of infrastructure for Low-Visibility Operations/Surface Movement Guidance and Control Systems (LVO/SMGCS). Twenty-five flight crews completed 21 short taxi scenarios under combinations of the following variables and levels: Runway visual range (RVR; 300, 500, 1000 ft); Enhanced-Flight-Vision System in head-up display (on/off); airport infrastructure - 3 levels. Two scenarios dealt with detecting obstacles near the taxi path. In both studies, the use of EFVS resulted in fewer route deviations, the majority of which occurred at 300 feet RVR with edge lights and either a standard painted centerline (Level 1) or a painted centerline with LVO/SMGCS "enhancements" but without centerline lights (Level 2). Deviation from taxiway centerline was variable, but was consistent between display conditions (EFVS/no EFVS) (mean <4 ft). Larger turn angles and lower visibilities were associated with slower rates of travel. Flight crews in both studies detected the right-side obstacle the majority of the time, and about twice as often as they detected the left-side obstacle. Regardless of EFVS, flight crews in both studies made more route deviations on larger turns and right turns. Pilot feedback suggested the issue was loss of visual references to the turn, particularly without centerline lights. Recommendations are provided regarding the benefits and limitations of EFVS for low-visibility taxi operations, procedures for low-visibility taxi operations in general, and suggestions for future research.

Keywords: Enhanced flight vision systems · Pilot performance · Transport aircraft

1 Introduction

1.1 Background

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

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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 1200 to 500 feet RVR and Level 2 is at visibilities from 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), a sensor-based system, based upon light in the infrared spectrum, which display a sensor image of the outside scene on a head-up display (HUD). Additionally, a proposed Protected Low Visibility Taxi Routes program change provides support for suitably equipped aircraft operating via procedural mitigations 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 such operations were demonstrated to be safe, it might increase access to airports that do not currently have an LVO/SMGCS plan. Although the FAA does not regulate taxi operations, the FAA is interested in understanding how to better support taxi operations without compromising safety, particularly in reduced-visibility and reduced-infrastructure conditions.

There have been a number of studies that have looked at the use of forward-looking perspective displays and map displays to support low-visibility taxi operations. These fall into several categories which include: forward-looking synthetic-vision displays (head down, HDD, or head up, HUD), forward-looking sensor-based displays (HDD or HUD), and map displays (plan-view or exocentric perspective). Each of the various types, some in isolation and some in conjunction with other displays, has shown a potential for improving the safety and efficiency of aircraft operations.

The focus of this examination was limited, however, to a sensor-based display in light of (1) the fact that there have been numerous studies performed using data-base oriented displays to facilitate low-visibility operations (maps: Lorenz and Biella, 2006; Battiste et al. 1996; Yeh and Chandra 2003, and perspective forward-looking displays: McCann et al. 1997; Beringer et al. 2018), (2) a lesser number on use of EFVS (e.g. 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 that are unlikely to be contained and thus displayed). Thus, it has been suggested that a sensor-based system that can provide surveillance ahead of the aircraft at distances greater than that possible with the unaided eye is preferred for this type of operation. A number of EFVS systems have now become available and are, as such, candidates for supporting low-visibility operations.

The intent of this study 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. The manipulations included a wide range of turn angles along the taxi paths, some unconventional paths, and trials where there were obstructions/hazards in order to fully exercise the potential use of the sensor/display system and the crews' abilities to perform the task. Additionally, data were collected for simulated wide-bodied aircraft (Boeing 777) and narrow-bodied aircraft (Boeing 737) operations given that how crews anticipate turns is dependent upon the placement of the nose wheel relative to the pilot's viewpoint.

2 Method

2.1 Participants

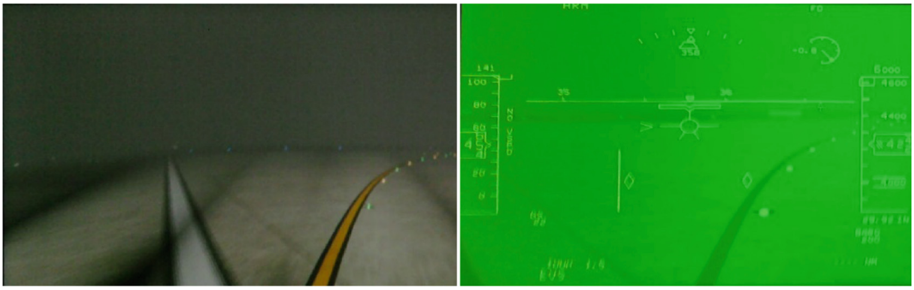
Twenty-four B-777 pilots (12 two-person flight crews) participated in Phase 1 and 26 B-737 pilots (13 flight crews) from various airlines participated in Phase 2. Both pilots in each crew were required to have at least 10 h flight time within the past 30 days. The pilot flying was required to have a least 100 h 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 qualified for the previous five years. Each individual 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 = 0–35) and B-737 pilots had 12 years (SD = 9, Range = 0.5–30). All pilots were compensated for their participation.

2.2 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 infrared (IR) based EFVS image and airport simulation. The simulators were operated with the motion on to provide additional feedback (operational realism) to the pilots.

Enhanced Flight Vision System (EFVS). The IR-based EFVS simulated image 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 trials. 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). One exception was that the HUD FOV in both simulators was greater than the minimum requirement of 20° horizontally by 15° vertically (Study 1 FOV was 30° × 15° and Study 2 was 32° × 15°).

Example out-the-window and HUD/EFVS views are depicted in Figs. 1A and B.



A B

Fig. 1. (A) Example out-the-window view from simulator left seat and (B) example view of the HUD EFVS image.

2.3 Design

The study measured the effect of three variables on pilot performance:

1. RVR (3 levels): 300, 500, or 1000 feet
2. Airport infrastructure (3 levels):
   a. Level 1 (L1): Standard centerline (6” wide) with edge lights
   b. Level 2 (L2): Level 1 plus centerline with LVO/SMGCS “enhancements” (12” wide with black border)
   c. Level 3 (L3): Level 2 plus centerline lights
3. EFVS (2 levels): on or off (when ‘off’, EFVS image turned off, HUD symbology left on).

These variable levels were combined to create a 3 × 3 × 2 fully-crossed within-subject factorial design with flight crew as the replication factor (Table 1). That is to say, each flight crew performed one taxi trial for each of the experimental conditions.

Table 1. Experimental conditions (taxiway edge lights were always present). Heavily shaded cells with hite text indicate the 18 cells of the 3 × 3 × 2 factorial design.

RVR (ft)	Infrastructure	EFVS	
		On	Off
300	Standard centerline + edge lights (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**

2.4 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 minimal 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°, 90°, and >90°, (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 were designed to pass near a truck parked at the edge of the taxiway to assess to what degree an object that might pose a potential hazard might be detected. A third was conducted that used LVO/CMGCS centerline enhancements and centerline lighting only designated route lighted) in 300 feet RVR with the EFVS off to provide a baseline reference condition.

3 Procedure

Due to simulator availability, Phase 1 flight crews began the study at night (starting at approximately 7:30 PM) local time. For Phase 2, pilots began the study in the morning (8:00 AM) or early evening (5:00 PM), local time. The entire study took between 4–5 h for each flight crew to complete.

When crews arrived at the simulator facility, they were seated in a briefing room with a researcher to complete the pre-experiment paperwork and briefing. Each pilot read and signed an Informed Consent Form, filled out the background questionnaire concerning general pilot experience as well as LVO/SMGCS and EFVS, and viewed a PowerPoint briefing describing the EFVS (Phase 2 only), and a short verbal briefing which outlined the basic study procedures (Phase 1 and 2). Pilots were told that they would be asked to traverse some non-standard routes, including some with extreme turns. During the briefing, each pilot was also given paper sheets for each scenario that contained the ATC instructions, EFVS setting (on or “hide”), and the aircraft’s starting position on a portion of the airport chart. Pilots were informed that they would not be able to use an airport moving map during the taxi scenarios.

After the briefing, pilots entered the simulator and completed a practice taxi scenario with the EFVS on in 500 feet RVR with LVO/SMGCS “enhanced” painted centerlines, centerline lights, and edge lights. The purpose of the practice trial was to generate pilot familiarity with the simulator and EFVS settings. Following the practice scenario, pilots were given a chance to ask questions before beginning the 21 experimental trials. Each taxi trial took approximately 5–10 min to complete. A 15 to 20 min break was provided halfway through the scenarios. Two researchers sat in the simulator cab during the scenarios—one acted as “live” ATC and the other observed and took notes.

At the completion of the trials, the flight crew returned to the briefing room where each pilot completed their own post-experiment questionnaire. Once these had been completed, the researcher asked the pilots for general comments or questions, and provided an overview of the purpose of the study. The entire session required between 4 and 5 h. As the results of both phases were similar, they will be presented together by type of performance measure.

4 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 (Fig. 2). 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 visibilities. Overall, the percentage of deviations roughly linearly decreased as visibility increased.

Interestingly, the pattern of deviations relative to increasing taxiway infrastructure was not entirely as anticipated. Level 3 did exhibit the lowest number of deviations (Fig. 3). 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 (Fig. 4). 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 simulated sensor field of view during the turn, which possibly led to a lesser chance of

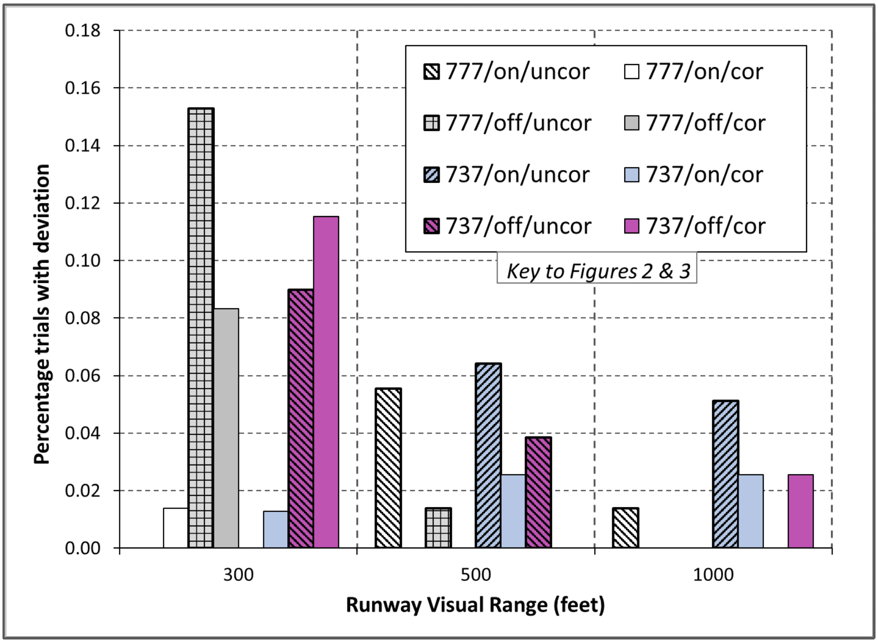


Fig. 2. Percentage of trials with corrected or uncorrected taxi deviations by RVR, EFVS on/off, and flight simulator type.

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.

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.

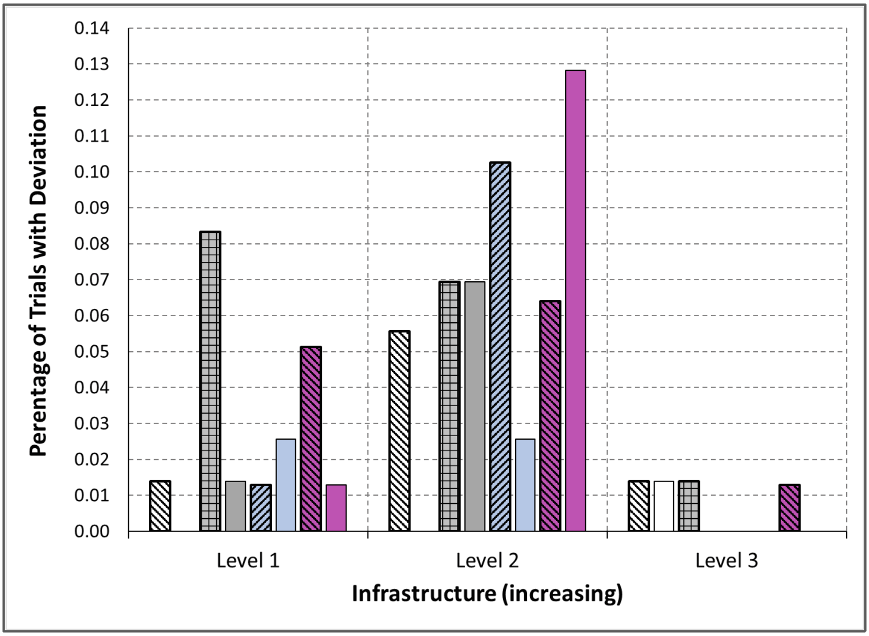


Fig. 3. Percentage of trials with corrected or uncorrected taxi deviations by level of infrastructure, EFVS on/off, and flight simulator type.

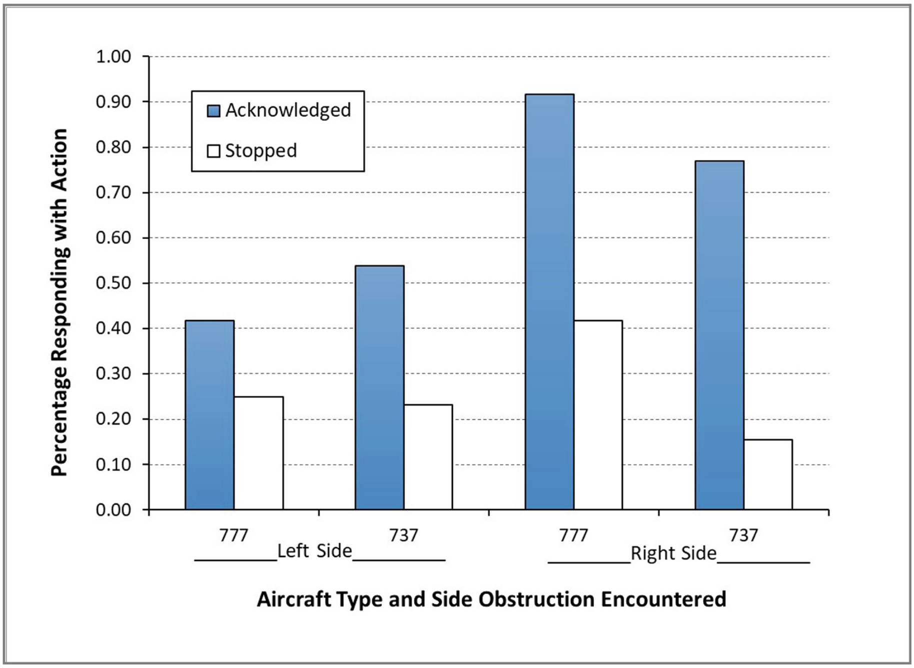


Fig. 4. Pilot responses (percentages) to an obstacle near the taxiway by aircraft type and object location.

5 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. The EFVS may also increase the probability of detecting obstacles in low-visibility conditions. However, obstacles that are outside the sensor's FOV could be missed.

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° 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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