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LIST OF ACRONYMS

Acronym	Term
AC	Advisory Circular
ANOVA	Analysis of Variance
ATC	Air Traffic Control
ATP	Air Transport Pilot
CAT	Category
CFI	Certified Flight Instructor
CFII	Certified Flight Instructor – Instrument
EFB	Electronic Flight Bag
EFVS	Enhanced Flight Vision System
EMM	Electronic Moving Map
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FO	First Officer
FOV	Field of View
HDD	Head Down Display
HUD	Head Up Display
KSLC	Salt Lake City International Airport
LAAS	Local-Area Augmentation System
LSD	Least Significant Difference
LVO/SMGCS	Low-Visibility Operations/Surface Movement Guidance and Control System
PFD	Primary Flight Display
PIC	Pilot In Command
RVR	Runway Visual Range
SD	Standard Deviation
SME	Subject Matter Expert
SV	Synthetic Vision
SVS	Synthetic Vision System
SVGS	Synthetic Vision Guidance System
WAAS	Wide-Area Augmentation System

EXECUTIVE SUMMARY

Two studies 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). Study 1 was conducted in a Boeing 777 (B-777) simulator with B-777 pilots to represent wide-body aircraft types, and Study 2 was conducted in a Boeing 737 (B-737) simulator with B-737 pilots to represent narrow-body aircraft types. The method was the same for both studies. Flight crews completed 18 short taxi scenarios under combinations of the following conditions:

1. Runway visual range (RVR; in ft)
    a. 300
    b. 500
    c. 1000
2. EFVS
    a. On
    b. Off
3. Airport infrastructure (each level an extension of the previous level)
    a. Level 1: Standard painted centerline + edge lights (baseline)
    b. Level 2: Level 1 plus LVO/SMGCS painted centerline "enhancements" (wider line with black border)
    c. Level 3: Level 2 plus centerline lights

To examine potential limitations of the EFVS on turns, all 18 scenarios contained at least one of the following turn types as a sampling variable: 90°, >90°, and <90°. Two additional scenarios examined the flight crew's ability to detect obstacles through the EFVS in 300 feet RVR; a truck parked on the edge of a taxiway came into the flight crew's view just after completing a turn. In one of the scenarios, the truck was forward and to the right side of the aircraft and initially visible through the EFVS. In the other, the truck was on the left side and outside the EFVS field of view.

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). On average, expected rate-of-travel decrements at lower RVR were marginally reduced with the EFVS on as compared with the EFVS off, and rate of travel decreased from RVR 1000 feet to RVR 300 feet (10 to 8 knots in B-777; 13.9 to 11.3 for B-737). During obstruction-detection scenarios, flight crews in both studies detected the a truck on the right side of the aircraft the majority of the time, and about twice as often as they detected that appearing on the left side. Regardless of EFVS, flight crews in both studies made more route deviations on sharp turns and right turns. Pilot feedback suggested that these types of turns were difficult due to the loss of visual references to the turn, particularly when there were no centerline lights. Based on the findings, 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.

INTRODUCTION

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 (FAA, 2012). The current LVO/SMGCS program has two levels: Level 1 is at visibilities under 1200 feet to 500 feet RVR and Level 2 is at visibilities under 500 feet to 300 feet RVR. The FAA is interested in whether an Enhanced Flight Vision System (EFVS) can aid pilots in taxiing safely in low-visibility conditions when LVO/SMGCS infrastructure is not present. If such operations were demonstrated to be safe, it might increase access to airports that do not 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 reducing safety, particularly in reduced-visibility conditions.

Studies have been conducted that have looked at proposed aids for conducting surface operations in restricted visibility (e.g. McCann, Andre, Begault., Foyle, & Wenzel, 1997). These investigations and concept demonstrations have included both the use of forward-looking perspective displays and the implementation of map displays to support low-visibility taxi operations, options that could be used in lieu of established low-visibility-operations airport infrastructure. These fall into several categories which include: forward-looking synthetic-vision displays (head down, HDD, or head up, HUD; Synthetic Vision Guidance Systems - SVGS), forward-looking sensor-based displays (HDD or HUD; Enhanced Vision System (EVS), EFVS), 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 following is a very brief sampling of representative display research that has been conducted as well as the potential strengths and limitations of each type of system examined, which leads to the consideration of EFVS as a potentially viable tool for low-visibility taxi.

Lorenz and Biella (2006) examined the possible use of a head-down perspective-view exocentric taxi map for low-visibility operations. They determined that use of the electronic moving map (EMM) in conjunction with other data components greatly increased the accuracy of taxi operations and reduced errors, as compared with natural vision or a primary flight display (PFD) representation only, without the supposed negative effects of additional head-down time spent looking at the EMM. Positive outcomes were also supported by much earlier work on maps displays (Battiste, Downs, & McCann, 1996). Additional work has been done to define information priorities expressed by transport pilots regarding what is portrayed on such moving maps, although these priorities were not specific to low-visibility operations (Yeh & Chandra, 2003).

It was recognized that additional displays (in the context of an integrated display system) might be effective in enhancing performance under low-visibility conditions (which includes reducing the impact reduced visibilities have on rate of travel as compared with those seen in good visibilities), and this was approached (McCann, Andre, Begault, Foyle, & Wenzel, 1997) by adding a head-up synthetic-cues display that outlined/highlighted the taxi path with an overlay of synthetic imagery, over the out-the-window view, on the HUD. This approach demonstrated that in 700 feet RVR conditions, comparative rates of travel were less impacted when using the map display alone, and were further restored by the addition of the HUD symbology. The addition of these displays was also associated with reports of reduced pilot workload. The use of synthetic imagery in a forward-looking view was then extended to approach and landing tasks and found useful (Beringer, Domino, & Kamienski, 2018). The use of a synthetic vision display or a sensor-based (e.g., EFVS) system as an aid for approach and landing was examined by Kramer et al. (2013). Findings indicated that it might be possible to expand the portion of the visual segment of the approach in which EFVS could be used in lieu of natural vision (from 100 feet to touchdown) in RVRs as low as 1000 feet. It also appeared that the use of a synthetic vision system (SVS) could help lower Decision Height for approaches using a HUD.

Thus, moving maps, dependent upon the level of accuracy attainable, SVSs and EFVSs appeared to be potentially viable components for helping to support various low-visibility flight/taxi operations. However, the use of synthetic vision (SV) is subject to certain factors that may affect the accuracy/registration of its depiction: (1) The graphical depiction of the outside world, as presented with a head-down or head-up SVS and other geo-referenced displays, is generated from a database internal to the display system, meaning (a) that accuracy is dependent upon the accuracy of the aircraft location data (Wide-Area or Local-Area Augmentation Systems for GPS; WAAS, LAAS), (b) accuracy of the image is also dependent upon the detail of the data used to create the database, and (c) changes made to the airport environment (e.g., closed taxiways, new construction) will not be present in the model if it is not updated frequently. (2) The image, being generated from a stored database, will not contain obstacles or obstructions that are "transient" in nature and that have not been specifically entered into the database. Thus, this image will not reflect incursions by other vehicles or animals, or the presence of debris (accumulated snow, parts from vehicles or aircraft, etc.). It has thus been argued 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.

Given these data and the interest in the potential for expanding operations in low-visibility conditions, two studies were conducted to examine the use of EFVS in lieu of LVO/SMGCS infrastructure for low-visibility taxi operations. The studies were identical except that they were conducted using different aircraft simulation platforms in order to generalize the results across different classes of aircraft. Study 1 was conducted in a Boeing 777 (B-777) simulator to represent a wide-body aircraft and Study 2 was conducted in a Boeing 737 (B-737) simulator to represent a narrow-body aircraft. Study 2 was an add-on study recommended to include an aircraft class that was the more likely to be operating in airport environments with reduced infrastructure There are differences in the characteristics of wide- and narrow-body aircraft that could affect the operational effectiveness of EFVS during taxi operations, particularly on turns. In wide-body aircraft, pilots may have to execute judgmental oversteering in turns (e.g., delayed turns) because the nose wheel is located significantly behind the flight deck. When executing judgmental oversteering, the pilot's visual reference to the turn (e.g., taxiway centerline) passes outside the EFVS field of view (FOV) before it is time to initiate a turn. In narrow-body aircraft, where the nose wheel is typically located beneath the flight deck, there is a greater chance that the visual reference to the turn will be within the EFVS FOV, as long as the turn is less than 90 degrees, up until just before initiating the turn. This is particularly true for turns less than 45 degrees having lead lines that are clearly indicated. Other differences between wide- and narrow-body aircraft that could affect the operational effectiveness of EFVS in low-visibility taxi operations include the different look-down angles from the flight deck and the EFVS sensor placement, which could affect the amount of parallax and/or the flight crew's taxi strategy. However, these other specifics vary from aircraft to aircraft and installation to installation and are considerations that were beyond the scope of this investigation.

The intent of these studies 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.

METHOD

The same method was used for Study 1 and Study 2, with the exception that Study 1 was conducted in a B-777 simulator with B-777 pilots and Study 2 was conducted in a B-737 simulator with B-737 pilots. All of the B-777 Captains had experience using the EFVS in operations, but most B-737 pilots did not. Study 2 pilots were given a briefing on the EFVS before entering the simulator.

Participants

Twenty-four FedEx B-777 pilots (12 flight crews) participated in Study 1 and 26 B-737 pilots (13 flight crews) from various airlines participated in Study 2. Flight crews were recruited based on the following criteria:

- Both pilots had flown a minimum of approximately 10 hours within the past 30 days.
- The pilot flying had a minimum of 100 hours of head up display (HUD) experience. For B-777 pilots, HUD experience was as pilot-in-command in an aircraft equipped with an EFVS.
- At least one crewmember was Category (CAT)-III qualified for at least five years.
- Flight crews were 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). Their flight hours are shown in Table 1.

Table 1. Pilots' flight hours (Study 1 and Study 2).

Flight Hours	Pilots	Mean	SD	Range
Total flight hours	B-777	11,196	5,632	3,000-24,600
	B-737	15,335	7,286	3,800-28,000
Flight hours in the past month	B-777	34	26	0-80*
	B-737	97	123	0-590
LVO/SMGCS (<1200 ft RVR) flight hours (excluding simulator)	B-777	61	202	0-1,000
	B-737	13	27	0-100
LVO/SMGCS (<1200 ft RVR) simulator hours	B-777	139	413	0-2,000
	B-737	14	15	0-50
Surface operation hours between 1200 ft and 600 ft RVR	B-777	64	203	0-1,000
	B-737	8	8	0-25
Surface operation hours below 600 ft RVR	B-777	8	18	0-75
	B-737	5	7	0-25

Note: One pilot indicated he had been on leave for the past month, but had been current as of the previous month.

In the studies, only the left-seat pilot (from this point forward, referred to as the Captain) had an EFVS. Ten of the 12 B-777 Captains had previously used an EFVS in actual operations (the others had used it in the simulator as part of their flight instructor duties); seven reported using it on a Rockwell Collins HUD (the same make as the simulator's EFVS), and three did not indicate what make/model of EFVS they used. Two of the 13 B-737 Captains had previously used an EFVS; although they did not specify the display type (HUD or other), one pilot used a Rockwell Collins EFVS and the other used a BAE EFVS. On average, B-777 Captains logged an estimated 474 hours operating with an EFVS (*SD*=768, *Range*=5-2,000). The two B-737 Captains who had used an EFVS had an estimated 9,200 hours and 15 hours with the EFVS, respectively. Figure 1 shows the number of B-777 and B-737 pilots who had used an EFVS in each flight phase. All 10 B-777 Captains and one B-737 Captain had used an EFVS during taxi operations. Seven of the B-777 Captains had used it in all six flight phases, but none of the B-737 had used it in every phase.

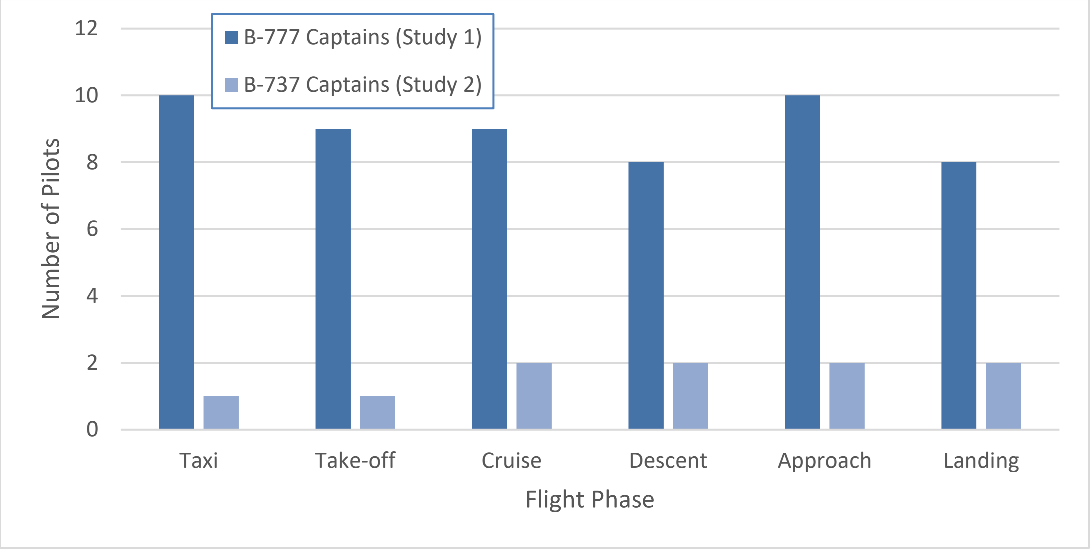


Figure 1. Captains' EFVS use by flight phase (Study 1 and Study 2).

Simulated Environment

Simulator. Although Study 1 and Study 2 were conducted in different simulators, both used the same EFVS Kollsman II infrared airport model. The simulator for Study 1 was a CAE B-777F level D full-flight simulator operated at the FedEx Flight Training Center in Memphis, TN. Study 2 was conducted in a CAE Boeing 737NG level D full-flight simulator operated by Flight Standards Flight Operations Simulation Branch at the Mike Monroney Aeronautical Center in Oklahoma City, OK. The simulators were operated with the motion on to provide additional feedback to the pilots.

Enhanced Flight Vision System (EFVS). The 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 trials. Settings assumed a minimum performance scenario based on minimum standards for image characteristics, flight information, and visibility criteria as described in AC 90-106 (FAA, 2010) and DO-315B (RTCA, 2011), 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 degrees horizontally by 15 degrees vertically (Study 1 FOV was 30° x 15° and Study 2 was 32° x 15°). No dynamic navigation displays, e.g., moving maps, were present on the flight decks so as to isolate the effects of presence/absence of EFVS from any other potential influences.

Airport conditions. Pilots performed taxi scenarios at a simulation of Salt Lake City (KSLC) 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.

Air traffic control. Standardized air traffic control (ATC) instructions were provided to the flight crews verbally by a researcher, seated in the simulator cab, who acted as “live” ATC. The taxi instructions were also provided to both pilots on paper so that there would be no confusion about the taxi routes. ATC instructions were developed with an ATC SME in compliance with FAA Order JO7110.65W (FAA, 2015) and with ICAO Doc 9830 (ICAO, 2004) and Doc 9870 (ICAO, 2007). “Live” ATC also responded to flight-crew queries or requests for clarification about the taxi instructions, but they did not provide information about where the aircraft was on the airport, as ATC was assumed not to have airport surface detection equipment.

Study 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: Standard painted centerline (6” wide) and edge lights
    b. Level 2: Level 1 plus centerline with LVO/SMGCS “enhancements” (12” wide with black border)
    c. Level 3: Level 2 plus centerline lights

3. EFVS (2 levels): on or off (when off, the EFVS was put in “hide” mode so that the HUD symbology was still visible without the EFVS)

The different levels of each of the above variables were combined to create 18 different experimental conditions, as shown in Table 2. Each flight crew performed one taxi trial for each of the experimental conditions. As such, this was a 3x3x2 fully-crossed factorial design with flight crew as the replication factor.

Table 2. Experimental conditions (taxiway edge lights were always present).

RVR	Infrastructure	EFVS	
		On	Off
300 ft	Standard centerline and edge lights (Level 1; L1)	300-L1-on	300-L1-off
	+centerline enhancement (Level 2; L2)	300-L2-on	300-L2-off
	+ centerline lights (Level 3; L3)	300-L3-on	300-L3-off
500 ft	Level 1	500-L1-on	500-L1-off
	Level 2	500-L2-on	500-L2-off
	Level 3	500-L3-on	500-L3-off
1000 ft	Level 1	1000-L1-on	1000-L1-off
	Level 2	1000-L2-on	1000-L2-off
	Level 3	1000-L3-on	1000-L3-off

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

Taxi Scenarios

A taxi scenario was created for each of the 18 conditions. The scenarios were designed to be consistent in the level of complexity. The following criteria were applied to each scenario:

- All routes contained at least one of each of the following turns: <90 degree, 90 degree, and >90 degree.
- To the extent possible, scenarios were balanced for the number of left and right turns.
- Some routes intentionally bypassed turn opportunities to force flight crews to recognize their turn location (i.e., flight crews were not always instructed to turn at the first intersection).
- All scenarios began on a taxiway or runway. Due to the layout of KSLC and the taxi scenario requirements above, some scenarios required flight crews to taxi non-standard routes according to LVO/SMGCS procedures at KSLC. For example, some scenarios required flight crews to taxi in the wrong direction on an LVO/SMGCS taxiway. Pilots were briefed about the non-standard routes prior to performing the scenarios, and the pilots’ taxi charts were altered to remove directional route symbology. In some instances where an unusual route was required, an explanation for that route (i.e., debris on a taxiway or construction, etc.) was offered.
- Using the above criteria, 12 possible taxi routes were identified at KSLC. Given that there were not enough routes to assign to all 18 conditions, half of the routes were used for more than one condition. To mitigate learning effects, the presentation order of the repeated taxi routes was spread out so that each route was completed once toward the

beginning of the experiment and once toward the end. The taxi routes are provided in Appendix A.

Three additional scenarios were included in addition to the 18 above (for a total of 21):

- Two “off-nominal” scenarios conducted in 300 feet RVR with a standard painted centerline and edge lights, with EFVS on. Each off-nominal scenario involved a pickup truck stopped on the edge of the taxiway just as the participants’ aircraft completed a turn. The truck did not obstruct the taxiway, but was close enough to potentially require an action by the flight crew (e.g., to avoid hitting the engine nacelle). In one of the off-nominal scenarios, the truck was on the right side of the aircraft following a right turn. In the other, the truck was on the left side following a left turn. The purpose of the off-nominal scenarios was to examine whether the EFVS, given its limited FOV, helped flight crews to detect an obstruction that was located outside of the forward FOV of the sensor/display.
- One “LVO/SMGCS” (Low-visibility infrastructure reference baseline) scenario conducted with centerline enhancements and LVO/SMGCS centerline lighting (i.e., centerline lights were only illuminated on the prescribed taxi route) in 300 feet RVR with EFVS off. The scenario did not contain any other LVO/SMGCS infrastructure, such as clearance bar lights or geographic position markings. This scenario was included to serve as a baseline to compare flight-crew performance with and without LVO/SMGCS centerline lights as this configuration eliminates ambiguity regarding the intended route (i.e., only one route is illuminated at a time in actual practice).

The 21 scenarios were presented to flight crews in one of two reverse orders (Order 1, Order 2) which were predetermined to maximize the space between trials of the same condition (e.g., so that the same level of each variable was not presented in succession). The orders were counterbalanced across flight crews such that half of the flight crews completed the trials in Order 1 and the other half completed the trials in Order 2.

Data Collection

The following system parameters (including aircraft performance) were recorded from the simulator:

- Latitude and longitude
- Heading
- Ground speed
- Applied braking
- Throttle position
- Tiller position
- Elapsed time (within the simulator trial)
- Wall-clock time
- Status indicator for wheels on or off pavement

Video and audio recordings of the flight deck and the EFVS repeater were also collected. These recordings, along with researcher observations, were used to determine the number and contexts of flight crew disorientations, adherence to required taxi route, and compliance with

ATC instructions. Flight crew queries and stopping to reconfirm ATC direction or other information with the Tower were tracked, and counted as correct actions by the flight crews.

The following data were gathered from pilot self-report:

- Each pilot's background experience
- Each pilot's opinions on the post-experiment questionnaire (questions were slightly different depending on whether the pilot was in the left or right seat)
- Flight-crew comments during the debriefing

PROCEDURE

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

When they arrived at the simulator facility, flight crews were seated in a briefing room with a researcher to complete the pre-experiment paperwork and briefing. First, each pilot read and signed an Informed Consent Form, which described the participant's rights and responsibilities. Second, each pilot filled out the background questionnaire that asked about their general pilot experience as well as LVO/SMGCS and EFVS experience (see Appendix B). Third, pilots were given a PowerPoint briefing describing the EFVS (Study 2 only), and a short verbal briefing that outlined the basic study procedures (Study 1 and 2). Pilots were told that they would be asked to taxi 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 their 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 get used to the simulator and EFVS settings. Following the practice scenario, pilots were given a chance to ask questions before beginning the 21 experimental scenarios.

Each of the 21 experimental scenarios took approximately 5-10 minutes to complete. A 15 to 20 minute break was provided halfway through the scenarios. Two researchers sat in the simulator cab during the scenarios—one acted as "live" ATC and the other observed and took notes. For Study 1, the observer also initiated the scenarios and data recording. In Study 2, the scenarios and data recording were initiated by a simulator engineer in the control room. In both the simulator and in the control room, the researchers and engineer viewed two monitors, one that depicted the left-seat pilot's EFVS and another that showed an airport moving map.

After all of the scenarios were completed, the flight crew returned to the briefing room to complete the post-experiment questionnaires. Each pilot was given a separate questionnaire that asked about their general pilot experience as well as LVO/SMGVS and EFVS experience (Appendix D)) and they were asked not to discuss their answers while completing the questionnaire. Once both pilots completed their questionnaires, the researcher asked the pilots for general comments or questions, and provided an overview of the purpose of the study.

RESULTS

Study 1

Route deviations. Route deviations were defined as missed turns or turns on the wrong taxiway. In some cases, flight crews almost missed a turn or started to make a wrong turn but were able to correct back onto the intended route. The number of route deviations, including wrong turns that were corrected, is presented in Table 3 at each level of EFVS, RVR, and infrastructure (the number of corrected turns are in parentheses). The majority of route deviations were committed in 300 feet RVR with EFVS off, with either a standard painted centerline only or a painted centerline with LVO/SMGCS enhancements (no lights). Note that each combination of variables (each cell in the table) represents a single scenario. Route deviations were mostly consistent within each scenario, that is, flight crews usually missed the same turn or made a wrong turn on the same taxiway. Note that the trend across RVR was a decrease in deviations as the RVR increased, which is consistent with expectations. The result regarding infrastructure was not linear, with moderate infrastructure being associated with more deviations than either low- or high-infrastructure levels, which was true for both corrected and uncorrected errors.

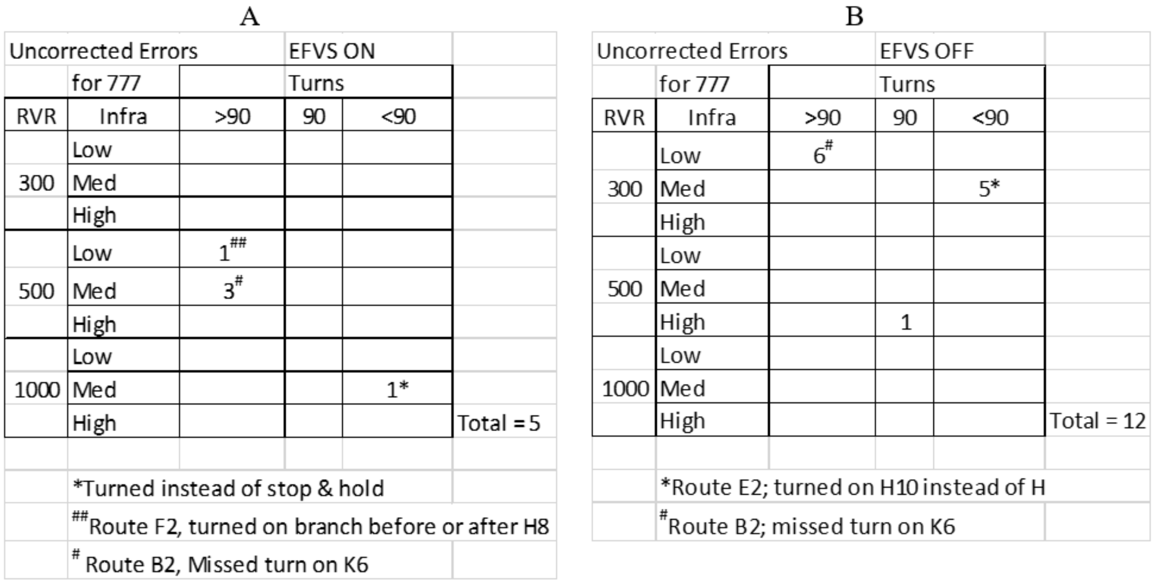
Table 3. Frequency of route deviations by RVR, EFVS, and infrastructure (Study 1).

Infrastructure					
RVR (ft)	EFVS	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)	*Total*
300	On	0	0	1 (1)	*1 (1)*
	Off	7 (1)	10 (5)	0	*17 (6)*
500	On	1 (0)	3 (0)	0	*4 (0)*
	Off	0	0	1 (0)	*1 (0)*
1000	On	0	1 (0)	0	*1 (0)*
	Off	0	0	0	*0*
Total		*8 (1)*	*14 (5)*	*2 (1)*	*24 (7)*

Note: Corrected turns are in parentheses.

It is also useful to recast the data to show only the uncorrected errors as they are distributed by RVR, infrastructure, and category of turn and divided at the highest level between EFVS on and EFVS off. If we look at Table 4. Frequency of uncorrected turn errors by RVR, Infrastructure, Turn Angle and by (A) EFVS On and (B) EFVS Off (Study 1).Table 4A and 4B it is immediately apparent that, with EFVS ON, which is the condition of interest, 4 of the 5 uncorrected errors occurred where there were turns exceeding 90 degrees. Thus, excluding turns greater than 90 degrees in any proposed EFVS route would potentially prevent all but the one uncorrected error with EFVS on. Further, half of the uncorrected errors with EFVS off were also on turns exceeding 90 degrees, and thus one might, by the same turn –category exclusion, reduce uncorrected errors, even without EFVS, by half. Comparing across what would then remain still presents a 1:6 advantage for EFVS being on. Given the extremely small number of events and small sample size, this particular difference is not directly testable using inferential statistics.

Table 4. Frequency of uncorrected turn errors by RVR, Infrastructure, Turn Angle and by (A) EFVS On and (B) EFVS Off (Study 1).



A

Uncorrected Errors			EFVS ON		
	for 777		Turns		
RVR	Infra	>90	90	<90	
	Low				
300	Med				
	High				
	Low	1##			
500	Med	3#			
	High				
	Low				
1000	Med			1*	
	High				Total = 5

*Turned instead of stop & hold

##Route F2, turned on branch before or after H8

Route B2, Missed turn on K6

B

Uncorrected Errors			EFVS OFF		
	for 777		Turns		
RVR	Infra	>90	90	<90	
	Low	6#			
300	Med			5*	
	High				
	Low				
500	Med				
	High		1		
	Low				
1000	Med				
	High				Total = 12

*Route E2; turned on H10 instead of H

#Route B2; missed turn on K6

Returning to look at all deviations, corrected and uncorrected, all but one of the route deviations (n=23) occurred at an intersection where the flight crew was instructed to turn (one crew turned when they were supposed to go straight). Table 5 shows the number of route deviations by turn angle for each of the 23 instructed turns. Most route deviations occurred on turns that were either less than or greater than 90 degrees. However, on turns less than 90 degrees, flight crews were able to correct back on the intended route about 50% of the time. Flight crews were not able to correct most of the route deviations on turns greater than 90 degrees. All of the route deviations occurred on right turns which was not surprising given the lack of visual surveillance possible in that direction from the left seat. This is especially true of turns of 90 degrees or more. Each crew had, over the course of the main-design trials, 22 required turns of <90 degrees, 21 turns of 90 degrees, and 18 turns of >90 degrees, and thus a reasonably balanced sampling. A deviation that was not corrected would, of course, alter the total number of turns executed as those in the remainder of the route would not be experienced.

Table 5. Frequency of route deviations by turn angle (Study 1).

Turn Angle	Wrong/Missed Turns
<90°	11 (6)
90°	1 (0)
>90°	11 (1)

Note: Corrected turns are in parentheses.

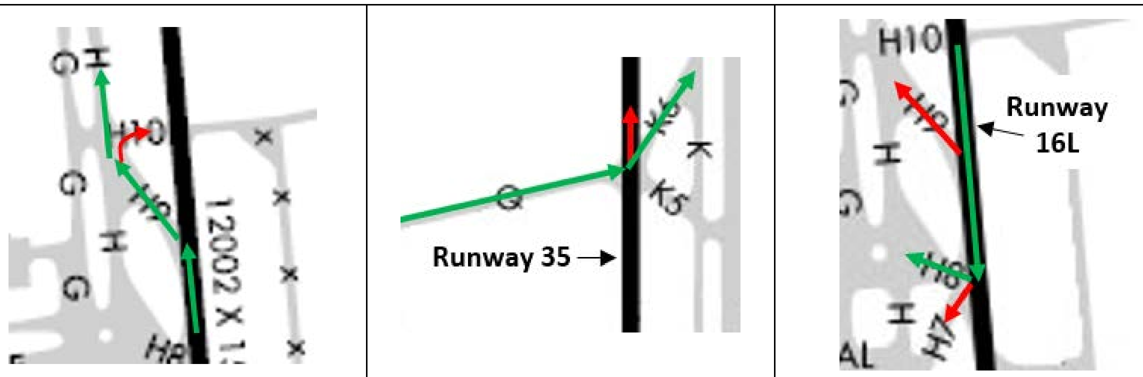
Table 6 shows the number of route deviations by intersection complexity. Intersection complexity was defined by the number of possible taxiways (2, 3, or 4 branches) that the flight crew could take at each prescribed turn location; presumably, the higher the number, the greater the chance that flight crews would follow the wrong centerline and make a wrong turn. Route deviations were committed approximately equally at intersections with two and three branching taxiways. There was only one route deviation at an intersection with four branching taxiways. Note that there were only 10 four-branch intersections across all of the scenarios, compared to 26 and 30 two- and three-branch intersections, respectively. Therefore, there were fewer opportunities to make errors at four-branch intersections.

Table 6. Frequency of route deviations by intersection complexity (Study 1).

Intersection Complexity	Wrong/Missed Turns
2	12 (5)
3	11 (2)
4	1 (0)

Note: Corrected turns are in parentheses.

As mentioned previously, most route deviations were consistent within each scenario (i.e., committed at the same turn or intersection). There were three intersections where more than one flight crew deviated from the route. The three intersections are shown in Figure 2; the instructed routes are depicted in green and the deviations are depicted in red.



Coming from taxiway H9, 10 flight crews made a wrong turn onto taxiway H10 instead of H.

Crossing runway 35 from Q to K6, seven flight crews missed taxiway K6.

Coming from runway 16L, one flight crew turned on taxiway H9 instead of H8. Two flight crews turned on H7 instead of H8.

Figure 2. Intersections with common route deviations (Study 1). Note: Routes in green, deviations in red.

Errors at intersections in Figure 2 were further examined by looking at the simulator video recordings and Google Earth[1] images (Google, 2018). At intersection 1, there appeared to be discrepancy between the simulator visual model and what would be expected on the actual airport. On the actual airport, the line for taxiway H10 intersects taxiway H, but in the simulator model, there was a clear line for taxiway H10 leading off of taxiway H9 (see Figure 3 for a comparison). Flight crews tended to follow this line thinking it was the lead-off line for H. With no EFVS, 300 feet RVR visibility, and no centerline lights or signage, flight crews could not see far enough or did not have enough information to know that the line was leading in the wrong direction.

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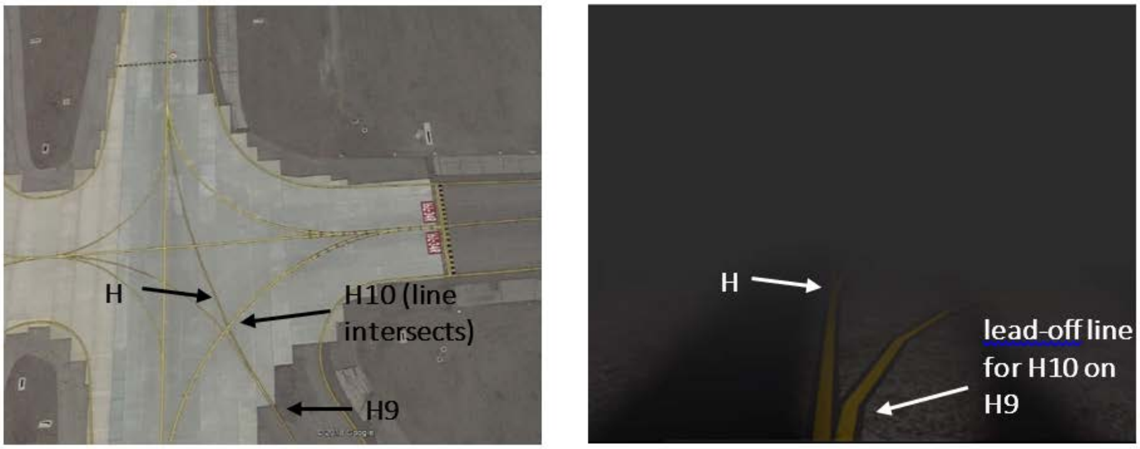
[1] Google (2018). Google Earth image of Salt Lake City International Airport (SLC), Salt Lake City, UT. Retrieved May 13, 2018, from https://www.google.com/earth.



A

B

Figure 3. Intersection images from (A) Google Earth and (B) simulator out-the-window view on H9.

Intersections 2 and 3 had multiple crossing taxi lines which, under low visibility, could be confused with the taxi line that flight crews were expected to follow. Moreover, the taxi instructions followed non-standard routes, and there were no clear lead-off lines for the instructed turn. Google Earth images of intersection 2 and 3 are shown in Figure 4 and Figure 5, respectively.

In intersection 2, flight crews coming off taxiway Q turned left on the runway and started looking for a lead-off line for taxiway K6. However, once the flight crew turned on the runway, the line for K6 was already behind them.

Figure 4. Layout of intersection 2 and lead-on/lead-off lines.

At intersection 3, flight crews exited the runway by following the lead-off line for taxiway H7. There was no lead-off line for taxiway H8, but it did intersect with H7. However, if the flight crew waited to see the taxi line for H8 to make the turn, it would probably be too late to make the hard right turn onto H8.

Figure 5. Layout of intersection 3 and lead-on/lead-off lines.

Two additional things are worth noting here concerning turn errors. First, if one looks at the total number of errors broken down by crews, it must be pointed out that 33% of the B-777 crews were responsible for 50% of the deviations (not evenly distributed across crews). This tends to make the interpretation of descriptive statistics more difficult (see Appendix B for plots of deviations by crew). If, however, one overlooks this problem for the moment and recasts the uncorrected errors as the probability that the aircraft would not arrive at the specified destination on the airport surface, then we can look at Table 7 and see that the results are mixed across EFVS on / EFVS off. Specifically, with EFVS off in 300 feet RVR, the probability of NOT completing the taxi run was calculated as 0.50 in low infrastructure (L1) and 0.42 in medium infrastructure (L2), whereas the same conditions with EFVS on had a zero probability of not completing the taxi run (1.00 success rate). On the other hand, in 500 feet RVR the same probabilities (cells) were 0.00 and 0.08 for EFVS off, and 0.08 and 0.25 with EFVS on (lower success rates). Additionally, in low infrastructure with EFVS off, the probability of completion was 1.00 (0 fail) whereas it was .92 (.08 fail) with EFVS on. Again, the frequency of occurrence for these events was so small that no inferential statistical tests were appropriate for any type of comparison. The criterion for terminating these runs must be kept in mind here as a run was ended if the crew made a clearly wrong turn and did not attempt to correct it or if the crew admitted, after-the-fact, that they had somehow erred and were lost. Thus, there was no “wandering about” allowed to attempt to subsequently correct an overt turn error well after the error had been committed.

Table 7. Calculated probabilities of failure to complete taxi route tabulated by RVR, Infrastructure, and EFVS of and off (Study 1).

INFRASTRUCTURE			
RVR/EFVS	L1 (Low)	L2 (Medium)	L3 (High)
300/On	0.00	0.00	0.00
300/Off	0.50	0.42	0.00
500/On	0.08	0.25	0.00
500/Off	0.00	0.08	0.00
1000/On	0.08	0.00	0.00
1000/Off	0.00	0.00	0.00

Note: Green = EFVS on, white = EFVS off and no difference from on, yellow = EFVS on was better, rose = EFVS off was better.

Centerline tracking. Centerline tracking was recorded two ways: First, the flight simulator recorded whether the aircraft wheels were on or off the taxiway (versus off of the hard surface) throughout each scenario. Flight crews stayed on the taxiway for all scenarios. Second, centerline deviations were calculated on straight taxi segments. Turn segments were excluded for several reasons, both behavioral and technical. First, flight crews were expected to intentionally oversteer on turns, and thus the registered navigation center of the aircraft could depart from the centerline momentarily. Second, the precise location of the curved sections of the path (lead lines, etc.) were graphical only (out-the-window view) and not defined in the simulator database. An effective algorithm was not identified that could generate the paths in lat/long coordinates. For the straight-line segments, an algorithm was developed to calculate the centerline deviations using latitude and longitude coordinates of the nose wheel, recorded from the simulator, and centerline coordinates at each intersection in the route, obtained from the simulator visual model database. The nose wheel track and centerline were plotted against time for each flight crew and taxi scenario, and the plots were used to manually identify times when the straight segments started and ended (i.e., when the nose wheel track began to return to or diverge from a straight path, indicating the end or start of a turn).

The mean absolute deviation (regardless of direction) from the centerline was calculated across all straight segments for each scenario. The centerline deviations were highly variable with many outliers that could not be explained by measurement error, so no statistical tests were conducted. The box plots in Figures 6 through 8 show the distribution of absolute centerline deviations by EFVS, RVR, and infrastructure, respectively. The red “X” represents the mean and the lower, middle, and upper lines that form the box represent the 25th, 50th, and 75th percentiles, respectively. The error bars represent the minimum and maximum.

On average, the magnitude of centerline deviations was approximately the same with EFVS off as it was with EFVS on. Increases in RVR were associated with a decrease in the mean deviation from the centerline. There was also an unexpected increase in the mean deviation as the level of infrastructure increased. Flight crews may have positioned their nose wheel on the centerline during the standard centerline condition because it was the only line available.

However, the “enhanced” centerline had a border and centerline lights were offset from the centerline; with these two infrastructure types, flight crews may have positioned the nose wheel on the border or centerline lights rather than the center stripe. Nevertheless, the largest mean deviation across all conditions was four feet, which is small from an operational perspective. Moreover, the median centerline deviations were approximately equal across the different levels of each variable.

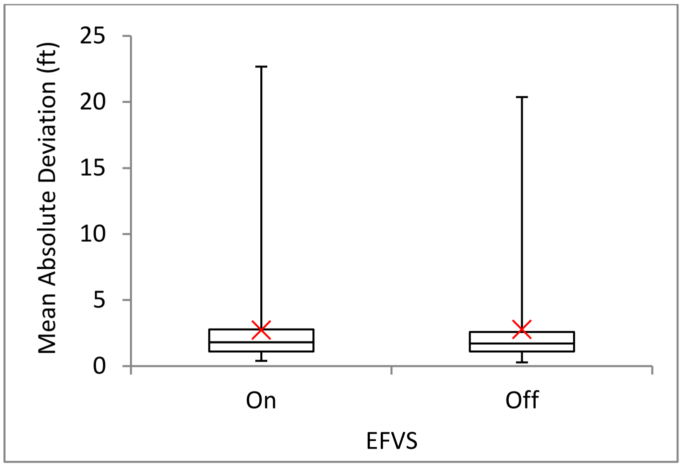


Figure 6. Centerline deviations by EFVS condition (Study 1) showing mean (red X), 25th, 50th, 75th percentiles (box limits), and range (vertical line extent).

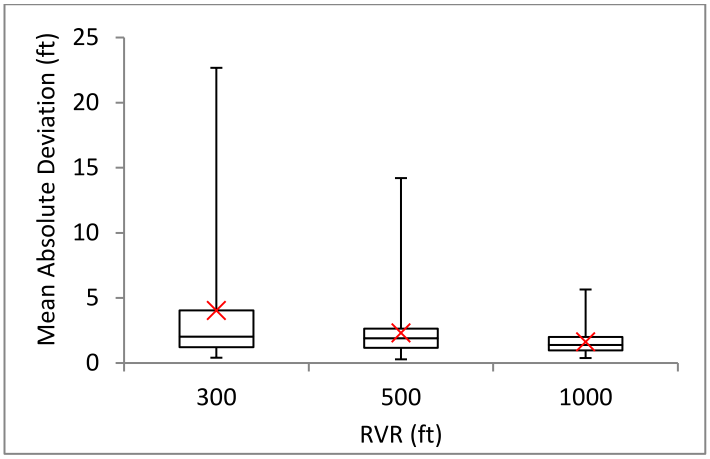


Figure 7. Centerline deviations by RVR (Study 1).

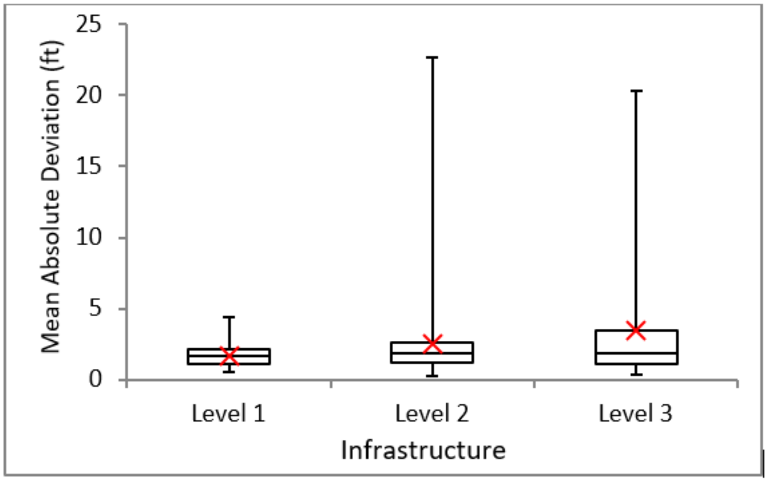


Figure 8. Centerline deviations by infrastructure (Study 1).

It should be noted, regarding the oversteer issue, that observation of the crews indicated most of their attention on turns was outside of the HUD, even with EFVS on, and that the oversteer requirement becomes more necessary/evident as the angle of turn is increased. For the smaller turns, the crews were able to view whatever infrastructure existed and was visible to the EFVS through the HUD in a number of cases. However, for the larger turns (45 or more degrees), the captain was most frequently looking beyond the FOV of the HUD/sensor, meaning directly at the out-the-window view. As mentioned previously, much of the problem observed with turns of 90+ degrees made to the right was because everything was not only out of the FOV of the sensor, but also out of the FOV of the captain as seen through the right-side flight-deck windows. Even in the less-extreme turns, many of the cues for the delayed initiation of the turn were out of the sensor FOV well before turn initiation. The pilot serving as captain was observed, frequently, to look out the left-side window to monitor the sideline for the taxiway (noted specifically in the obstruction-avoidance discussion later). Pilot opinion on this issue is documented in the section covering the post-test debriefing.

Rate of travel. One would anticipate that reduced RVR would cause reductions in rate of travel as a function of the amount of visual route preview available. One would also expect that an impoverishment of visual cues due to reduced infrastructure would have a similar effect. Finally, it could be expected that sharper turns would require greater reductions in rate of travel than small-angle turns. One possible outcome would also be that the introduction of EFVS might restore some of those missing visual cues, under certain circumstances, and thus decrease the decrements that would otherwise be seen in rate of travel that resulted from visual-cue deprivation. To examine these points, the mean rate of travel, excluding stops (where groundspeed=0), was calculated for each scenario. A repeated-measures Analysis of Variance (ANOVA) tested for main effects and interactions of EFVS, RVR, and infrastructure. There were significant main effects of all three variables. Mean rate of travel was less affected when EFVS was on than with EFVS off (-.43 knots), $F(1,11) = 7.72$, $p < .05$. Considering the mean total taxi time of seven minutes (420 seconds), this suggests that mean taxi times were about 18 seconds less with EFVS, which is only about 4%. As expected, rate of travel showed less of a decrement as RVR and infrastructure increased; RVR - $F(2,22) = 43.72$, $p < .001$, and Infrastructure - $F(2,22) = 25.07$, $p < .001$ (post-hoc comparisons were conducted using Fisher's Least Significant

Difference (LSD), with the Bonferroni correction to adjust for family-wise error rate; all $p < .01$). The largest difference in rate of travel between RVR conditions was 1.76 knots, which equates to 1 minute and 15 seconds less total taxi time. The largest difference between infrastructure conditions was .67 knots, which equates to 29 seconds less total taxi time. Table 8 shows the mean rate of travel for each level of each variable. Note that of all the differences observed, the difference attributable to EFVS was, in fact, the smallest, and this difference is discussed further in the next paragraph (interaction between EFVS and RVR).

Table 8. Mean rate-of-travel main effects for EFVS, RVR, and Infrastructure (Study 1).

Variable	Level	Mean	SD
EFVS	On	9.36	1.84
	Off	8.93	1.56
RVR (ft)	On	8.27	1.25
	Off	9.15	1.73
Infrastructure	Level 1	8.75	1.64
	Level 2	9.28	1.48
	Level 3	9.42	1.95

There was also a significant interaction of EFVS with RVR, $F(2,22) = 9.09$, $p < .01$. Figure 9 shows the mean rate of travel by each level of EFVS and RVR. There was no effect of EFVS in the worst-possible case, 300 feet RVR, but flight crews showed less rate-of-travel decrement at 500 feet RVR when the EFVS was on than when it was off. At 1000 feet RVR, flight crews showed the least decrement (relative to 300 feet RVR) regardless of whether the EFVS was on or off, but there was no significant difference at either 300 or 1000 between EFVS on and EFVS off. One can surmise that this was because (1) at 300 feet RVR EFVS was not contributing because of the overall poor visibility and (2) at 1000 feet RVR visibility was good enough that EFVS did not provide additional cues beyond what was useful at near distance.

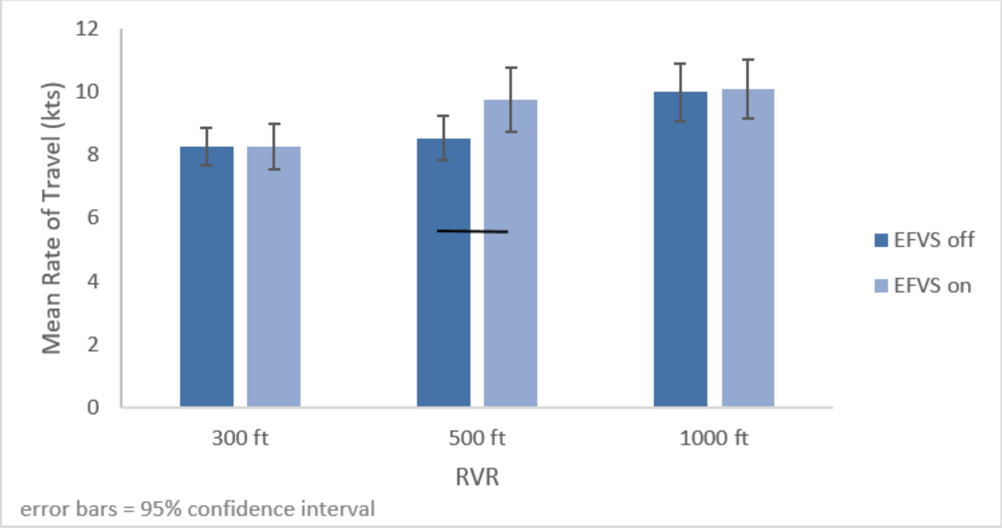


Figure 9. Mean rate of travel by EFVS and RVR (Study 1). Note: Statistically significant post-hoc comparisons (LSD, $p < .05$) at each level of RVR are represented by a line connecting the bars.

The interaction of EFVS and infrastructure was also significant, *F*(2,22) = 18.11, *p* < .001. Figure 10 shows the mean rate of travel by each level of EFVS and infrastructure. There was no effect of EFVS with a standard painted centerline. However, flight crews showed less rate-of-travel decrement with the EFVS on than with the EFVS off when there was an LVO/SMGCS "enhanced" centerline, with or without centerline lights. Again, however, the differences were extremely small and, in many cases, likely of no operational significance.

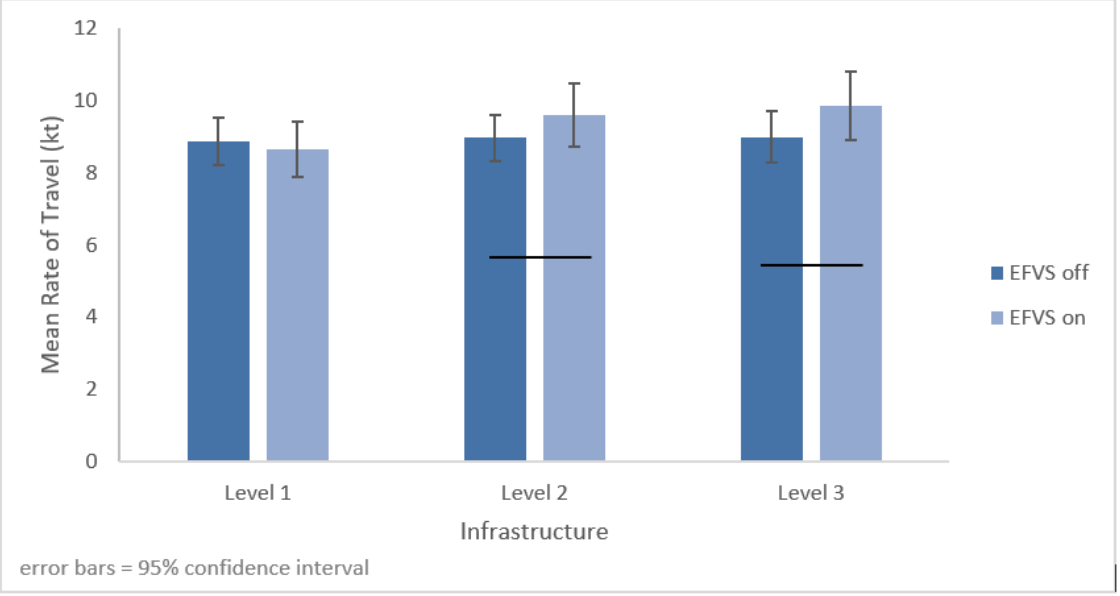


Figure 10. Mean rate of travel by EFVS and infrastructure (Study 1). Note: Statistically significant post-hoc comparisons (LSD, *p* < .05) are represented by a line connecting the bars.

There was a significant interaction of RVR and infrastructure, *F*(4,44) = 7.62, *p* < .001. This illustrates, again, what was already expected – that there would be main effects of both of these as a function of visual-cue impoverishment, and that they would be additive to some degree. Figure 11 shows the mean rate of travel by each level of RVR and infrastructure. The effect of RVR on rate of travel was different depending on the level of infrastructure. With a standard painted centerline only, flight crews only exhibited a reasonable reduction in decrement of rate of travel at 1000 feet RVR (statistical significance). With an "enhanced" painted centerline only (no lights), flight crews experienced a more moderate reduction in decrement at 500 feet RVR. With centerline lights, flight crews experienced regular reductions in decrements at each increase in RVR; rate of travel further increased at 1000 feet RVR, relative to the rate of travel at 1000 feet when there was no centerline lighting. As noted, the trend across RVR was similar at L1 (lowest) and L3 (highest) infrastructures but not across RVRs at L2 (medium) infrastructure.

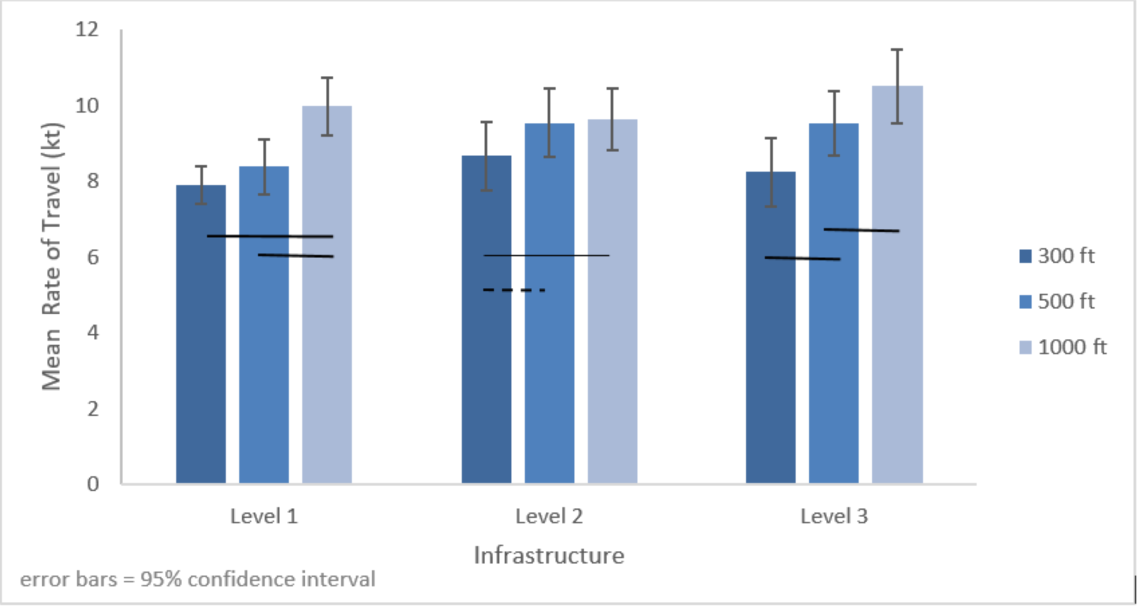


Figure 11. Mean rate of travel by RVR and infrastructure (Study 1). Note: Statistically significant post-hoc comparisons (LSD, *p* < .05) are represented by a solid line connecting the bars. The dashed line represents a moderately significant difference (*p* < .10).

Separate analyses were conducted to assess the effect of turn and intersection characteristics on the minimum rate of travel during turns (excluding stops, where groundspeed=0). The beginning and end of each turn was identified during the centerline deviation analysis by manually pinpointing times when the straight segments (and thus turns) started and ended on the plot of centerline deviations against time. Separate one-way repeated-measures ANOVAs[2] examined the effect of three turn/intersection characteristics on the mean minimum rate of travel during turns: turn angle (<90º, 90º, >90º), turn direction (left or right), and intersection complexity (2, 3, or 4 branching taxiways).

There was a statistically significant effect of turn angle, *F*(2,22) = 78.99, *p* < .01. Fisher's LSD tests revealed that the minimum rate of travel during turns was significantly slower as turn angle increased (all *p* <.001 with the Bonferroni correction applied). Again, this was an entirely expected result. The mean minimum rate of travel during turns is shown Figure 12 by turn angle.

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[2] To adjust for the family-wise error rate, the Bonferroni correction was applied to the p-values for these and all subsequent multiple ANOVAs and pairwise comparisons.

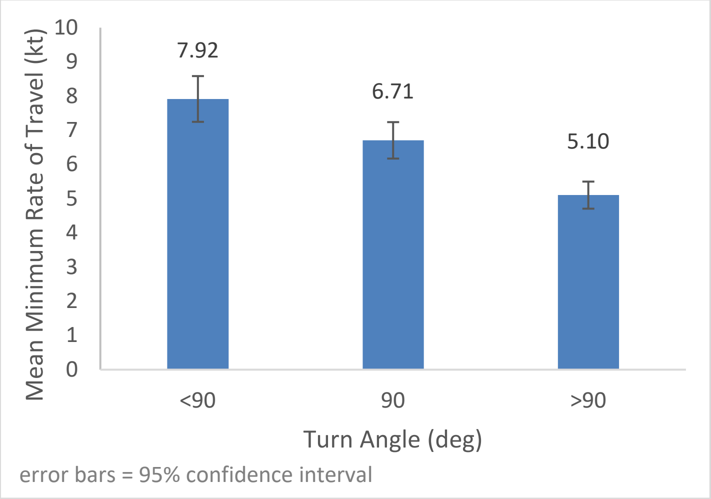


Figure 12. Mean minimum rate of travel during turns by turn angle (Study 1).

There was also a significant effect of turn direction, with the mean minimum rate of travel being slower during left turns than during right turns, *F*(1,11) = 14.80, *p* < .05. The mean minimum rate of travel is shown in Figure 13 for left and right turns. This difference, while statistically significant, is so small (3/4 knot) that it appears to have no implication operationally.

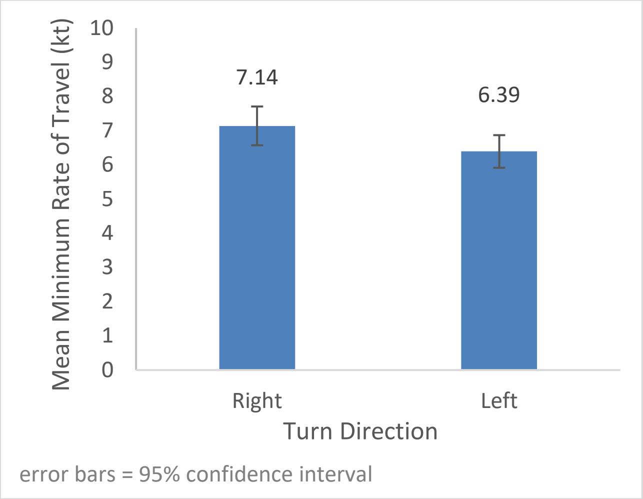


Figure 13. Mean minimum rate of travel during turns by direction (Study 1).

Finally, there was a significant effect of intersection complexity on the mean minimum rate of travel during turns, *F*(2,22) = 13.08, *p* < .01. Turns that were initiated at intersections with three branches were significantly slower than turns initiated at intersections with two or four branches (the mean minimum rate of travel was not significantly different between turns of two and four branches). This result was counterintuitive because rate of travel was expected to be slower at increasing levels of complexity. However, it is possible that this finding is due to a confounding effect of one or more other variables. For example, proportionally more of the four-branch intersections were located in scenarios conducted at 1000 feet RVR than scenarios conducted at 300 or 500 feet RVR, whereas two- and three-branch intersections were distributed approximately equally across all levels of RVR. In this example, the higher mean rates of travel at four-branch intersections might be driven by the higher overall rate of travel at 1000 feet RVR. Additionally, the complexity metric was a relatively simple one and likely did not capture a number of things that contributed to or hindered decisions being made and thus, indirectly or directly, overall rate of travel. The mean minimum rate of travel is shown in Figure 14 by intersection complexity.

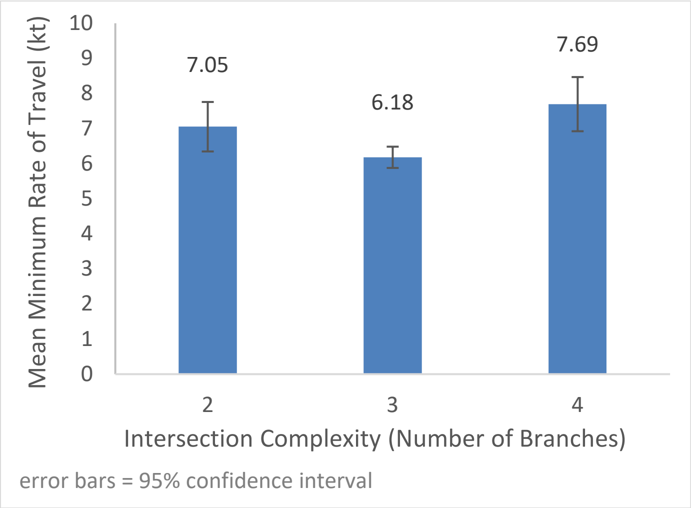


Figure 14. Mean minimum rate of travel during turns by intersection complexity (Study 1).

Obstacle detection. Flight-crew responses to the truck in the off-nominal scenarios were examined by watching the scenario video recordings. The number of flight crews who acknowledged the truck (made note of it verbally) and/or stopped are provided in Table 9.

Table 9. Frequency of pilot responses to obstacle by location and response category (Study 1).

Action	Right Side	Left Side
Acknowledged truck	11	5
Stopped	5	3

Eleven of the 12 flight crews acknowledged the truck on the right side. Five of the 11 times, the First Officer was the one who acknowledged it, though one of these times the First Officer only acknowledged the truck after the scenario had been terminated (if a flight crew failed to respond to the truck, the researcher would terminate the scenario after the aircraft had passed the truck). The Captain acknowledged the right-side truck four out of the 11 times, and all four times he or she appeared to be looking through the EFVS. One of the 11 flight crews who noticed the right-side truck acknowledged it simultaneously (while the Captain was looking through the EFVS). For one flight crew, the person who acknowledged the truck could not be determined from the video. The time to detect the truck was calculated from the time the flight crew started taxiing. On average, First Officers detected the truck six seconds sooner than Captains did (one First Officer's time was omitted from the calculation of the mean because the crew stopped for several seconds before the truck came into view). Five flight crews stopped for the truck on the right side. Four of them contacted ATC. For one flight crew, the scenario was terminated after they stopped, and it was not clear whether they intended to contact ATC. Of the six fight crews who continued, three said that they were clear of the truck, one did not seem concerned about the truck, and one was the crew who only acknowledged the truck after the scenario was terminated (one can likely assume that they judged that the aircraft was clear of the truck in passing). In the post-experiment debrief, one of the flight crews said that they would have stopped for the truck during actual operations.

It should be noted that there were specific behaviors observed that were correlated with outcomes of this task. One that was particularly notable was that where the "captain" was not only looking through the HUD but was also looking out the left side window to try to follow the taxiway edge line. In these specific cases it was inevitable that with the left-seat pilot thus focused to the opposite side of the aircraft, the right-seat pilot would have a higher likelihood of detecting the truck to the forward and right side. Note that the truck was briefly visible in the HUD EFVS during the jog to the right along that taxiway before the aircraft was required to turn north again.

Five of the 12 flight crews acknowledged the truck on the left side. Four of the five times, the Captain was the one who acknowledged it; each time, the Captain appeared to be looking out the left-side window when he or she saw it. Three flight crews stopped for the left-side truck; two of them contacted ATC, but the other crew said that they would have contacted ATC during actual operations. Of the two flight crews who did not stop, one crew seemed unconcerned about the truck, only noting, "He's still there." The other flight crew who did not stop noted during the debriefing that they had already passed the truck when they saw it. Note here that the behavior of the left-seat pilot in looking out the left side window likely facilitated the detection of the truck as opposed to the previous scenario where it reduced the likelihood of detection. This was particularly important because this truck was not visible in the EFVS FOV because of the geometry of the turn (obstacle was on the inside of the turn and close enough to the turn point so as to not necessarily be within the sensor's FOV during the turn or after it was completed).

LVO/SMGCS scenario. During the LVO/SMGCS scenario, flight crews taxied in 300 feet RVR with the EFVS off. The route had a painted centerline with LVO/SMGCS enhancements, edge lights, and centerline lights. The difference between the LVO/SMGCS scenario and other scenarios in this study was that only the instructed route had centerline lights (i.e., pilots could "follow the greens" to their destination). However, like the other scenarios, there were no other LVO/SMGCS lights or markings (e.g., clearance bar lights or geographic position markings).

Flight crews did not commit any route deviations during the LVO/SMGCS scenario, which is mostly consistent with the other two "matching" scenarios conducted at 300 feet RVR with centerline lights. (The "matching" scenarios had centerline lights visible on all taxiways, not just the cleared route.) There was only one route deviation in the matching scenarios.

The mean absolute deviation from the taxiway centerline was 1.68 feet (*SD*=1.00), which is smaller than the mean deviation in the matching scenarios with EFVS off (*M*=4.39, *SD*=5.05) and with EFVS on (*M*=5.11, *SD*=3.62). Across all scenarios (i.e., all combinations of conditions, excluding the LVO/SMGCS scenario), the mean absolute centerline deviation was 2.75 feet (*SD*=3.25). Note, however, that these data were highly variable with outliers as large as 20 feet. In the LVO/SMGCS scenario, the largest deviation was about four feet from the centerline.

The mean rate of travel (excluding stops) throughout the entire LVO/SMGCS scenario was 8.36 knots (*SD*=1.30), compared to a mean of 8.71 knots (*SD*=1.27) in the matching scenario with EFVS off and 7.76 knots (*SD*=1.58) in the matching scenario with EFVS on. The average rate of travel across all scenarios was 9.15 knots (*SD*=1.72).

Pilot opinions. Pilot-opinion data from the post-experiment questionnaire were analyzed based on question type:

- Yes/no and multiple choice (chi-square, if the data met the assumptions for the statistical test, i.e., $<20\%$ of the expected frequencies were ≥ 5)
- Free-response (no statistical analysis; comments were placed into categories if three or more pilots mentioned the same topic)

The questionnaire results are summarized in the following sections. Results are organized by question topic (as they were presented in the questionnaire).

EFVS operations. Pilots were asked to describe via free-response any operational concerns they had or anticipated with the use of EFVS for taxi in low visibility. Responses were categorized based on the type of concern (e.g., concerns about turns and infrastructure). Only categories that were mentioned by three or more pilots are reported.

Of the total 24 pilots, 11 pilots (6 Captains and 5 First Officers) said they had no concerns. Six pilots had concerns about the effectiveness of EFVS under certain environmental conditions that might be encountered in real-world operations (not specifically concerning the simulation):

- “If there is no EFVS visual due to environmental conditions, EFVS causes some visual distortions in the HUD when on”
- “Only real issue in real life is moisture has a significant effect”
- “In some scenarios the obscuration did not allow the EFVS to give much more visibility than no EFVS and actually caused me to concentrate so hard on the EFVS image that my other visual cues were missed”
- “Depends on humidity and light contrast for good vision”
- “[The EFVS] seems to have little effect in precipitation”
- “Does not work well in fog”

Pilots were also asked to respond “yes” or “no” to whether they felt an EFVS repeater display should be available to the First Officer. Of the total 24 pilots, 22 pilots (11 Captains and 11 First Officers) answered “yes,” $\chi^2 = 36.33$, $p < .0001$. A follow-up question asked these 22 pilots whether they would prefer the repeater display as a HUD, head-down equivalent, or either (no preference). Significantly more pilots preferred the HUD display, $\chi^2 = 19.73$, $p < .0001$.

Pilots operating as First Officer were asked how having the EFVS imagery available to the Captain affected their task as First Officer during taxi operations (i.e., if it elevated, decreased, or did not affect their workload), and then they provided the reasoning for their answer via free-response. Eight of the 12 First Officers replied that the Captain having an EFVS did not affect their workload, and all of them noted that they still had to perform their First Officer duties (e.g., maintain position awareness) regardless of the EFVS. Of the other four (out of 12 total) First Officers, three said that their workload was elevated and one said that it decreased.

Position awareness. Pilots were asked whether they had sufficient awareness to verify their position on the airport and navigate effectively. There were no statistically significant differences in pilot responses, that is, approximately half answered “yes” and half answered “no.” Another question asked pilots to estimate how much (in percent) different sources of information contributed to their position awareness. The mean percentage for each information source is provided in Figure 15 for Captains and Figure 16 for First Officers. Responses were analyzed separately for Captains and First Officers because their response options were slightly different, using a Friedman two-way ANOVA by ranks. Captains felt that the following contributed approximately equally to their position awareness (i.e., no significant differences): First Officer reports of information obtained through direct observation, the Captain's own direct observation of airport infrastructure, and the EFVS as seen through the HUD. First Officers felt that their own direct observation of airport infrastructure contributed more to their position awareness than the Captain's reports of information as seen through the HUD, $\chi_r^2 = 6.75$, $p < .05$.

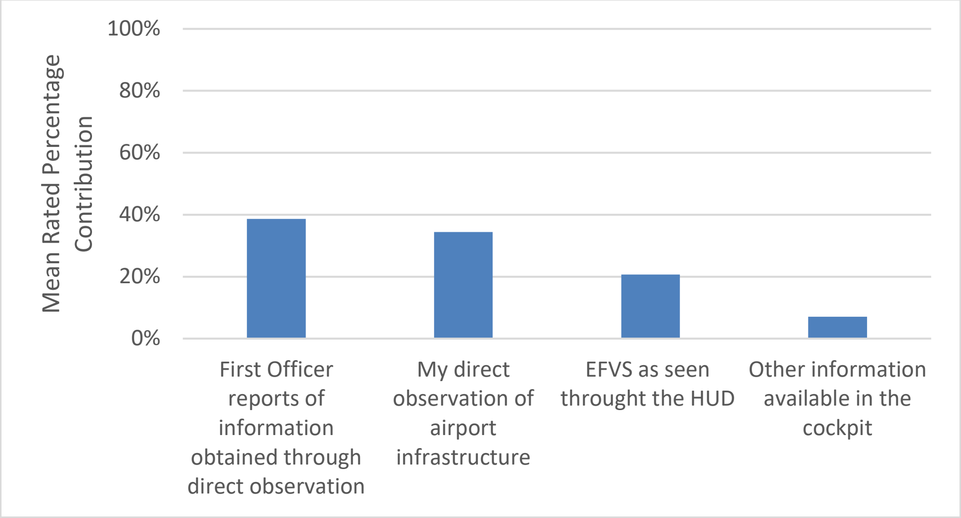


Figure 15. Captains' rankings of contributions to position awareness (Study 1).

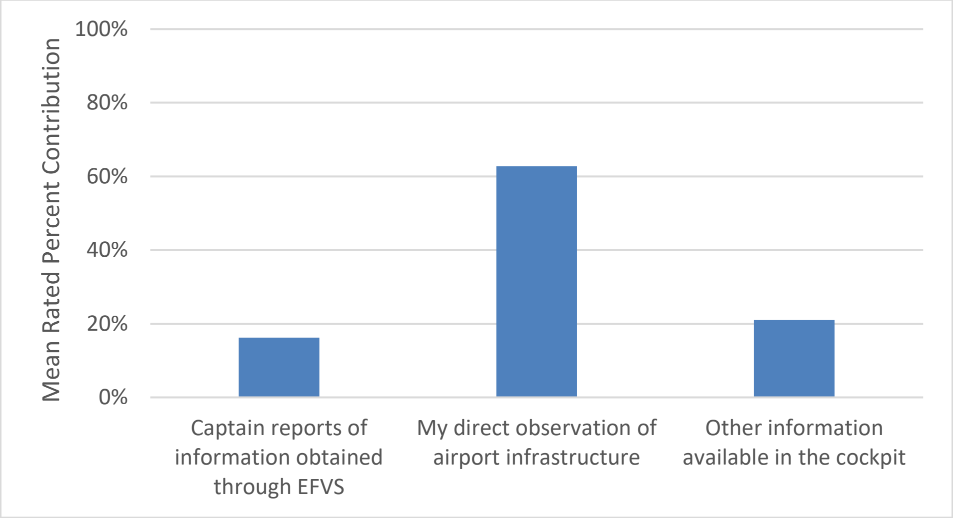


Figure 16. First Officers' rankings of contributions to position awareness (Study 1).

Pilots were also asked to list, in order of preference, any additional airport infrastructure or flight deck resources they felt were needed to aid them in establishing position awareness. Four pilots said they did not need any additional infrastructure. Other pilots did list additional infrastructure, from which three categories were identified: lights, signs, and markings. The number of pilots who wrote down something in each category is shown in Table 10 by order of preference. Note that pilots did not always specify the exact type of infrastructure needed in each

Twenty pilots (12 Captains and 8 First Officers) answered “yes” when asked if there was a difference between left and right turns (statistically significant, $\chi^2 = 10.67$, $p < .01$). When asked to describe what factors caused the experiences to be different, 10 of the 12 Captains said that right turns were more difficult, and five of the eight First Officers said that left turns were more difficult. In general, the factors given by both Captains and First Officers related to the loss of visual cues on turns to the opposite side of the aircraft.

There was also a statistically significant finding when pilots were asked if there was a difference between wide and sharp turns ($\chi^2 = 11.64$, $p < .0001$), with 19 pilots (10 Captains and 9 First Officers) answering “yes” (only three pilots said “no” and two pilots did not answer the question). Eleven of the 19 pilots (7 Captains and 4 First Officers) commented that sharp turns were more difficult. Factors given by both Captains and First Officers included loss of visual references (7 pilots), limited EFVS FOV (3 pilots), and difficulty oversteering (3 pilots) on sharp turns.

Workload. Using a 3-point scale (low, medium, high), pilots were asked to rate the contribution of RVR, turn severity, and reduced infrastructure to increased workload. Responses were mixed, that is, an approximately equal number of pilots selected low, medium, and high ratings for each factor (no statistically significant differences).

Communication. Pilots were asked how effectively information was communicated to them given that only the Captain had access to the EFVS and the First Officer was dependent on the Captain to convey critical information that may only be available in the EFVS. Answers were provided by choosing one of three options. Figure 18 shows the number of pilots who chose each response option. Most pilots felt that the communication was adequately effective, and this finding was statistically significant, $\chi^2 = 7.75$, $p < .05$.

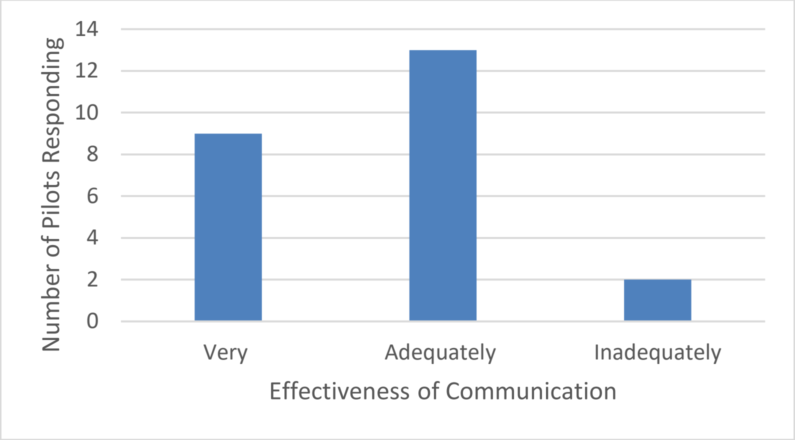


Figure 18. Rated communication effectiveness (Study 1).

Study 1 summary. Flight crews committed route deviations in 11% of the total 216 trials (12 crews x 18 conditions), but they were able to correct back on the route 29% of the time. Most route deviations occurred at 300 feet RVR with the EFVS off, with either a standard painted centerline only or a painted centerline with LVO/SMGCS enhancements (no lights). All deviations occurred during right turns, and mostly during turns greater than or less than 90 degrees. Intersection complexity did not appear to have an effect on route deviations.

Flight crews kept the aircraft on the taxiway throughout all scenarios (e.g., did not leave the hard-surfaced areas). The mean deviation from the taxiway centerline was similar across EFVS conditions, and deviations decreased as visibility improved. Deviations were larger at increasing levels of infrastructure, which might be explained by flight crews positioning the nose wheel over the wide centerline border or centerline lights, rather than the center stripe. Across all combinations of conditions, centerline deviations were on average small (about four feet). The deviations were also highly variable and the median deviation was approximately equal across conditions.

Flight crews showed less rate-of-travel decrement as RVR and infrastructure increased. There was also a small increase in rate of travel with EFVS on compared to EFVS off, but at less than .5 knots, the difference accounted for about 4% total taxi time. The effect of EFVS on rate of travel differed depending on the level of RVR and infrastructure. With EFVS on, flight crews showed a smaller decrement at 500 feet RVR (relative to 300 feet). With EFVS off, the gain was only seen at 1000 feet. There was no effect of EFVS use when taxiing with a standard painted centerline only, but flight crews showed less decrement in rate of travel with EFVS on than with EFVS off when there was an LVO/SMGCS “enhanced” centerline, both with and without centerline lights. During turns, flight crews taxied slower on left turns than on right turns. They also taxied slower as turn angle increased. Flight crews were expected to proceed more slowly as intersection complexity increased, but the intersections with the highest-calculated complexity were traversed more quickly, likely due to a confounding effect of one or more other variables such as RVR.

There were two scenarios where a truck was parked just off the side of the taxiway, and it came into view just as the flight crew completed a turn. Almost all flight crews acknowledged the truck on the right side, and Captains and First Officers acknowledged the truck about equally. When the Captain acknowledged it, he or she was looking through the EFVS. First Officers detected the right-side truck six seconds faster than Captains did. About half of the flight crews acknowledged the truck on the left side; most of the time, it was the Captain who saw it out the left-side window and acknowledged it. Flight crews stopped for the truck (on the left and right) about half of the time that they acknowledged seeing it.

During the LVO/SMGCS scenario with centerline lights only on the cleared route, flight crews tended to have smaller centerline deviations compared to the rest of the scenarios, including two “matching” scenarios conducted under the same RVR with centerline lights (one with EFVS and one without). The use of EFVS under these conditions did not improve centerline deviations to the level of the LVO/SMGCS scenario. Rate of travel in the LVO/SMGCS scenario was similar to the rate of travel in the rest of the scenarios.

When asked for their opinions following the experiment, about half of the pilots (an equal mix of Captains and First Officers) said they had no concerns about the use of EFVS for low-visibility operations. Those who did have concerns expressed issues with the effectiveness of EFVS under certain environmental conditions, for example, when there is precipitation. Most pilots wanted a HUD with an EFVS repeater on the First Officer’s side.

Pilots’ opinions were mixed as to whether they had sufficient awareness to verify their position and navigate effectively during the experiment. For Captains, a combination of the First Officer’s reports and the Captain’s own observations (through the EFVS or out the window) contributed to his or her position awareness. First Officers reported relying mostly on their own observations for position awareness. The majority of pilots felt they needed additional airport infrastructure to aid them in establishing position awareness. In order of the most cited, their preferred types of infrastructure included increased or improved lighting, signage, and markings. The majority of pilots also felt they needed additional flight deck resources to aid in establishing position awareness—in most cases, an EFB/moving map with ownship and/or a HUD/EFVS for the First Officer.

Captains tended to feel that right turns were more difficult and First Officers felt that left turns were more difficult, mostly due to the loss of visual cues on the opposite side of the aircraft. Both Captains and First Officers agreed that sharp turns were more difficult than wide turns due to factors such as loss of visual references, limited EFVS FOV, and difficulty oversteering. These opinions are consistent with the performance data, which showed more route deviations on right turns and sharp turns greater than 90 degrees. Rates of travel were also slower on sharper turns. For the B-777, that aircraft is limited to operational turns not to exceed 90 degrees, and thus one would not expect B-777 crews to be conducting the >90 degrees turns, encountered in this study, in the operational environment.

Pilots did not reach consensus as to how much RVR, reduced infrastructure, and turn severity contributed to increased workload. Most pilots felt that information was communicated adequately and effectively between crewmembers, considering that the Captain had an EFVS and the first officer did not.

Study 2

Route deviations. Route deviations were defined as missed hold short positions, missed turns, or turns on the wrong taxiway. In some cases, flight crews almost missed a turn or started to make a wrong turn but were able to correct back onto the intended route. The number of route deviations, including wrong turns that were corrected, is presented in Table 12 at each level of EFVS, RVR, and infrastructure (the number of corrected turns are in parentheses). Flight crews made 34 route deviations, 15 of which were corrected. The majority of route deviations were committed under 300 feet RVR with EFVS off, with only a standard painted centerline or a painted centerline with LVO/SMGCS enhancements (no lights). Across RVR and EFVS conditions, the majority of deviations occurred when the only available taxiway infrastructure was the painted centerline with LVO/SMGCS enhancements. Note that each combination of variables (each cell in the table) represents a single route, so it is possible that routes assigned to the enhanced centerline condition were unintentionally more difficult than the other routes. Route deviations were mostly consistent within each scenario, that is, most of the time flight crews missed the same turn or made a wrong turn on the same taxiway.

Table 12. Frequency of route deviations by RVR, EFVS, and infrastructure (Study 2).

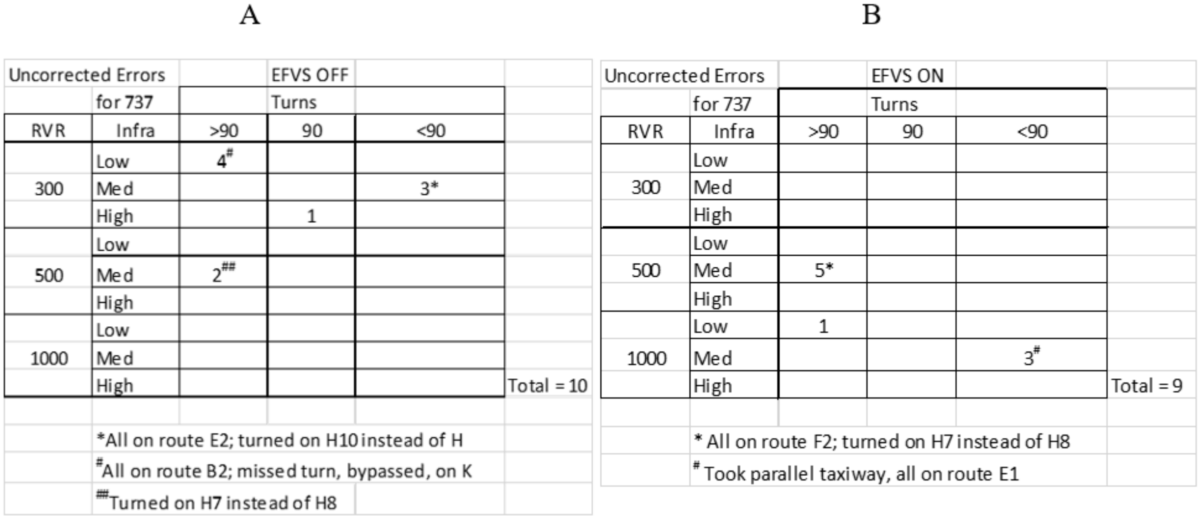
Infrastructure					
RVR (ft)	EFVS	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)	*Total*
300	On	0	0	0	*0*
	Off	5 (1)	11 (8)	1 (0)	*17 (9)*
500	On	2 (2)	5 (0)	0	*7 (2)*
	Off	0	2 (0)	0	*2 (0)*
1000	On	1 (0)	5 (2)	0	*6 (2)*

Infrastructure					
	Off	0	2 (2)	0	*2 (2)*
Total		*8 (3)*	*25 (12)*	*1 (0)*	*34 (15)*

Note: Corrected turns are in parentheses.

Again, it is useful to recast the data to show only the uncorrected errors as they are distributed by RVR and infrastructure, and divided at the highest level between EFVS on and EFVS off. If we look at Tables 13 A and 13B it is immediately apparent that, with EFVS ON, which is the condition of interest, 6 of the 9 uncorrected errors occurred where there were turns exceeding 90 degrees. Again, excluding turns greater than 90 degrees would potentially prevent two thirds of the uncorrected errors with EFVS on. Further, 6 of the 10 uncorrected errors with EFVS off were also on turns exceeding 90 degrees, and thus one might, by the same turn-category exclusion, reduce uncorrected errors, even without EFVS, by almost two thirds. Comparing across what would then remain puts errors roughly equivalent between EFVS on and EFVS off, with the same number of errors in turns less than 90 degrees, both in L2 (medium infrastructure), but in different RVR situations. Once again, given the extremely small number of events, the small sample size, and the small difference, this particular difference is not directly testable using inferential statistics.

Table 13. Frequency of uncorrected turn errors by RVR, Infrastructure, Turn Angle and by (A) EFVS On and (B) EFVS Off (Study 2).



A

Uncorrected Errors			EFVS OFF		
	for 737		Turns		
RVR	Infra	>90	90	<90	
	Low	4#			
300	Med			3*	
	High		1		
	Low				
500	Med	2##			
	High				
	Low				
1000	Med				
	High				Total = 10

*All on route E2; turned on H10 instead of H

#All on route B2; missed turn, bypassed, on K

##Turned on H7 instead of H8

B

Uncorrected Errors			EFVS ON		
	for 737		Turns		
RVR	Infra	>90	90	<90	
	Low				
300	Med				
	High				
	Low				
500	Med	5*			
	High				
	Low	1			
1000	Med			3#	
	High				Total = 9

* All on route F2; turned on H7 instead of H8

\# Took parallel taxiway, all on route E1

Revisiting this by turn angle only, twenty-nine of the 34 route deviations occurred at an intersection where the flight crew was instructed to turn (4 flight crews went straight on the wrong taxiway, 1 passed the instructed hold short position, and 1 started to turn on a taxiway that was several taxiways away from the instructed intersection). Table 14 shows the total number of route deviations by turn angle for each of the 29 instructed turns. Most route deviations occurred on turns that were either less than or greater than 90 degrees. On turns less than 90 degrees, flight crews were able to correct back on the intended route more than 50% of the time. Flight crews were not able to correct most of the route deviations on turns greater than 90 degrees. All but one of the route deviations occurred during right turns.

Table 14. Frequency of route deviations by turn angle (Study 2).

Turn Angle	Wrong/Missed Turns
<90°	13 (9)
90°	1 (0)
>90°	14 (3)

Note: Corrected turns are in parentheses.

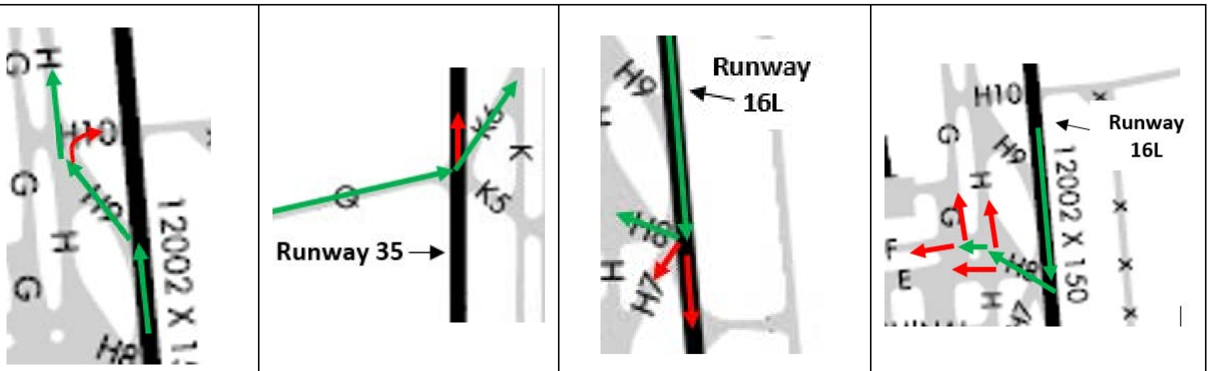
Table 15 shows the number of route deviations by intersection complexity. Most route deviations occurred at intersections with two or three branching taxiways. Flight crews deviated from the route at an intersection with four branches about half as often as they did at two- or three-branch intersections. Note that there were only 10 four-branch intersections across all of the scenarios, compared to 26 and 30 two- and three-branch intersections, respectively. Therefore, there were fewer opportunities to make errors on four-branch intersections.

Table 15. Frequency of route deviations by intersection complexity (Study 2).

Intersection Complexity	Wrong/Missed Turns
2	12 (9)
3	15 (3)
4	6 (3)

Note: Corrected turns are in parentheses.

There were four intersections where more than one flight crew deviated from the route at the same intersection. The four intersections are depicted in Figure 19; the instructed routes are depicted in green and the deviations are depicted in red. Note that, because some scenarios were presented twice (under a different combination of variables), the number of flight crews who committed each deviation may represent more than one cell in Table 12.



Intersection 1 – Coming from taxiway H9, 11 flight crews made a wrong turn onto taxiway H10 instead of H.

Intersection 2 – Crossing runway 35 from Q to K6, seven flight crews missed taxiway K6.

Intersection 3 – Coming from runway 16L, six flight crews turned on H7 instead of H8. One flight crew passed the turn on H8.

Intersection 4 – Coming from taxiway H8, three flight crews made a wrong turn on one of the following taxiways: H, G, and E. One flight crew passed the hold short point at G on F.

Figure 19. Intersections with common route deviations (Study 2). Routes in green, deviations in red.

As in Study 1, errors at intersections in Figure 19 were further examined by looking at the simulator video recordings and Google Earth images. Since the intersections and errors were the same for intersections 1-3, a discussion of these errors was provided under the “Route deviations” section for Study 1.

Intersection 4 was large with multiple off-shooting taxi lines, as shown in Figure 20. Flight crews were confused by signage and had difficulty determining which line led to which taxiway. This scenario was conducted with EFVS on, in 1000 feet RVR visibility, and Level 2 infrastructure.

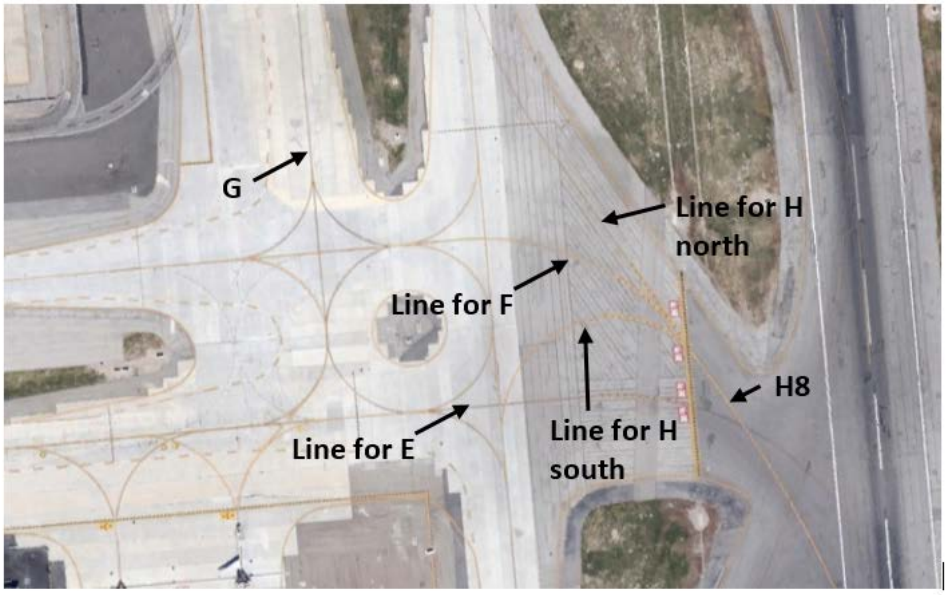


Figure 20. Layout of intersection 4 and lead-on/lead-off lines.

Regarding successful-completion probabilities for Study 2, they are limited by the same factors as mentioned in Study 1. Again, only 23% of the crews were responsible for committing 47% of the deviations, and thus a non-uniform distribution across crews (see Appendix B for plots of deviations by crews). However, if one did wish to look at the likelihood, based upon these particular data, of NOT completing the taxi route to the desired location, that is depicted in Table 16 following. As in Study 1, we can see higher potential failure probabilities operating in 300 feet RVR when the EFVS is off than when it is on and, in fact, there were no uncorrected errors for any infrastructure level in 300 feet RVR when EFVS was on (as noted in the earlier table of uncorrected errors). Again, we see a higher potential for failure to complete under RVR 500 and medium (L2) infrastructure when the EFVS is on. Comparably, potential for failure to complete was also higher in RVR 1000 feet, for low and medium infrastructure, when the EFVS was on. The same limitations in interpreting low-frequency events apply here as mentioned in Study 1, along with the caveat about criteria for terminating a run.

Table 16. Calculated probabilities of failure to complete taxi route tabulated by RVR, Infrastructure, and EFVS of and off (Study 1).

INFRASTRUCTURE			
RVR/EFVS	L1 (Low)	L2 (Medium)	L3 (High)
300/On	0.00	0.00	0.00
300/Off	0.33	0.25	0.08
500/On	0.00	0.42	0.00
500/Off	0.00	0.17	0.00
1000/On	0.08	0.25	0.00
1000/Off	0.00	0.00	0.00

Note: Green = EFVS on, white = EFVS off and no difference from on, yellow = EFVS on was better, rose = EFVS off was better.

Centerline tracking. Centerline tracking was recorded two ways: First, the flight simulator recorded whether the aircraft wheels were on or off the taxiway (versus in the grass) throughout each scenario. Second, centerline deviations were calculated on straight taxi segments, using the same method as described for Study 1.

No flight crews taxied off the pavement at any point throughout the scenarios. The centerline deviations were highly variable, and no statistical tests were conducted. The box plots in Figures 21-23 show the distribution of absolute centerline deviations by EFVS, RVR, and infrastructure, respectively.

The median centerline deviation appeared to be similar across all conditions. The mean deviation was slightly smaller with EFVS on than with EFVS off. Increases in RVR were associated with a decrease in the mean deviation from the centerline. Across infrastructure conditions, the mean centerline deviation was highest with a standard painted centerline, followed by an LVO/SMGCS "enhanced" centerline with lights, and then an "enhanced" centerline with no lights. Regardless of the differences between conditions, the largest mean deviation across all conditions was just over four feet, which is small from an operational perspective.

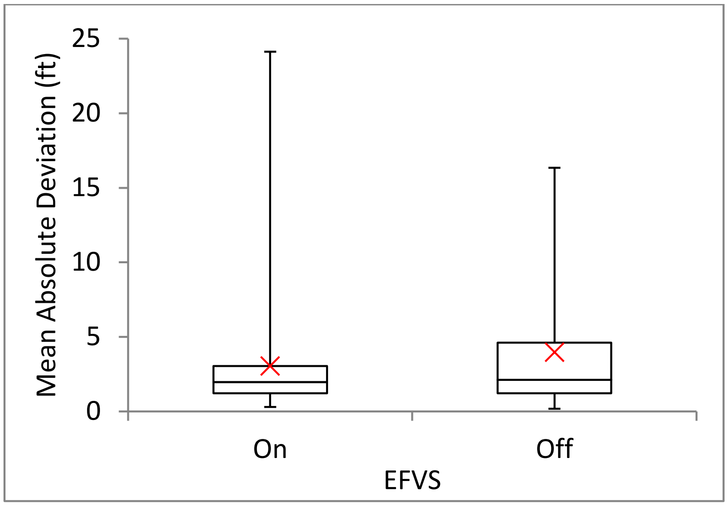


Figure 21. Centerline deviations by EFVS condition (Study 2).

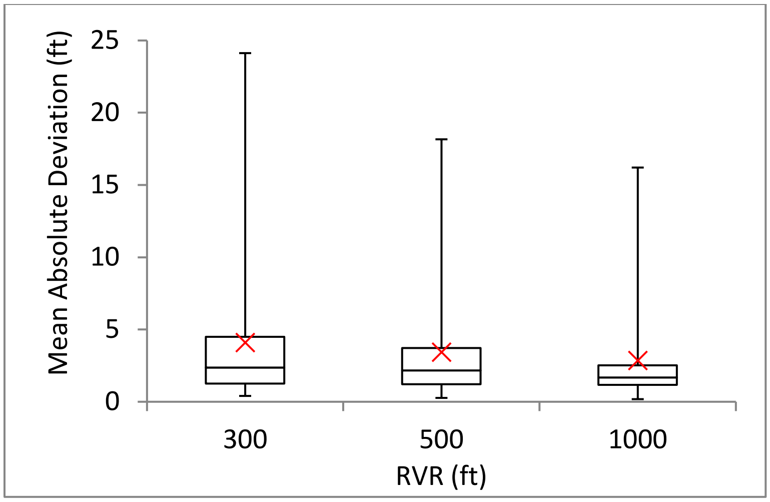


Figure 22. Centerline deviations by RVR (Study 2).

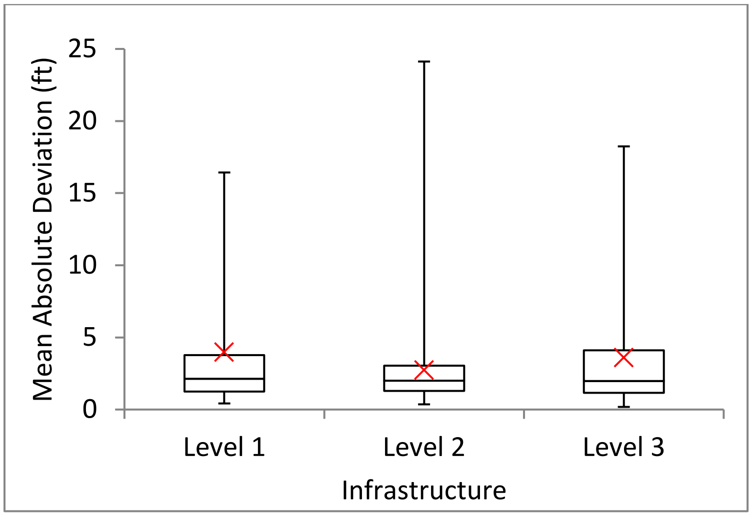


Figure 23. Centerline deviations by infrastructure (Study 2).

Rate of travel. The expectations for rate-of-travel results were essentially the same as stated in the Study 1 Results section. The mean rate of travel was calculated in the same fashion as in Study 1. A repeated-measures ANOVA tested for the main effects and interactions of EFVS, RVR, and infrastructure. As anticipated, there were significant main effects of all three variables. Flight crews showed less decrement (1.04 knots less) with EFVS on than with EFVS off, $F(1,11) = 26.19$, $p < .001$. Considering the mean total taxi time of 5.5 minutes (330 seconds), this difference equates to about 10% shorter total taxi time. Flight crews also showed less rate-of-travel decrement as RVR and infrastructure increased (as in Study 1); RVR - $F(2,22) = 93.82$, $p < .001$, and Infrastructure - $F(2,22) = 22.92$, $p < .001$ (post-hoc comparisons were conducted using Fisher's LSD with the Bonferroni correction; all $p < .05$). The largest difference between RVR conditions was 2.63 knots, which equates to almost 27% shorter total taxi time. The largest difference between infrastructure conditions was 1.07 knots, which equates to a 10.6% reduction in total taxi time. Table 17 shows the mean rate of travel for each level of each variable. Note that the two larger decrement reductions are for visibility (RVR) and infrastructure variations.

Table 17. Mean rate-of-travel main effects for EFVS, RVR, and Infrastructure (Study 2).

Variable	Level	Mean	SD
EFVS	On	13.28	2.37
	Off	12.24	2.03
RVR (ft)	300	11.27	1.80
	500	13.11	2.20
	1000	13.90	1.92
Infrastructure	Level 1	12.25	2.14
	Level 2	12.71	2.13
	Level 3	13.32	2.40

There was again, as in Study 1, a significant interaction of EFVS with RVR, *F*(2,22) = 4.48, *p* < .05. Figure 24 shows the mean rate of travel by each level of EFVS and RVR. Flight crews showed a smaller rate=of-travel decrement with EFVS on than with EFVS off at all three levels of RVR, but the difference was greatest at 500 feet RVR. With EFVS off, the decrement decreased steadily as RVR increased. With EFVS on, flight crews showed the least decrement at 500 feet RVR, where, for all practical purposes, it plateaued.

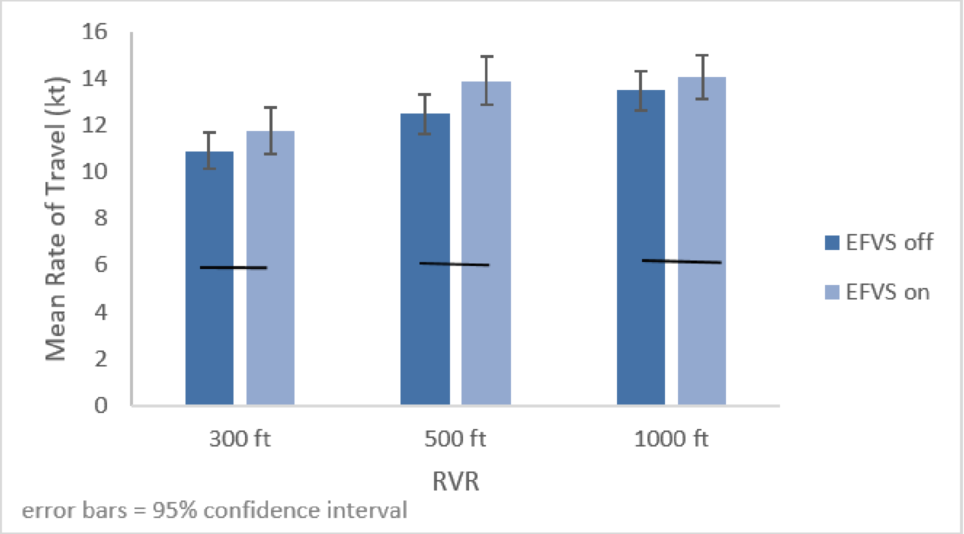


Figure 24. Mean rate of travel by EFVS and RVR (Study 2). Note: Statistically significant post-hoc comparisons (LSD, *p* < .05) at each level of RVR are represented by a line connecting the bars.

The interaction of EFVS and infrastructure was also significant, *F*(2,22) = 19.13, *p* < .001. Figure 25 shows the average rate of travel by each level of EFVS and infrastructure. There was no beneficial effect of EFVS with only a standard painted centerline, but flight crews showed a smaller decrement in rate of travel with EFVS on than with EFVS off when there was an LVO/SMGCS “enhanced” centerline, with or without centerline lights.

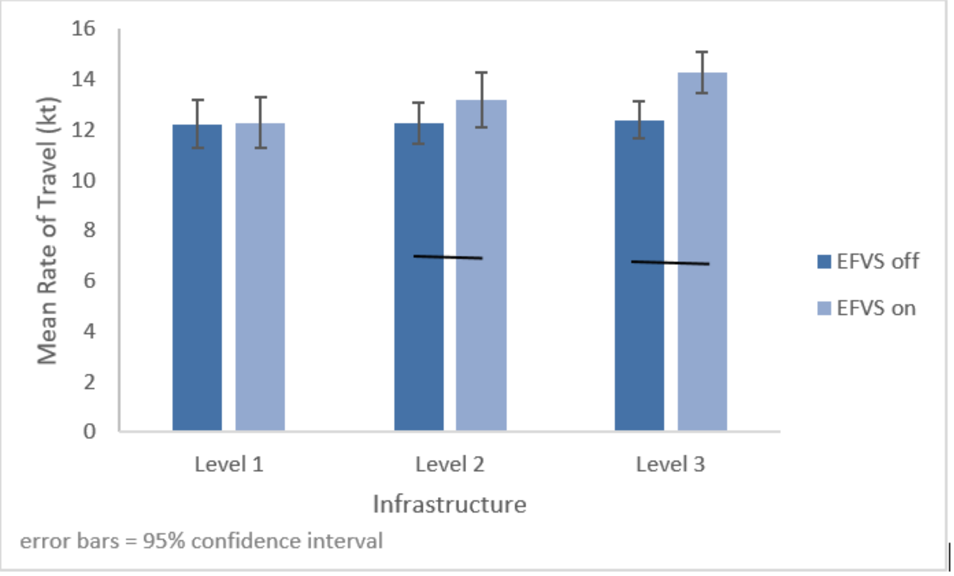


Figure 25. Mean rate of travel by EFVS and infrastructure (Study 2). Note: Statistically significant post-hoc comparisons (LSD, *p* < .05) at each level of infrastructure are represented by a line connecting the bars.

Once again, there was a significant interaction of RVR and infrastructure, *F*(4,44) = 4.55, *p* < .01. Figure 26 shows the mean rate of travel by each level of RVR and infrastructure. The effect RVR was different depending on the level of infrastructure. With a standard painted centerline, flight crews exhibited a moderate difference between 300 feet and 500 feet RVR, and a statistically significant one between 500 feet and 1000 feet RVR. With an “enhanced” painted centerline both with and without centerline lights, the only significant difference in rate of travel between successive RVR levels was from 300 feet to 500 feet RVR; rate of travel was approximately the same at 500 feet as it was at 1000 feet RVR.

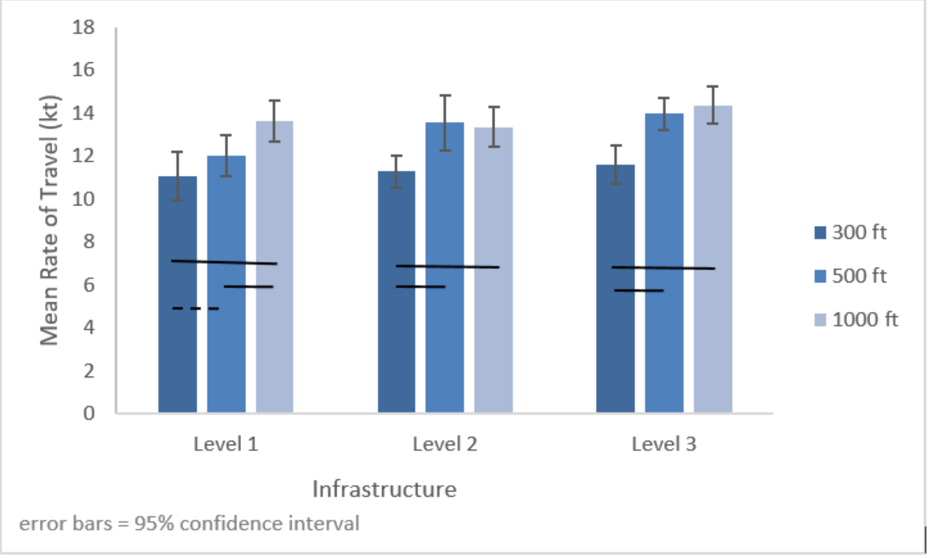


Figure 26. Mean rate of travel by RVR and infrastructure (Study 2). Note: Statistically significant post-hoc comparisons (LSD, *p* < .05) are represented by a solid line connecting the bars. The dashed line

represents a moderately significant difference ($p < .10$).

Separate one-way repeated-measures ANOVAs examined the effect of turn angle, turn direction, and intersection complexity on the mean minimum rate of travel during turns. There was, again, a statistically significant effect of turn angle, $F(2,24) = 115.86$, $p < .01$. Fisher's LSD tests revealed that the minimum rate of travel during turns was significantly slower as turn angle increased (all $p < .05$ with the Bonferroni correction applied). The mean minimum rate of travel during turns is shown Figure 27 by turn angle.

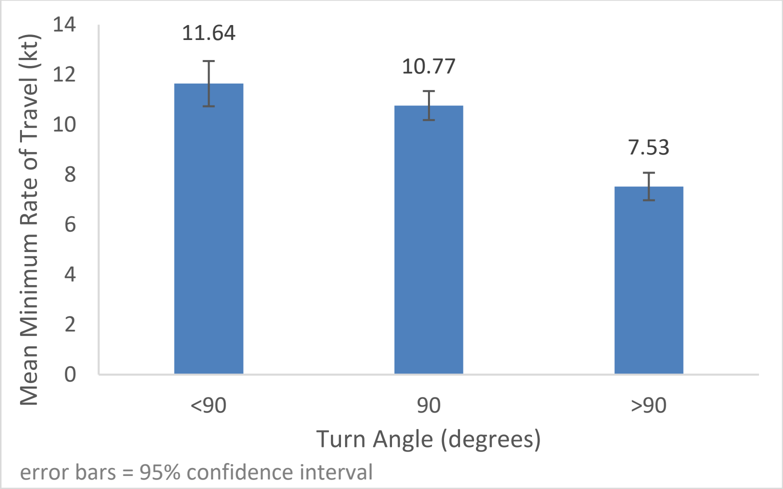


Figure 27. Mean minimum rate of travel during turns by turn angle (Study 2).

There was also a significant effect of turn direction, with the mean minimum rate of travel being slower during left turns than during right turns, $F(1,12) = 8.72$, $p < .05$. The mean minimum rate of travel is shown in Figure 28 for left and right turns.

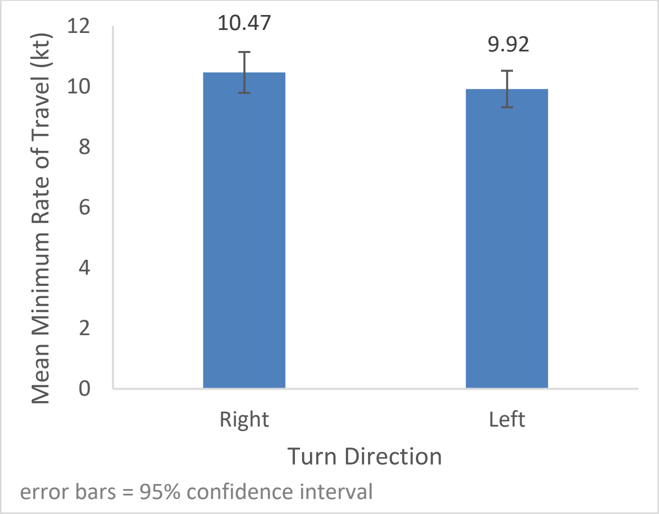


Figure 28. Mean minimum rate of travel during turns by direction (Study 2).

Finally, there was a significant effect of intersection complexity on the mean minimum rate of travel during turns, $F(2,24) = 17.21$, $p < .01$. Turns that were initiated at intersections with three branches were significantly slower than turns initiated at intersections with two or four branches (the mean minimum rate of travel was not significantly different between turns of two and four branches). Although this finding was surprising from a theoretical standpoint, the same pattern occurred in Study 1. Interpretation of this result, however, is subject to the same limitations brought forward in the Results section of Study 1. The mean minimum rate of travel is shown in Figure 29 by intersection complexity.

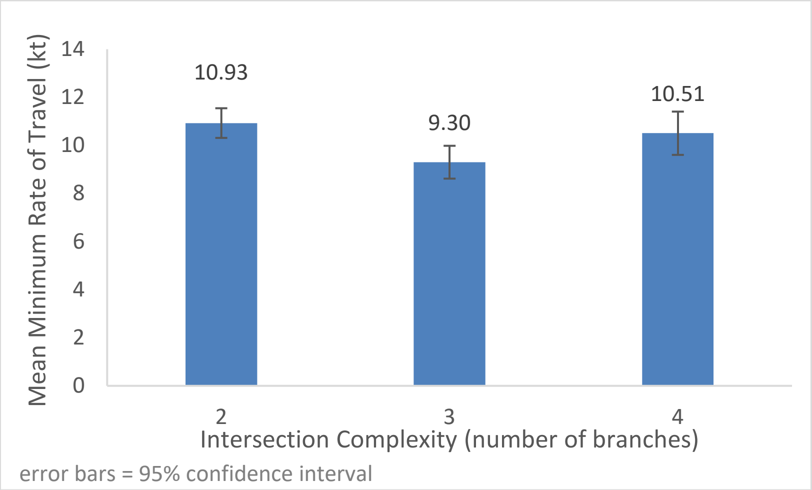


Figure 29. Mean minimum rate of travel during turns by intersection complexity (Study 2).

Obstacle detection. Flight-crew responses to the truck in the off-nominal scenarios were examined by watching the scenario video recordings. The number of flight crews who acknowledged the truck (made note of it verbally) and stopped are provided in Table 18 for both right- and left-side trucks.

Table 18. Frequency of pilot responses to obstacle by location and response category (Study 2).

Action	Right Side	Left Side
Acknowledged truck	10	7
Stopped	2	3

Ten of the 13 flight crews acknowledged the truck on the right side. Six of the 10 times, the First Officer was the one who acknowledged it. The Captain acknowledged it four out of the 10 times. In the videos, it was not clear whether the Captains were looking through the EFVS when they acknowledged the truck. However, one Captain verbally reported that he saw it through the EFVS. For another two crews, the truck was visible in the EFVS display when the Captain acknowledged it, so it is possible that the Captain saw it through the EFVS. On average, First Officers detected the right-side truck three seconds sooner than Captains did. Two flight crews stopped for the truck on the right side; both contacted ATC. Of the eight fight crews who did not stop, four felt that they were clear of the truck and one felt they had already passed the truck (as indicated by flight crews’ discussions during the scenario). The other three flight crews did not seem concerned about the truck.

Seven of the 13 flight crews acknowledged the truck when it appeared on the left side. Three of the seven times, the Captain was the one who acknowledged it. In the videos, it was not clear where the Captain was looking when he or she acknowledged the truck, but it is reasonable to assume that he or she saw the truck through the left-side window because it was outside the EFVS FOV. The Captain was looking through the EFVS in three of the four cases where the First Officer was the one who acknowledged the truck (as indicted by his or her comments or physical interactions with the EFVS), which may explain why the Captain did not see the truck first. Three flight crews stopped for the left-side truck and contacted ATC. Of the four crews who did not stop, three stated that they were clear of the truck and one appeared unconcerned.

LVO/SMGCS scenario. Flight crews did not commit any route deviations during the LVO/SMGCS scenario. In the "matching" scenarios with centerline lights visible on all taxiways (not just on the cleared route), there was only one route deviation.

The mean absolute deviation from the taxiway centerline was 2.40 feet (*SD*=1.13), which is smaller than the mean deviation in the matching scenarios with EFVS off (*M*=3.93, *SD*=4.69) and with EFVS on (*M*=4.75, *SD*=3.70). Across all scenarios (i.e., all combinations of conditions, excluding the LVO/SMGCS scenario), the mean absolute centerline deviation was 3.51 feet (*SD*=3.79). Note, however, that these data were highly variable with outliers as large as 24 feet. In the LVO/SMGCS scenario, the largest deviation was about five feet from the centerline.

The mean rate of travel (excluding stops) throughout the entire LVO/SMGCS scenario was 12.96 knots (*SD*=2.66), compared to a mean of 12.09 knots (*SD*=1.57) in the matching scenario with EFVS off and 11.00 knots (*SD*=1.50) in the matching scenario with EFVS on. The mean rate of travel across all scenarios was 12.76 knots (*SD*=2.26).

Pilot opinions. Pilot opinion data from the Study 2 post-experiment questionnaire were analyzed in the same way as the Study 1 data, with the exception of few questions. The Study 1 and Study 2 questionnaires asked the same questions, but for Study 2 some of the response items were converted to 100-point rating scales to encourage better pilot responses. Rating scale questions were analyzed using an ANOVA. The results are summarized below by question topic.

EFVS operations. When asked if they had or anticipated any operational concerns with the use of EFVS for taxi in low visibility, 17 of the 26 total pilots (6 Captains and 11 First Officers] said they had no concerns. Those who did have concerns included four pilots (3 Captains and 1 First Officer) who made comments about the EFVS FOV:

- "Field of view is smaller"
- "In big turns greater than 90 degrees, there is an abrupt discontinuity in what you can see, i.e., in the HUD vs outside"
- "Restricted side view is concern. Oversteer we [sic] difficult as you lose sight of targets when oversteer. Larger [aircraft require] more oversteer"
- "Seeing objects or obstacles to the side is very difficult in low light or low visibility conditions. The First Officer will also be accomplishing checklists. This will be a challenge"

Another four pilots (3 Captains and 1 First Officer) had concerns about the EFVS visuals:

- "To me, sensor placement critical to minimize parallax"
- "Vision is enhanced, but loss of ability to read signage is significant"
- "Difficult to see markings when they don't show on the EFVS...it just shows an empty rectangle. Blue taxi lights look green"

- "Many of the markings and signs aren't visible through the EFVS and so the person using it is sometimes disoriented. Overall I think it enhances situation awareness for the crew though"

Pilots were also asked whether they felt an EFVS repeater display should be available to the First Officer. Twenty-three of the 26 total pilots said that they would like an EFVS repeater for the First Officer, $\chi^2 = 15.38$, $p < .001$. When asked what type of display they would prefer for an EFVS repeater, 12 pilots said they would prefer an EFVS on a HUD, five preferred a head-down display, and six felt either display would suffice (no preference).

Pilots operating as First Officer were asked how having the EFVS imagery available to the Captain affected their task as First Officer during taxi operations (i.e., if it elevated, decreased, or did not affect their workload). The number of First officers who provided each answer is shown in Table 19.

Table 19. Frequency of first officers' responses to the Effect of EFVS on perceived workload (Study 2).

Effect on Workload	Number of First Officers
Elevated	3
Decreased	5
None (did not affect)	5

First Officers were also asked to provide reasoning for their answers. Of the five pilots who felt their workload decreased, four provided reasons relevant to the Captain's increased situation awareness and/or the Captain's ability to see, compared to their own:

- "Decreased my workload however I felt slightly out of the situational awareness compared to the environment that the captain was working with. I believe it would just overall [sic] the safety and situational awareness of the crew having the ability to see the same information in real time"
- "Felt the [Captain] had better situational awareness of the overall taxi operation"
- "[The Captain] has a greater situation awareness window"
- "[The Captain] had a better forward looking visual"

The three pilots who felt their workload was elevated noted that they had to support the Captain due to EFVS limitations or low-visibility in general:

- "Was straining to see to try and keep up with what Captain could see. In turns, he'd lose that EVSA* [sic] visual and it was important for me to be heads up when turning right" (*pilot was referring to EFVS visual image).
- "I felt that I had to give the Captain progressive instructions due to him not seeing markings at tines [sic] or being heads up in the HUD vs. consulting the chart"
- "Due to low visibility conditions, I was concentrating on backing the Captain up during taxi"

Position Awareness. Pilots were asked whether they had sufficient awareness to verify their position on the airport and navigate effectively. There were no statistically significant differences in pilot responses, that is, approximately half answered "yes" and half answered "no." Another question asked pilots to estimate how much different sources of information (pilot reports, airport infrastructure, EFVS, and other information) contributed to their position awareness. Both Captains and First Officers felt that the following items contributed approximately equally to their position awareness (i.e., no significant differences): crewmember's reports of information obtained through direct observation, their own direct observation of airport infrastructure, and what the Captain saw (and reported to the First Officer) through the EFVS.

Pilots were asked whether they felt any additional airport infrastructure or flight deck resources were needed to aid them in establishing position awareness. Nineteen of the 26 total pilots felt that they needed additional airport infrastructure, and only seven pilots did not, $\chi^2 = 5.54$, $p < .05$. Those who felt additional infrastructure was needed were asked to list, in order of preference, what infrastructure they would prefer. Pilots listed taxiway markings, lighting, and signage; the number of pilots who listed each is shown in Table 20. Of the eight pilots who preferred additional taxiway markings, four specifically mentioned painted taxiway designators, particularly where multiple taxiways converge (3 pilots). Six pilots said they would prefer better or more lighting (centerline lights, lead-on/off lights, closer-spaced edge lights, stop bars). Five pilots preferred improved signage. Most pilots only listed one piece of infrastructure as their preference.

Table 20. Frequency of pilot preferences for airport infrastructure (Study 2).

Infrastructure	Number of Pilots
Markings	8
Lighting	6
Signage	5

Nineteen of the 26 total pilots felt that they needed additional flight deck resources, $\chi^2 = 5.54$, $p < .05$. The majority of comments (13 pilots) indicated that pilots preferred to have an EFB/moving map with ownship to help them to establish position awareness. Again, most pilots only listed one preference.

Turns. Pilots were asked to rate how much different pieces of taxiway infrastructure contributed to supporting accurate turns, both with and without the EFVS. Ratings were made by placing an X on a line with anchors "small amount" and "large amount." For data analysis, the position of the X was converted to a number between 1 and 100, with 1 = "small amount" and 100 = "large amount." The data were analyzed using a 2 (EFVS) x 4 (infrastructure) repeated-measures ANOVA. There was no significant effect of EFVS availability, but there was an effect of infrastructure, $F(3,66) = 4.49$, $p < .01$. Post-hoc Fisher's LSD tests revealed that centerline lighting had a significantly greater contribution than edge lighting ($p < .05$), and a marginally significantly greater contribution than LVO/SMGCS "enhanced" and standard painted centerlines (both $p < .10$). There was a marginally significant ($p < .10$) interaction between EFVS and infrastructure. The mean pilot ratings are shown in Figure 30.

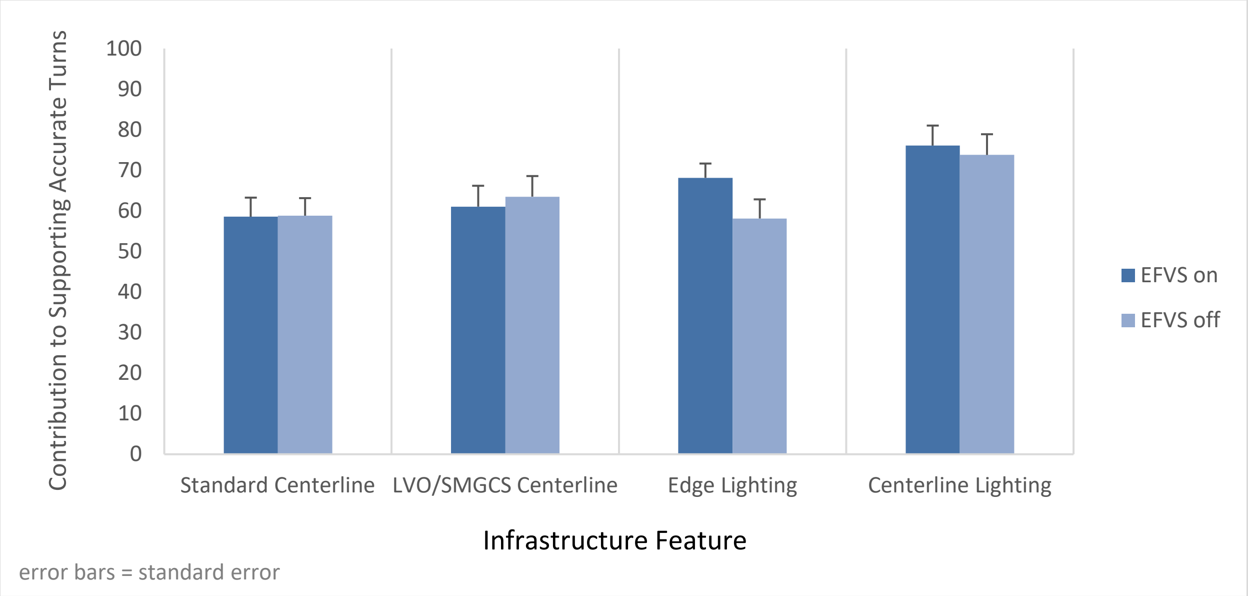


Figure 30. Pilots' subjective rating of contribution of infrastructure for making turns (Study 2).

When asked if there was a difference between left and right turns, approximately half of the pilots said "yes" and half said "no" (i.e., no significant difference). Of those who said yes, eight pilots (6 Captains and 2 First Officers) indicated that right turns were harder, and the most common factor that contributed to the difference was the ability to see the turn (5 pilots). Twenty of the 25 total pilots (one pilot left the question blank) felt that there was a difference between wide and sharp turns, and this finding was statistically significant, $\chi^2 = 5.54$, $p < .05$. Nine pilots (4 Captains and 5 First Officers) indicated that sharp turns were harder. Factors included HUD visibility or FOV (5 pilots), and a lack of lights or markings (4 pilots).

Workload. Pilots were asked to judge the degree to which reductions in infrastructure, turn severity, and RVR contributed to increased workload by placing an X on a line with anchors "small amount" and "large amount." The position of the X was converted to a number between 1 and 100, with 1 = "small amount" and 100 = "large amount" and data were analyzed using a one-way repeated-measures ANOVA. There was a statistically significant difference in pilots' ratings, $F(2,50) = 5.58$, $p < .01$. Post-hoc Fisher's LSD tests indicated that the severity of turns had a significantly lower contribution than reductions in infrastructure ($p < .05$) and a moderately lower contribution than RVR ($p < .10$). The mean ratings are shown in Figure 31.

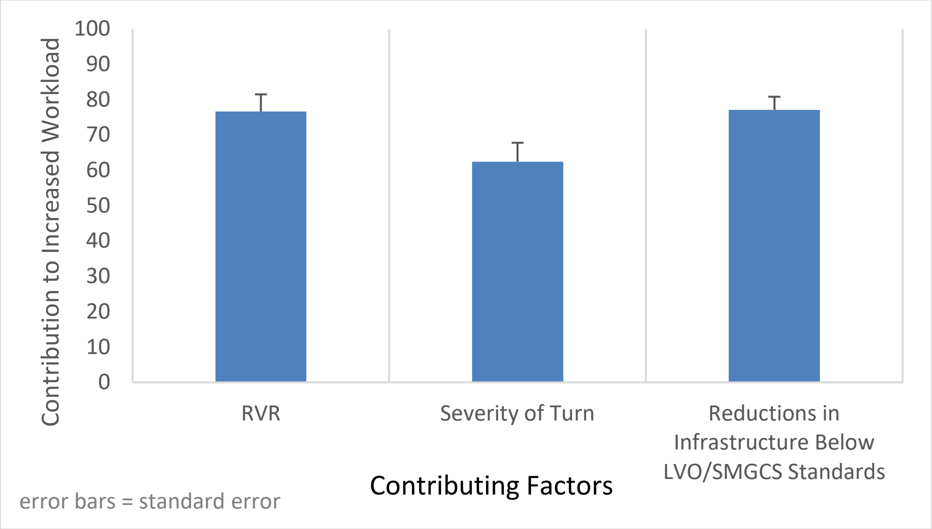


Figure 31. Contributions to increased workload (Study 2).

Communication. Pilots were asked how effectively information was communicated to them given that only the Captain had access to the EFVS and the First Officer was dependent on the Captain to convey critical information that may only be available in the EFVS. Answers were provided by choosing one of three options: very, adequately, or inadequately effectively. There was a statistically significant difference between the number of pilots who chose each option, $\chi^2 = 18.77$, $p < .001$. Eighteen of the 26 pilots felt that information was communicated adequately effectively, and eight pilots felt it was communicated very effectively. No pilots selected "inadequately."

Study 2 summary. Flight crews committed route deviations in 15% of the total 234 trials (13 crews x 18 conditions), but they were able to correct back on the route 44% of the time. Most route deviations occurred at 300 feet RVR with the EFVS off and no centerline lights, with only a standard painted centerline or a painted centerline with LVO/SMGCS enhancements (wide painted centerline). In addition, most deviations occurred during right turns and turns greater than or less than 90 degrees. Intersection complexity did not appear to have an effect on route deviations.

Flight crews kept the aircraft on the taxiway throughout all scenarios (e.g., did not veer off into the grass). The mean deviation from the taxiway centerline was smaller with EFVS on than with EFVS off, and deviations got smaller as RVR increased. Deviations were largest with a standard painted centerline, followed by an LVO/SMGCS "enhanced" centerline (wider line) with lights, then an "enhanced" centerline without lights. Across all combinations of conditions, centerline deviations were on average small (about four feet). The deviations were also highly variable and the median deviation was approximately equal across conditions.

Flight crews showed less rate-of-travel decrement as RVR and infrastructure increased. There was also one-knot less decrement in rate of travel with EFVS on compared to EFVS off. The effect of EFVS on rate of travel differed depending on the level of RVR and infrastructure. With EFVS off, rate of travel increased steadily, as expected, as RVR increased, but with EFVS on, crews achieved their best rate of travel at 500 feet RVR (where it plateaued). There was no effect of EFVS when taxiing with a standard painted centerline only, but flight less decrement was observed with EFVS on than with EFVS off when there was an LVO/SMGCS "enhanced" centerline, both with and without centerline lights. During turns, flight crews taxied slower on left turns than on right turns. They also taxied slower as turn angle increased. Flight crews were expected to taxi slower as intersection complexity increased, but the intersections with the highest and lowest complexity had faster rates of travel than the intersections with medium complexity, possibly due to a confounding effect of one or more other variables such as RVR. It should be noted that mean time to complete a scenario in Study 2 was 5.5 minutes, whereas mean time to complete a scenario in Study 1 was 7 minutes. This was not surprising when one takes into account that the B-737 crews taxied faster, in general, than the B-777 crews.

There were two scenarios where a truck was parked just off the side of the taxiway, and it came into view as the flight crew completed a turn. All but three flight crews acknowledged the truck on the right side, and Captains and First Officers acknowledged the truck about equally. First Officers detected the right-side truck three seconds faster than Captains did. About half of the flight crews acknowledged the truck on the left side, and again, Captains and First Officers acknowledged it about equally.

During the LVO/SMGCS scenario with centerline lights only on the cleared route, flight crews tended to have smaller centerline deviations compared to the rest of the scenarios, including two "matching" scenarios conducted under the same RVR with centerline lights (one with EFVS and one without). The use of EFVS under these conditions did not improve centerline deviations to the level of the LVO/SMGCS scenario. Rate of travel was slightly faster in the LVO/SMGCS scenario than in the matching scenarios, which is wholly unsurprising given the absence of errors and the unequivocal guidance cues.

When asked for their opinions following the experiment, half of the Captains and nearly all of the First Officers had no concerns about the use of EFVS for low-visibility taxi operations. Those who did have concerns expressed issues with the EFVS FOV and/or visuals. The majority of pilots wanted an EFVS repeater display on the First Officer's side, but consensus was not obtained on the type of repeater that pilots preferred (HUD or head-down display).

Responses were mixed as to whether or not pilots felt they had sufficient position awareness to verify their position on the airport and navigate effectively. When asked what contributed to their position awareness, Captains and First Officers perceived there to be an approximately equal contribution of the First Officer's direct observation and the Captain's observation (both through the EFVS and out the window). The majority of pilots felt they needed additional airport infrastructure to aid them in establishing position awareness. Their preferred types of infrastructure included increased or improved markings (e.g., painted taxiway designators, particularly at complex intersections), lighting (centerline lights, lead-on/off lights, closer-spaced edge lights, stop bars), and signage. The majority of pilots also felt they needed additional flight deck resources to aid in establishing position awareness—in most cases, an EFB/moving map with ownship.

Pilots considered centerline lighting to contribute most to their supporting accurate turns, compared to edge lights and LVO/SMGCS "enhanced" and standard painted centerlines. Each piece of infrastructure was rated as having between a medium and large contribution. Pilots did not agree on whether they experienced a difference between right and left turns, but those who did think there was a difference expressed the opinion that right turns were harder due to the inability to see the turn. The majority of pilots felt that sharp turns were harder due to HUD visibility or FOV. These opinions are consistent with the performance data, which showed more route deviations during right turns and sharp turns greater than 90 degrees.

Pilots considered RVR, turn severity, and reductions in infrastructure to have a medium to large contribution to increased workload. However, pilots rated the contribution of RVR and reductions in infrastructure higher than turn severity. Most pilots felt that information was communicated effectively between crewmembers, considering that the Captain had an EFVS and the First Officer did not.

SUMMARY AND DISCUSSION

The purpose of this study was to examine the effectiveness of an EFVS for taxiing in low visibility with minimal to no LVO/SMGCS infrastructure. Study 1 examined EFVS effectiveness in a B-777 simulator to represent wide-body aircraft types. Study 2 examined EFVS effectiveness in a B-737 simulator to represent narrow-body aircraft types.

Flight crews in both studies were generally able to complete the taxi scenarios. B-777 crews deviated from the route slightly less often than B-737 crews did (11% vs. 15% of all trials), but B-737 crews corrected back onto the route more often than B-777 crews did (44% vs. 29% of the time). Given the size of the B-777 compared to the B-737, it may have been easier for B-737 crews to maneuver the aircraft back onto the taxiway following a missed or wrong turn. With centerline lighting at an RVR of 500 feet or above, both B-777 and B-737 flight crews were generally able to navigate successfully with or without the EFVS. At 300 feet RVR without centerline lighting, however, EFVS appeared to provide a benefit over no EFVS. The majority of all route deviations occurred under these conditions with the EFVS off, whereas only one crew had a deviation under the same conditions with EFVS on.

No flight crews diverged from the taxiway (e.g., left the hard surface) in either study. For B-777 crews, the mean deviation from the centerline was about the same with EFVS on as it was with EFVS off. For B-737 crews, the mean centerline deviation was slightly smaller with EFVS on than with EFVS off. The mean deviation decreased for both sets of crews as RVR increased. With regard to taxiway infrastructure, B-777 flight crews had larger mean centerline deviations as infrastructure increased. B-737 flight crews had the largest mean deviation with a standard painted centerline only, followed by an LVO/SMGCS "enhanced" centerline with centerline lights, and then an "enhanced" centerline without lights. The differences between B-777 and B-737 flight crews with regard to centerline deviations across infrastructure conditions might be explained by the aircraft characteristics. In the B-777, where the nose wheel is located behind the flight deck, flight crews may have positioned their nose wheel on the centerline lights or the border of wide centerlines rather than on the center stripe. The B-737 nose wheel is located directly underneath the flight deck, and it may be easier to align with the center stripe due to it being closer to the pilot. Nevertheless, the mean centerline deviations were small in both studies, at about four feet in either direction. Moreover, the centerline deviations were variable for all conditions, and the median centerline deviations were approximately equal across all conditions.

In both studies, crews exhibited a smaller rate-of-travel decrement with the EFVS on than with the EFVS off. The difference was larger for B-737 flight crews than for B-777 flight crews, undoubtedly because the B-737 crews all taxied faster in general, but in either case, the difference was small (less than .5 knots for B-777 crews and about 1 knot for B-737 crews). In general, both sets of flight crews showed a reduction in rate-of-travel decrement as RVR and infrastructure increased, but the effects were qualified by EFVS use. With EFVS on, both sets of flight crews showed the least decrement at 500 feet RVR, where it plateaued. With EFVS off, flight crews only reached their best rate at 1000 feet RVR. Flight crews had the slowest rate at 300 feet, where the use of EFVS did not enhance rate of travel for B-777 flight crews, and only slightly enhanced rate of travel for B-737 flight crews. At 1000 feet RVR, B-777 flight crews showed the least decrement regardless of the EFVS use, and B-737 flight crews exhibited only a small positive difference with the EFVS on as compared with the EFVS off. With regard to infrastructure, both sets of flight crews had the slowest rates of travel with a standard painted centerline, regardless of EFVS use. With an LVO/SMGCS "enhanced" centerline, with or without lights, flight crews showed less rate-of-travel decrement with the EFVS on than with the EFVS off. There was also an interactive effect of RVR and infrastructure on rates of travel in both studies. With only a standard painted centerline, both sets of flight crews showed the least decrement at 1000 feet RVR. With an "enhanced" centerline, with or without lights, flight crews showed the least decrements at 500 feet and 1000 feet RVR. That is, the increased infrastructure seemed to enable crews to compensate for the lower RVRs to a certain degree. As noted previously, B-777 flight crews taxied more slowly than did B-737 flight crews (about 8.5 vs. 13 knots), probably due to the B-777's larger size and weight. B-777 crews also had more experience taxiing in real-world low visibility conditions than the B-737 crews did, and a few of them noted during the debrief that they try to keep the aircraft around 10 knots when taxiing in low visibility. The majority of B-737 pilots' low-visibility taxi experience was in the simulator during simulated LVO/SMGCS operations, where they may have been more comfortable taxiing at higher rates due to the additional LVO/SMGCS infrastructure and the safety of the simulator.

The EFVS may have helped Captains to detect a truck parked on the right side of the taxiway, just as the aircraft completed a right turn. Almost all fight crews detected the right-side-located truck, and Captains and First Officers detected it equally in both studies. When the Captain was the one who detected it, he or she appeared to see it through the EFVS. First Officers tended to detect the right-side-located truck sooner than Captains did—by six seconds in the B-777 and three seconds in the B-737. The EFVS may not provide an advantage in flight crews' detection time above what would be expected with a vigilant First Officer, but it may improve the Captain's ability to detect right-side obstacles. Essentially, it increases the chances that one of the crewmembers would detect an obstacle on the right side in low visibility conditions, especially if the First Officer happens to be heads-down when the obstacle comes into view. Obstacles on the left side, however, were outside of the EFVS FOV. During the left turn, Captains tended to look out the left-side window. Only about half of the flight crews detected the left-side truck. In the B-777, the Captain was usually the one who noticed the truck. In the B-737, Captains and First Officers noticed it about equally.

The studies also examined the impact of different turn characteristics on taxi performance. Across both studies, all but one of the route deviations was committed on a right turn. When taxiing in low visibility with minimal infrastructure, the Captain may lose sight of the centerline, particularly on right turns. (During the experiment, the researchers in the simulator cab observed several instances where the First Officer had to direct the Captain along a turn because the Captain could not see the line.) On the post-experiment questionnaire, B-777 Captains indicated that right turns were harder (and First Officers felt the opposite) due to the loss of visual references on the opposite side. B-737 pilots had mixed opinions as to whether there was a difference between left and right turns. Interestingly, both B-777 and B-737 flight crews taxied slightly faster during right turns than they did during left turns. For both sets of flight crews, the majority of route deviations also occurred at turns that were either greater than or less than 90 degrees. On the post-experiment questionnaire, B-777 and B-737 pilots said that sharp turns were more difficult than wide turns due to EFVS FOV and loss or lack of visual references. Additionally, B-777 pilots mentioned difficulty oversteering on sharp turns. Both B-777 and B-737 flight crews taxied slower as the turn angle increased. (As noted previously, B-777 crews do not exceed 90 degrees in turns operationally as the Boeing AFM limitation prohibits it.)

Flight crews performed one LVO/SMGCS scenario to serve as a baseline on which to compare taxi performance. In the LVO/SMGCS scenario, centerline lighting was available only along the cleared taxi route so that flight crews could “follow the greens” to the cleared destination. B-777 and B-737 flight crews tracked the centerline more closely during the LVO/SMGCS scenario than they did in other scenarios, including two “matching” scenarios conducted under the same RVR with centerline lights (one with and one without EFVS). For B-777 flight crews, rates of travel during the LVO/SMGCS scenario were no faster than those in the matching scenarios. For B-737 flight crews, rates of travel were only slightly faster in the LVO/SMGCS scenario than in the matching scenarios. Note that the LVO/SMGCS scenario was lacking some of the infrastructure required for U.S. airports to operate under LVO/SMGCS, such as clearance-bar lights or geographic position markings. The “follow the greens” concept is also more common internationally than it is in the U.S., although during the debriefing, some of the B-777 pilots indicated their familiarity with the concept in Singapore or London.

In the post-experiment questionnaire, pilots were asked to provide their opinions about the use of EFVS. Generally, pilots from both studies had mixed opinions when it came to having concerns about the use of EFVS for low-visibility operations. The exception was B-737 First Officers, almost all of whom had no concerns. For B-777 pilots, the most common concern was that the EFVS is less effective under certain environmental conditions (e.g., precipitation or fog). All of the B-777 Captains had experience using an EFVS in operations (and First Officers may have had indirect experience with it), which may explain why they had concerns about the EFVS under some conditions not present in the study. For B-737 pilots, the most common concerns were the restricted EFVS FOV and limitations regarding EFVS visuals (e.g., parallax, blue lights showing up as green). Despite their concerns, both groups of pilots generally felt that an EFVS repeater should be made available to the First Officer.

B-777 pilots reported mixed opinions as to whether they had sufficient awareness to verify their position and navigate effectively. B-737 pilots generally felt that they had sufficient awareness. To establish position awareness, neither B-777 nor B-737 pilots felt that they relied more on the EFVS than on direct observations out the window. Both groups of pilots believed that an airport moving map would improve their position awareness. The use of EFVS did not seem to improve pilots’ comfort with taxiing in low visibility in lieu of LVO/SMGCS infrastructure. Pilots generally agreed on the need for more or improved lights, signs, and/or markings to improve their position awareness. Note that there was missing signage in some scenarios where flight crews were asked to taxi the wrong way on a taxiway (signs appeared as black boxes from behind), which may explain pilots’ preference for signage. Moreover, signage is not readable through the EFVS, although this was explained to pilots in the briefing.

Limitations

These studies had some limitations which should be considered when interpreting the results or generalizing the results to other situations. Readers should be aware of a possible confounding effect of taxi route. Each of the 18 conditions was assigned a different taxi route, so it is possible that differences in taxi performance between any combinations of the study variables could have been influenced by taxi route. For example, because pilots taxied a different route with the EFVS on than with the EFVS off, it is unclear whether the EFVS actually alleviated rate-of-travel decrements because the EFVS was helpful or because the taxi route was easier. Although taxi routes were designed to be similar in complexity, they did vary in taxi distance. There were also some unexpectedly difficult turns and intersections in certain taxi routes, which were only realized after Study 1 began (but were observed in Study 2 as well).

In some scenarios, flight crews were instructed to taxi unconventional routes, for example, to go the wrong way on a high-speed taxiway. These routes were included to examine limitations on the type of turns that may be possible with EFVS. To introduce two caveats regarding the data, the probability of ATC issuing such clearances in actual operations (especially in low-visibility conditions) is relatively small. Second, some signage was not readable (issue with the out-the-window database) when flight crews taxied the wrong way on a taxiway (remarks made by some crews), possibly contributing to their loss of position awareness, despite it not seeming to affect flight crews' route accuracy.

These studies attempted to simulate difficult visual conditions for taxiing in low visibility with EFVS. However, three exceptions should be considered if one wishes to generalize the results. First, the infrastructure in these studies was a representation of the infrastructure at KSLC, but the quality of infrastructure can vary between airports. For example, taxiway centerline markings can vary in reflectivity, receptiveness to heat, and contrast between the paint and the concrete—all qualities that can affect how well the markings show up in the EFVS image. The taxiway markings in the KSLC simulator visual model appeared to be without wear or fade, but some runways had faded centerline markings and tire marks. A second limitation is that the EFVS FOV in both simulators was greater than the minimum FOV specified in the EFVS performance standards (20 degrees greater in Study 1 and 22 degrees greater in Study 2). Third, these studies were conducted in simulated nighttime conditions to represent the most common low-visibility conditions that pilots experience. The use of nighttime conditions also eliminated any solar contribution to surface heating and illumination. Although nighttime conditions represent a challenge for taxiing in low visibility, taxiing at dusk or dawn may be worse because there is minimal temperature difference between the taxiway surfaces and surroundings.

CONCLUSIONS AND RECOMMENDATIONS

The results of these studies demonstrated that flight crews in both wide- and narrow-body aircraft types were generally able to taxi with the EFVS in low-visibility conditions, but the conditions under which it is safe and efficient to do so may vary. The potential benefits and limitations of the EFVS are discussed first, followed by findings regarding low-visibility taxi routes. To conclude, recommendations are provided regarding the EFVS and low-visibility taxi operations in general, including suggestions for future research.

Based on the results of these studies, use of an EFVS may help flight crews to somewhat ameliorate the negative impact of low visibility on rate of travel, particularly at the “medium” levels of RVR and infrastructure presented in these studies (500 feet and “enhanced” centerlines, respectively), and thus see less of an impact on potential traffic throughput. At the lowest levels, the EFVS had little to no benefit on rate of travel, and at the highest levels, the EFVS may not be needed as comparative decreases in rate of travel were least overall. The EFVS may also increase the probability of detecting obstacles in low-visibility conditions. Having an EFVS on the Captain’s side may increase the chances that at least one of the crewmembers would see an obstacle on the right side of the aircraft (where objects are further from the Captain than they are from the First Officer), assuming that the obstacle is within the EFVS FOV. However, obstacles that are outside the FOV could be missed, particularly if the Captain is looking through the EFVS (and not in the direction of the object).

The EFVS provided a benefit to navigation performance at 300 feet RVR when there were no centerline lights. However, the 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 the EFVS. Note that these results should not be taken to suggest that taxi operations are safe in these conditions without the EFVS. Pilots had mixed opinions about whether they had sufficient awareness to verify their position and navigate effectively, and many commented that they needed additional infrastructure to improve their position awareness. B-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. 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.

Pilots did not feel that the EFVS contributed to their position awareness above what their own direct observations provided. Some pilots had concerns about the use of an EFVS in low-visibility operations, including the restricted EFVS FOV, limitations regarding the EFVS visuals (e.g., parallax, blue lights showing up as green), and the limited effectiveness of the EFVS under certain environmental conditions (e.g., precipitation or fog). Despite their concerns, both groups of pilots generally felt that an EFVS repeater should be made available to the First Officer. Pilots also felt that a moving map would provide improvements in position awareness.

These studies also examined possible limitations on taxi routes in low visibility with reduced infrastructure. As mentioned previously, right turns were difficult and were observed to have more errors, especially without centerline lighting. The studies 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 in low-visibility taxi operations. The taxi routes used in these studies were not designed to be complex, and although some complex intersections were noted, there were too few of them to make any conclusions about how effectively flight crews navigated them.

The following conclusions and recommendations were identified from the above findings:

1. No clear safety issues were observed when the EFVS was in use on the captain's side. The EFVS may help to ameliorate low-visibility-induced reductions in rate of travel (and by inference, throughput) by increasing available visual cues ahead of the aircraft as compared to those available without the display, and thus may also support the detection of obstructions near the aircraft's path that fall within the sensor FOV.
2. The EFVS may be helpful at 300 feet RVR without centerline lighting. However, the EFVS may not be sufficient to make right turns onto taxiways without centerline lighting at any RVR at or below 1000 feet due to the problems of cross-cockpit visual surveillance required for the task and cues being out of the FOV of the sensor.
3. Regardless of whether the EFVS was or was not employed, low-visibility taxi routes that contained turns greater than 90 degrees resulted in more route deviations and were characterized by many pilots as difficult. Taxi routes proposed for low visibility operations should consider these potential effects on pilot taxi performance, specifically to avoid any turns greater than 90, and turns where visual reference/guidance cues are likely to be out of the sensor FOV when needed by the PIC. The terms of this study dictated the use of a single HUD on the captain's side. Although some approved EFVS operations require a pilot-monitoring display of the sensor information, taxi operation using an EFVS do not require an approval, nor are they considered to be an EFVS operation under 14 CFR § 1.1. No data are available, to our knowledge, concerning taxi performance with two HUDs (an EFVS repeater on the First Officer's side). As such, it is not clear whether the repeater display may provide additional position awareness to the crew, or if it might detract from the FO's ability to exercise surveillance of the outside world using unaided vision for areas outside of the sensor's field of view. Specifically, given the obstruction-detection results, it is recommended that one crewmember be tasked with direct-vision surveillance of the environment. This is similar to common practice for rotorcraft crews using night-vision goggles.
4. Given previous research that has indicated advantages in removing ambiguity about geographical location of ownship by use of other types of displays, it is probably worthwhile to consider how an integrated display system (part of the avionics suite) of this category and of appropriate accuracy and resolution might aid in resolving some of the indeterminacies in perceiving aircraft location, experienced by some crews, by providing an additional potential source of positional awareness. It should be noted that some operators already employ such systems to aid in maintaining positional awareness during surface operations.
5. The EFVS may be more or less effective under different environmental conditions. Although benefits of the EFVS used under the most difficult visual conditions were limited in scope (B-777 reduction in uncorrected errors, some small reductions in rate-of-travel decrements), additional research may find benefits under conditions more favorable to optimal sensor performance specific to ground-based operations.
6. Additional research is encouraged to completely and accurately characterize taxi performance in low visibility by different levels of intersection complexity, and to arrive at a more comprehensive definition of complexity, as well as exploring how other relevant data might be provided on the flight deck to further enhance pilot performance.

ACKNOWLEDGMENTS

This technical report was prepared by the Aviation Human Factors Division at the John A. Volpe National Transportation Systems Center (Volpe Center), Cherokee CRC, LLC, and the Aerospace Human Factors Laboratory of the Federal Aviation Administration (FAA) Civil Aerospace Medical Institute (CAMI). This research was completed with funding from the FAA NextGen Human Factors Division and the CAMI Aerospace Human Factors Division under the Flight Deck Program Directive in support of the FAA Flight Operations Branch, Flight Standards. The study described herein was conducted in coordination with FedEx Corporation and the FAA Flight Operations Simulation Branch, Flight Standards.

We would like to thank our FAA program manager, Katrina Avers, as well as our technical sponsors Terry King and Bruce McGray. We would also like to thank Andrew Burns, Stephanie Chase, Randall Cooper, Esther Devanney, Megan France, Andrew Kendra, Hunter Klevgard, Larry Miller, Suzanne Thomas, Michelle Yeh, and Alan Yost for their work on this project. A special thank you to FedEx, especially Robert Riding and Mark Gouveia, for working with us to conduct this research with their facilities and pilots.

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