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The Use of Enhanced Flight Vision Systems (EFVS) for Low-visibility Takeoffs: Equivalence for Level of Safety

Dennis B. Beringer

Kelene A. Fercho

FAA Civil Aerospace Medical Institute

6500 South MacArthur Blvd.

Oklahoma City, OK 73169

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16. Abstract

Twelve Part 121 operations commercial-carrier crews completed low-visibility takeoffs at Memphis International Airport using an Enhanced Flight Vision System (EFVS). A 2x2x2x3 factorial design with runway visual range (500 and 700 feet RVR), runway edge lighting (High Intensity or Medium Intensity) and two levels of EFVS (either captain's Head-Up Display only or with additional first-officer's Head-Down repeater) was used along with supplemental sample points and several baseline trials representing current-authorization conditions. Tasks included normal takeoffs, EFVS failure (both continue and reject trials), and engine failure (reject). There were no significant main effects of display or infrastructure in the main design (500 and 700 feet RVR), and pilot performances in the experimental trials with EFVS were not markedly different from the baseline (current authorization) trials. All crews were able to stop the aircraft successfully on the runway during rejected takeoffs. Pilots uniformly believed they could successfully complete takeoffs or reject them in lower visibilities with EFVS as compared with using the Head-Up Display without EFVS, which was supported by observed performance.

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List of Abbreviations

Abbreviation	Term
AC	Advisory Circular
ATP	Air Transport Pilot
CAT	Category
CLL	Centerline Lights
EFVS	Enhanced Flight Vision System
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FO	First Officer
FOR	Field of Regard
GPS	Global Positioning System
HDD	Head Down Display
HIRL	High Intensity Runway Lights
HUD	Head Up Display
ILS	Instrument Landing System
IR	Infrared
KMEM	Memphis International Airport
LOC	Localizer
MIRL	Medium Intensity Runway Lights
OpSpec	Operations Specification
OTW	Out The Window
PFD	Primary Flight Display
PIC	Pilot in Command
RCLM	Runway Centerline Markings
RMSE	Root Mean Square Error
RTCA	Radio Technical Commission for Aeronautics
RVR	Runway Visual Range
SD	Standard Deviation
SME	Subject Matter Expert

Introduction

Low-visibility operations have been studied for several decades, with the intent of improving the ability to operate reliably and safely in these conditions to maximize the efficiency of the air transportation system. With the development of precision-approach landing aids such as the Instrument Landing System (ILS), and vertically guided approaches based on the Global Positioning System (GPS), it has been possible to incrementally reduce the visibility required to operate to and on properly equipped runways, relying primarily on the ground-based navigation and runway/airport infrastructure to support the operations. This infrastructure, especially that required for the lowest approved visibilities, may be expensive to install and maintain, and thus not all runways have been equipped and such infrastructure is normally found at airports where the operational demand could justify the costs of installation. As an example, the most recent flight procedure inventory summary lists only 41 published ILS Category II approaches, while there are over 1500 ILS Category I approaches with standard or above-standard minimums. Regarding takeoff and landing operations, there are airports, with no centerline lighting or high-intensity runway lights that are required by current Operations Specifications (OpSpecs) for low-visibility takeoffs that might be candidates for low-visibility operations with appropriate aircraft equipage.

The research described in this report evaluated the potential use of Enhanced Flight Vision Systems (EFVSs; FAA, 2010), in this case an infrared (IR) sensor image, as a possible substitute for some parts of airport/runway infrastructure as it applies to low-visibility takeoffs. The potential contribution of a head-down repeater display for the head-up EFVS display, for use by the first officer (FO), was also explored. This simulation was intended to provide data that could indicate whether pilot performance using EFVS displays with reduced airport infrastructure is sufficiently comparable to pilot performance obtained using the currently approved levels of infrastructure for takeoffs without EFVS as an aid. Current requirements (airport infrastructure, runway visual range, equipage) for IFR lower-than-standard takeoff minima are specified in OpSpec C078 (Part 121, scheduled carrier, operations; FAA, 2007) and OpSpec C079 (Part 135, on demand, operations; FAA, 2016; See Table 1).

Table 1 *Low-Visibility Takeoff Authorizations from OpSpecs C078 and C079.*

Serviceable Runway Visual Aid Required	Lowest Allowable Takeoff Minimum Authorization
If an RVR sensor is not available:	
Adequate visual reference, or any one of the following: HIRL/CLL/RCLM	¼ sm (400 m)
If an RVR sensor is available:	Note: Below RVR 1600, two operating RVR sensors are required. All operating RVR sensors are controlling (except per the note below for far-end sensors).
Adequate visual reference, or any one of the following: HIRL/CLL/RCLM	RVR 1600 (500 m)/NR/NR Mid-point can substitute for an unavailable touchdown.
Day: CLL or RCLM or HIRL Night: CLL or HIRL	RVR 1200 (350 m)/1200 (350 m)/1000 (300 m)
RCLM and HIRL, or CLL	RVR 1000/1000/1000 (300 m)
HIRL and CLL	RVR 600/600/600 (175 m) or RVR 500/500/500 (150 m)
With an approved HUD takeoff guidance system, HIRL, CLL, and CAT III ILS	RVR 300/300/300 (75 m)

It is necessary to make clear, at the outset, that this was an attempt to evaluate the safety of potential operations using sensor/display technology as a substitute for airport infrastructure, and to determine if removal of parts of this infrastructure in favor of sensors/displays caused a reduction in the safety of operations as reflected in distance from centerline, ability to reject a takeoff, and other aspects of the takeoff operation. It was not intended to make comparisons between performances with one set of infrastructure versus another or one configuration of displays versus another. Rather, it was intended to compare obtained performance with what we will refer to as "performance in baseline conditions." Thus, the major emphasis of this report is how performance in the experimental conditions where infrastructure was removed compares with the baseline performance that represented the environment reflecting the current authorizations for low-visibility takeoff.

Background and Previous Research

There have been numerous studies on the use of imaging displays for various tasks, some for ground operations and some for approach and landing. Studies involving low-visibility takeoff have been limited. The full range of studies has examined two types of imaging displays: those using synthetic vision (an image derived from a digital database specifying features of the terrain/airport), and those using sensor-derived displays (e.g., infrared images from a real-time sensor). The present effort, however, was specifically focused on the use of a real-time sensor-derived image of the field of regard (FOR) ahead of the aircraft. As such, the review of relevant literature is restricted to EVS (Enhanced Vision Systems) and EFVS (Enhanced Flight Vision Systems) deriving their image from a sensor, not from a digital database.

When evaluating a potential performance benefit of EFVS during low visibility approach and landing operations, there is converging evidence that an EFVS may safely support lower than standard visibility minima operations (Kramer et al., 2011; Shelton et al., 2012; Kramer et al., 2014; Kramer et al., 2015; Etherington et al., 2015; Prinzel et al., 2015). This may be because EFVS provides a visual advantage of two to three times over that of the out-the-window (OTW) view for the pilot flying (Kramer et al., 2014). In one example, when EFVS was used during simulated approach-to-land operations at 300 feet RVR, performance was well within visual performance standards of the first third of the runway and within the lateral confines of the runway (Etherington et al., 2015). Further, there was no appreciable difference in performance when comparing conditions that included touchdown zone and runway centerline lighting to those without runway lighting (Etherington et al., 2015). In similar research, but this time the approach-to-land flight testing was performed in an actual aircraft as opposed to a flight simulator, there again appeared to be a benefit to using EFVS (Shelton, 2012). When approach-to-land operations were flown at visibilities as low as 1000 feet RVR, pilots reported acceptable workload, indicated a preference for flight operations with EFVS over a conventional PFD, and also felt that the level of safety was better with the EFVS compared to a conventional PFD (Shelton et al., 2012). Although the approaches were flown as touch-and-go, making landing performance difficult to assess, the subjective feedback from the evaluation pilots suggested a benefit to EFVS (Shelton et al., 2012).

As mentioned previously, few studies have examined the utility of EFVS for low visibility ground-based procedures, such as departure or taxi operations. Rather, the vast majority of research on advanced vision systems has focused on low visibility approach-to-land operations. However, there are similar concepts between the two types of flight operations—that is, if in-cockpit technologies can support safe flight operations in reduced visibility conditions and with reduced ground lighting infrastructure, then operational credit for these technologies may be warranted. In one of the few examples that compared EFVS to a standard HUD for low visibility take-off operations, performance results suggested no difference in runway centerline tracking in visibilities as low as 300 feet RVR (Etherington et al., 2015). For this flight test evaluation, take-off operations with the standard HUD were conducted with runway centerline lighting, while those with EFVS did not include centerline lighting. It is important to note that no failures in the EFVS images were evaluated, nor were other types of lighting (i.e., runway edge lighting) included in the evaluation. However, the results of this study suggest that onboard flight-deck based EFVS may support low-visibility ground based operations, without necessitating costly ground infrastructure equipment or additional procedures. Similarly, the FAA has investigated the use of EFVS to support low-visibility surface movement operations, with results also supporting a performance benefit with EFVS during restricted visibility conditions (Sparko et al., 2019). In general, fewer route deviations were found when EFVS was used during low visibility taxi operations. This was particularly true at the lowest visibility included in the study design (300 feet RVR), and when centerline lighting was not available. Taken together, the results of both approach-to-land and ground based operations evaluations suggest that there may be a performance and safety benefit to EFVS, particularly at very low visibilities (300 feet RVR) and when airport or runway ground infrastructure is not available (Etherington et al., 2015; Sparko et al., 2019).

The present study evaluated the safety associated with low-visibility ground-based flight operations using EFVS as a substitute for runway lighting infrastructure. This work extends the body of research on EFVS by focusing on ground-based operations under intentionally challenging flight conditions. Specifically, take-off procedures were conducted during nighttime visibility conditions as low as 300 feet RVR, both with and without engine and EFVS failure conditions. Additionally, the effects of runway lighting—both centerline and edge lighting—were examined. If the performance and procedures during take-off operations with reduced runway infrastructure supplemented by EFVS were as safe as take-off operations representing current authorizations, operational credit may be warranted.

Method

Participants

Participants were 14 two-person flight crews, each pair of captain and FO being from the same commercial carrier, and having the following qualifications; (1) B-737 qualified, (2) each with a minimum of 10 hours flight time in the past 30 days, (3) pilot flying with a minimum of 100 hours HUD experience, (4) one crew member CAT III qualified for at least five years, and (5) U.S. citizens. They were recruited by a contractor and compensated for their participation.

Participants were not required to have been trained in the use of EFVS for four justifications. First, EFVS-experienced 737 crews are rare and not plentiful enough to populate the study. Second, a recent study (Beringer et al., 2019) found no operationally significant difference in performance between 777 *EFVS-trained* crews and 737 crews *without* EFVS training. Third, the IR image, being essentially a pictorial contact-analog display, should require less interpretation than other “representational” displays. Finally, the takeoff task is primarily one of maintaining alignment with the runway centerline using reference imagery (centerline, edge lights in the IR image) with little use of other features of the image and little exercise of distance estimation, narrowing the task to the interpretation of relevant features in the image.

Equipment

Flight Simulation and Environment

Simulator flights were conducted in a CAE Boeing 737 level D full-flight simulator operated by the Flight Standards Flight Operations Simulation Branch at the Mike Monroney Aeronautical Center in Oklahoma City, OK. This simulator contained a HUD (Rockwell-Collins) and a head-down display (HDD) on which the EFVS imagery, representing the thermal signatures of objects in the sensor field of view, was presented. Figure 1 depicts the right side of the simulator flight deck with the EFVS repeater display (head-down for the FO) shown on the navigation display, with Figure 2 showing the view through the HUD on the captain's side with the EFVS imagery enabled. The EFVS image was held constant at an apparent 1600 feet RVR to create a sensor-independent image that could be used as a standard for performance equivalent to an unaided-vision visibility of the same distance.

Figure 1

Instrument panel of the B-737 flight simulator showing the right-side instrumentation with the primary flight display on the far right and the EFVS repeater display in the center of the image

Figure 2

View through the HUD showing EFVS imagery enabled

EFVS Displays

The EFVS in the simulator modeled an infrared (IR) sensor that distinguished between radiant and thermal heat based on the simulator's atmospheric model. The EFVS imagery was displayed in two locations on the flight deck: (1) on a Rockwell-Collins HUD in front of the left-seat pilot and, in some conditions, (2) on a head-down repeater on the right side of the instrument panel in place of the MFD (nav display). This second location was for the FO to reference and was representative of what can be done to supply the same data to both pilots but in an aircraft with a single HUD. The FOR in the HUD was 32 degrees horizontally and 15 degrees vertically, exceeding the requirement in DO-315B (RTCA, 2011) for at least 20 degrees horizontally and 15 degrees vertically. The imagery was based upon the EFVS Kollsman II infrared airport model for KMEM.

The apparent visibility in the EFVS imagery was set at 1600 feet for all trials so that the conditions would represent a sensor system that could generate the equivalent of the situation where RVR is at 1600 feet or above (per rows one/two of Table 1). This produced a situation which was not specific to a particular kind of sensor and could be generalized to any system that could produce this type of imagery. The brightness of the HUD and EFVS were adjustable and pilots were allowed, as they would in the operational aircraft, to make adjustments under the supervision of the experimenter so that brightness was not set as high as to obscure view of outside runway features that were visible with natural vision. The head-down EFVS representation on the navigation display on the FO's side was also adjustable but was kept at a level where the brightness was not excessive and did not cause degradation of the visibility of the outside environment for the FO. Both displays were adjusted to present equivalent and acceptable levels of contrast in the images.

Experimental Design

The study used a within-subject design to minimize the effect of between-participant variance and make the sample size manageable. Two counter-balanced orders of presentation were used and evenly distributed across crews to minimize the impact of any potential intra-serial transfer of learning.

Core Design

The core of the design used four fully crossed variables (all factor levels appearing with all other factor levels, 2x2x2x3) on pilot performance, producing 24 unique combinations (see conditions 4 through 30 in Appendix A, Table A 1, Condition Specifications):

1) RVR (2 levels)
    a. 500 feet
    b. 700 feet

2) EFVS (2 levels)
    a. EFVS on HUD (Captain)
    b. EFVS on HUD (Captain) and head-down repeater display (FO)

3) Airport lighting infrastructure
    a. Runway edge lighting (2 levels)

i. High-intensity Runway Lights (HIRL)
ii. Medium-intensity Runway Lights (MIRL)

b. Runway centerline lighting (CLL) – always off

4) Task (3 levels)
   a. Normal takeoff
   b. EFVS failure 10 knots below V1 (Continue takeoff)
   c. Engine failure 10 knots below V1 (Reject takeoff)

Baseline Trials

Five (5) baseline trials were conducted. Baselines 1, 2, and 3 were normal takeoffs which were evenly distributed across each series of trials (beginning, middle, and end) to assess any possible learning effects across the simulator trials. Two additional baseline trials (Baseline 4 and Baseline 5) without EFVS but with runway centerline lights were used to represent the current OpSpec authorization. Baseline 5 involved an engine failure. (See Table A1 for a comprehensive list of trial conditions.)

Supplemental Trials

A set of trials (12) equivalent to those specified within a single level of RVR in the core design were conducted at 300 feet RVR, with the only difference being that in place of varying edge lighting (to remain fixed at HIRL), centerline lighting was varied (on, off) instead. This provided an index of the practicality of lower-visibility takeoff operations with EFVS (in the HUD) when either the full lighting infrastructure (meaning centerline lights and HIRLs) is present as compared with no centerline lights but with HIRLs. A bracketing set of trials (6) was included at 1000 feet RVR with no runway lighting but varying task (3 levels), as per previous specification, and EFVS repeater display (on/off).

Finally, a set of 4 trials where EFVS fails below 80 knots (75 to be used as point of failure) was included to represent the case where the sensor stops presenting the image below the speed at which it has been recommended that a takeoff should reasonably be continued (HUD manufacturer). These 4 trials required the pilots to reject the takeoff upon image failure. Two trials occurred at 300 feet RVR, one with centerline lights, one without. The two other trials occurred at 500 feet RVR and at 700 feet RVR. All had the EFVS repeater display on with HIRL.

Wind. Table A 1 also shows how wind direction and magnitude were used together as a sampling variable, distributed across trials, with each combination of wind direction and wind magnitude selected to produce a crosswind component of 15 knots, half from the left and half from the right. This is also graphically depicted, for simplicity, in Figure A 1.

Lighting. All trials were conducted in a simulated night environment. Nighttime conditions were chosen based on SME input to represent the more commonly encountered difficult low-visibility conditions rather than dusk or dawn times. However, visual comparisons of the lighting conditions under comparable RVR values did not reveal notable differences between the values under examination. As such, the study did not examine variations in particular levels or time-of-day lighting conditions (e.g., day/dusk). Additionally, the runway surface was damp to be consistent with an immediately prior study in the 737 simulator examining LOC guided takeoffs (Kratchounova et al., 2020).

Procedure

Preflight Briefing

Participants were provided, upon their arrival, with an Informed Consent form that outlined their responsibilities and rights regarding task performance, a brief description of the task, and participants' ability to halt the session at any time. Following their agreement to participate (signing of form), each completed a short pilot-experience assessment (Appendix G). Each participant then received detailed briefings regarding the takeoffs they would be conducting, the procedure to be used during training and during data collection, the equipment (simulator and displays), the emergency procedures that might be necessary should they need to exit the simulator or the facility, and the general intent of the study (30 slides in length). Any questions that arose were addressed by the test administrator at that time.

Practice/Training

Crews performed a taxi scenario along a prescribed route in the simulator in 700 feet RVR visibility to become familiar with the simulator's characteristics and the imagery presented in the EFVS display (HUD and repeater). If the participants indicated that they were comfortable with their understanding of how the EFVS represented the airport environment, the training/familiarization continued with a minimum of four practice takeoff trials. These were conducted in 700 feet RVR. Exit criterion was two consecutive trials, by the conclusion of the four, where the aircraft was kept within 20 feet of the centerline and the aircraft rotated at the appropriate time and climbed to 160 feet AGL without incident. If the crew indicated that they were comfortable with the simulator and the EFVS display after reaching exit criterion at four trials, they began the experiment scenarios. If the crew members were not comfortable with their performance or if they failed to reach the two-consecutive-trial criterion by the end of four trials, they were given additional practice trials and the number of trials needed and point of achievement of criterion deviation from centerline was noted. A short break in place for discussion of the next trials to follow was taken after the training session was completed. Although takeoff performance relative to deviation from centerline was monitored in real time during the takeoff practice runs, digital performance data were retained as well. Figure 3 shows the flight deck during a trial, and the captain's HUD is clearly visible at the top left of the image. The first officer's seat obscures viewing of the right-side instrumentation in this view (it is shown in Figure 1).

Figure 3

Infrared Image of Flight Simulator Flight Deck during a Trial

Experimental Flight Scenarios

Following the completion of training/familiarization, each crew conducted 51 low-visibility takeoffs from a 150-foot-wide runway at Memphis International Airport (KMEM; Appendix B). The trials included each combination of the prescribed displays (HUD only or HUD plus repeater), RVR, airport infrastructure, and an appropriate task as defined in the experiment matrix. Those takeoffs noted as "Normal" in the matrix contained no failures. Takeoffs to be rejected were (1) those during which an engine failure occurred below V1 (all engine failures were as such) and (2) those EFVS failures occurring below 80 knots. The latter was derived from recommendations referenced as being from Rockwell. The remaining third of the trials consisted of normal takeoffs. The simulator was fully configured for takeoff at the beginning of each trial and located on the runway in takeoff position. Prior to clearance to takeoff, crews were briefed on the current wind direction, wind velocity, and runway visual range. The simulator was then released and the crew conducted the takeoff.

Per the procedure used in other recent studies, the test conductor (from CAMI) in the simulator cab monitored the progress through the order of trials, set up to run across the matrix of trial-activation buttons from left to right and top to bottom (normal reading pattern), and notified the simulator operator if any activation was out of sequence. The buttons were coded to indicate not yet used, currently selected, or already completed. The test conductor called "cleared for takeoff" when the crew indicated they were ready, and the simulator operator initiated the trial. The test conductor and an observer recorded observations of the pilots' comments and behaviors during the simulation run. All data runs generated video records from two sources; (1) the video system installed in the simulator, showing four insets with flight deck, EFVS image, OTW forward view, and Primary Flight Display, and (2) a HD video camera (Sony Corp.) mounted on the aft bulkhead showing the majority of the instrument panel and the crew. This arrangement was used because the installed flight-deck camera was not sufficiently low-light sensitive, and thus the additional Sony HD camcorder with built-in infrared illuminator was used to capture the captain and FO in an image bright enough to allow easy interpretation of the actions/motions of each. Each run took just under 1 minute from release to simulator freeze at 160 feet (or simulator stopped on runway for aborted takeoffs), and the total cycle time from start of one takeoff to the next was within 2.5 minutes. Regular breaks were scheduled throughout the evaluation trials, some in place, some exiting the simulator. After all scenarios were completed, the flight crew was given a debriefing and an opportunity to ask questions and provide additional feedback. The full study time from start of pretest briefing to end of posttest briefing was between 3:20 to 4:00 in length.

Dependent Variables

Objective Data (Pilot and Aircraft Performance Variables)

Data variables recorded digitally from the simulator (at 5 Hz) included the following:

- Aircraft latitude and longitude

- Altitude (AGL, MSL) (feet)
- Magnetic heading (degrees)
- Deviation from runway centerline (feet)
- Airspeed and ground speed (knots)
- Acceleration/deceleration
- Throttle position (or percent thrust)
- Elapsed time (within the simulator trial) (to tenths of second)
- Wall clock time
- Event marker (to tag a specific moment or location within a scenario)
- Onset of failures used in the tasks
- Video and audio recordings of the flight deck

Subjective Data (Pilot Opinions)

Subjective data in the following categories were collected from the crews:

- Background questionnaire about pilot experience (pretest briefing)
- Pilot subjective assessments of acceptability of display configurations by RVR/lighting (posttest questionnaire)
- Pilot assessment of relative workload on a per-trial basis (four five-point anchored scales to examine visual effort, mental effort, physical effort, and perceived time pressure – anchor points at low, medium, and high); participants registered responses on an iPad mini on their side of the cockpit, no communication was allowed between participants during these ratings made at the conclusions of each trial.
- Post-test evaluations of display configurations (primary and supplemental; the latter repeats some questions in a slightly different manner to validate answers between sections)
- Pilot responses to open-ended questions during the debriefing

Results and Discussion

Data from two crews were excluded, one due to simulator errors that placed the winds as coming from incorrect directions, and one that was an extreme outlier in performance and stated having problems with the takeoffs. The 12 remaining sets of data were analyzed. Flight-performance data (deviation from runway centerline while in ground contact, stopping distance) were analyzed using ANOVA techniques with IBM SPSS Statistics for Windows version 24 (IBM Corp., Armonk, NY, USA). Additionally, equivalence testing was performed with the TOST equivalence testing R package (Lakens, 2017; Beringer & Ball, 2009) to evaluate the degree to which performance on specific trials appeared equivalent to baseline performance (an assessment of equivalent level of safety). Subjective data, specifically workload self-assessment, were analyzed using nonparametric statistics for ordinal data. Subjective assessments of acceptability of display configurations by RVR/lighting were tabulated for frequency distributions of selected responses.

Learning Effects Across Baselines

Prior to analysis of the complete data set, a quick check of the distributed baseline trials (Baselines 1, 2, and 3) was performed to see if learning occurred across the experimental session. Recall that there was a baseline at the beginning of the session, one in the middle of the order of trials, and one at the end. Although the counterbalancing of orders used was intended to offset just such an occurrence (learning effects), it is, nonetheless, useful to examine what did occur throughout the sessions. The three dependent measures to be used in the later analyses (absolute mean deviation from centerline, root-mean-squared-error around centerline, and absolute maximum deviation from centerline) were examined using ANOVA techniques. No significant effects of learning were found across the trials for any of the three dependent measures examined. A table of the results is presented in Appendix F.

Core Factorial Design (500 and 700 Feet RVR)

Flight Performance

Statistical analysis summary tables for the GLM test procedures discussed in this section are contained in Appendices C, D, and E, and can be referenced for specific details of the statistical tests conducted. Deviation from runway centerline was examined by calculating mean deviation (bias error), absolute maximum deviation, and root-mean-squared error (RMSe, variable error) for each run. To put the very small number of significant effects into perspective, there were 39 main effects, 45 two-way interactions, 21 three-way interactions, and 3 four-way interactions possible across the analyses (108 tested effects in the core design). Of these, a very small number (8 of 108 tested) attained statistical significance: 2 main effects (of 39), 3 two-way interactions (of 45), 3 three-way interactions (of 21), and no four-way interactions. Grouping by task, normal takeoffs had only two significant effects (a two-way and a three-way, and NO main effects), EFVS fail-continue had 5 effects (2 mains, 2 two-ways, and 1 three-way), and engine fails with rejected takeoffs had no significant effects. Considering the two "continue" tasks together, EFVS fail-continue and normal takeoffs, there were only 2 effects, one two-way and one three-way. The mean differences in each case were a matter of a few feet (ranging from 2 to 5 feet), and did not appear to have operational significance. There were no significant main effects of display and only two of infrastructure (edge lights) in the core design, which were again differences of only a few feet, both in the EFVS-fail-continue conditions, and they did not appear to be operationally significant. Of the several statistically significant but extremely small interactions (with, again, mean differences of a few feet), all appeared anomalous and of little or no operational consequence. As such, there appeared to be no appreciable systematic effects of the independent variables, within the limits in this part of the data (500 and 700 feet RVR; HIRL and MIRL; HUD or HUD + repeater; the three tasks), on crew centerline-tracking performance.

Although there were no operationally significant main effects regarding the deviation from runway centerline as a function of the manipulated visibility and infrastructure, it is necessary to look at the magnitude of deviation observed as an index of the safety of operations. Figures 4 and 5 show the cumulative frequency plots by category of deviation for both 500 and 700 feet RVR by the task types. One can see that for the continued takeoffs, the distributions were similar for both 500 and 700 feet visibilities and between the two tasks. As expected, the rejected takeoffs (engine failure) had greater maximum deviations from centerline, with one crew constituting an extreme outlier for that task under both visibilities. Note that in both cases, 90% of the max deviations for continued takeoffs fell at or below 10 feet for normal and 15 feet for EFVS failure. For the engine failures, 90% of the deviations were at or below 25 feet for 500 feet RVR and at or below 30 feet for 700 feet RVR.

Figure 4

Cumulative Distribution of Maximum Deviation from Runway Centerline (Feet) by Task, 500 Feet RVR

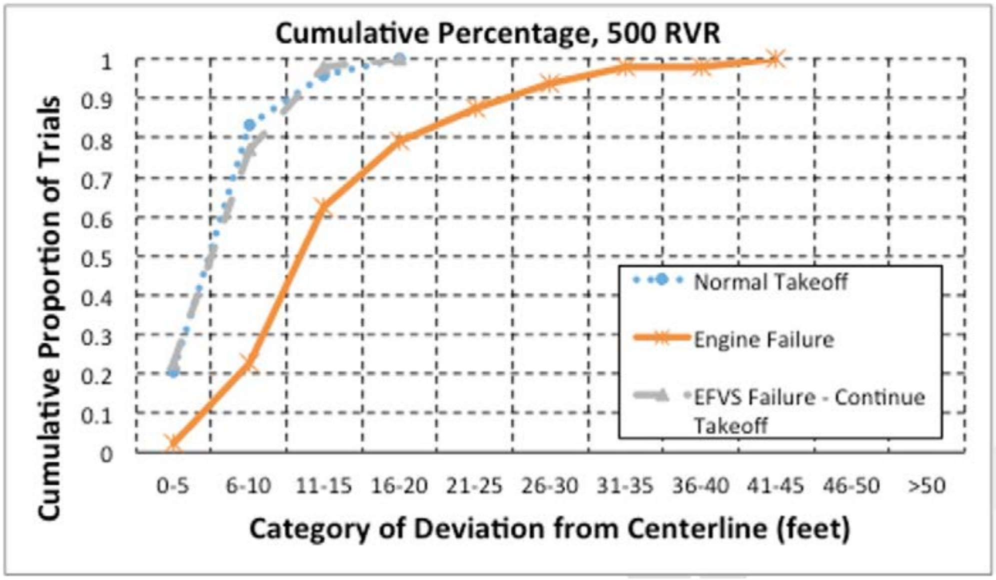
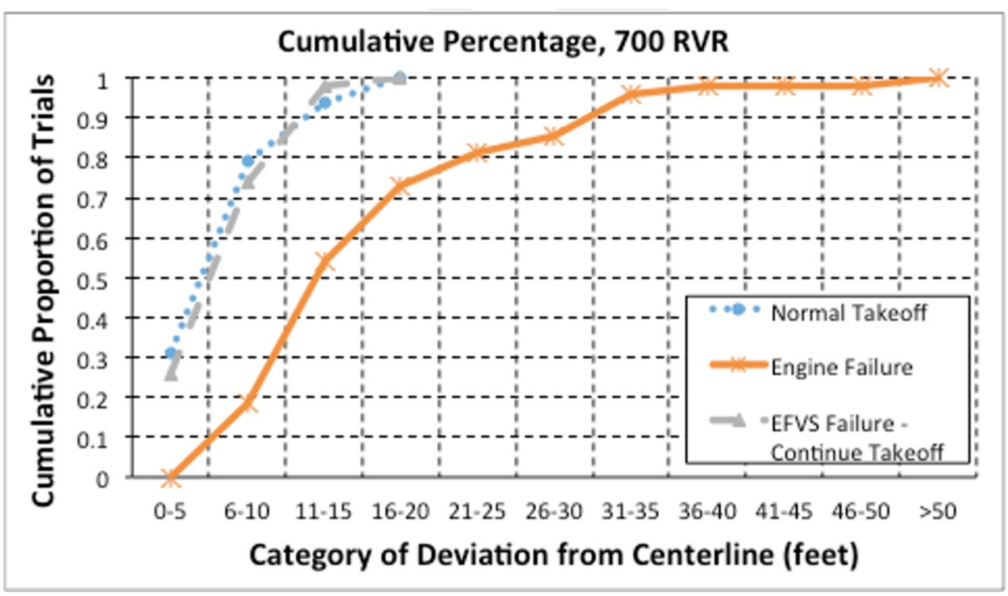


Figure 5

Cumulative Distribution of Maximum Deviation from Runway Centerline (Feet) by Task, 700 Feet RVR



Stopping Distance on Rejected Takeoffs

Results were similar (no significant differences) for deceleration/stopping distance within a task with no significant main effects for the primary dependent variables. Stopping distance grouped mainly as a function of time at which the failure occurred and the velocity attained prior to rejecting the takeoff. These two factors were, of course, positively correlated between the engine-failure trials and the EFVS-fail-reject trials as the engine failures occurred close to V1 (approximately at an indicated airspeed of 105 kts) and thus the aircraft was farther down the runway before it reached that velocity whereas the EFVS-fail-reject trials occurred at 75 kts, meaning the aircraft had not traveled as far prior to reaching that velocity and was traveling more slowly at the time the takeoff was rejected. As such, the engine-failure trials resulted in stopping points further along the runway than the EFVS-fail-reject trials due to the latter happening earlier in the takeoff run, and thus it was not meaningful to compare across these trials. Additionally, the only other major factor influencing stopping distance was headwind component, which was negatively correlated with stopping distance as expected.

Supplemental Trials & Baseline Measures

"Equivalent level of safety" is something that is frequently referenced when a new piece of equipment, display format, or procedure is proposed, indicating that a level of safety must be assured that is equivalent to that which prevails with current operations or equipment. As such, the most relevant comparisons are those between performance obtained with the conditions specified in the current operational authorization (our baselines) and those with the new or enhanced means of performing the task. What one would hope to find would be that the proposed operational conditions produced performance that was either (1) equivalent to or superior to performance in the currently authorized situations. Thus, we made several comparisons between obtained performance and baselines to examine the similarities in performance.

EFVS Versus Baselines Overview

There were several questions of interest regarding direct comparisons of outcomes to determine if one could see equivalent performance between the baseline conditions, which represented conditions having current authorizations, and some of the EFVS-employing conditions. The conditions examined limited what could be done post hoc with these comparisons, and in some cases it required choosing sets of conditions that were as close as the obtained set would allow. The condition labels, which are fully descriptive of the variable levels, are used to reference the conditions and have the following form:

3_H_N_CL_Norm; where each position contains the following data -

- First position – RVR in hundreds of feet
- Second position – edge lighting (H = HIRL, M = MIRL, N = none)
- Third position – EFVS repeater status (R = repeater on, N = none)
- Fourth position – centerline lighting (CL = centerline lights on, NCL = no centerline lights)
- Fifth position – Task (Norm = normal takeoff, ENG = engine failure, EVF = EFVS failure/continue)

In this example, the condition label *3_H_N_CL_Norm* represents 300 feet RVR (3), HIRL (H), no EFVS repeater (N), centerline lights on (CLL), normal takeoff (Norm). This condition is numbered in Appendix A as Condition 1.

Note that EFVS was on in the HUD in all conditions excepting the two baselines, 4 and 5, representing current authorizations. Recalling that all baselines were conducted at 500 feet RVR as the reference, these comparisons included 5 with baselines and, initially, four comparisons between experimental conditions (one ultimately disallowed):

1) Can EFVS substitute for centerline lighting at 500 feet RVR?
    a. Baseline 2 (500 feet RVR, EFVS on, centerline lighting off) versus
    b. : Baseline 4 (500 feet RVR, EFVS off, centerline lighting on)
2) Can EFVS substitute for centerline lighting at 300 feet RVR?
    a. 3_H_N_NCL_Norm (300 feet RVR, EFVS on, centerline lighting off, normal takeoff) versus
    b. Baseline 4 (500 feet RVR, EFVS off, centerline lighting on)
3) Can EFVS substitute for edge lighting?
    a. 7_H_N_Norm (700 feet RVR, HIRL on, centerline lighting off, normal takeoff) versus
    b. 10_N_N_Norm (1000 feet RVR, no edge lights, centerline lighting off, normal takeoff)

4) Can EFVS substitute for centerline lighting during engine-failure-reject operations at 500 feet RVR?
    a. 5_H_N_ENG (500 feet RVR, HIRL on, EFVS on, centerline lighting off, engine failure/reject) versus
    b. Baseline 5 (500 feet RVR, HIRL on, EFVS off, centerline lighting on, engine failure reject)
5) Is performance comparable between that obtained with "good" visibility with EFVS and without centerline/edge lighting and that obtained with the current authorization at 500 feet RVR?
    a. 10_N_N_Norm (1000 feet RVR, no edge/centerline lighting, normal takeoff) versus
    b. Baseline 4 (500 feet RVR, HIRL on, EFVS off, centerline lighting on)
6) Is performance comparable between that obtained with "good" visibility with EFVS and no runway lighting and that obtained with the current authorization at 500 feet RVR during an engine-failure rejected takeoff?
    a. 10_N_N_ENG (1000 feet RVR, no runway lighting, centerline lighting off, engine failure reject) versus
    b. Baseline 5 (500 feet RVR, HIRL on, EFVS off, centerline lighting on, engine failure reject)
7) Is performance comparable between that obtained with "good" visibility with EFVS with no runway lighting and that obtained in lower visibility with EFVS and MIRL only when EFVS fails near V1? (both continued takeoffs)
    a. 10_N_N_EVF (1000 feet RVR, no edge/centerline lighting, EFVS failure near V1) versus
    b. 7_M_N_EVF (700 feet RVR, MIRL on, centerline lighting off, EFVS failure near V1)
8) Does the loss of EFVS near V1 affect performance on a continued takeoff at 300 feet RVR?
    a. 3_H_N_NCL_Norm (300 feet RVR, HIRL on, EFVS on, centerline lighting off, normal takeoff) versus
    b. 3_H_N_NCL_EVF (300 feet RVR, HIRL on, EFVS on, centerline lighting off, EFVS failure near V1)
9) Does the loss of EFVS near V1 affect performance on a continued takeoff at 500 feet RVR?
    a. 5_H_N_Norm (500 feet RVR, HIRL on, EFVS on, centerline lighting off, normal takeoff) versus
    b. 5_H_N_EVF (500 feet RVR, HIRL on, EFVS on, centerline lighting off, EFVS failure near V1)

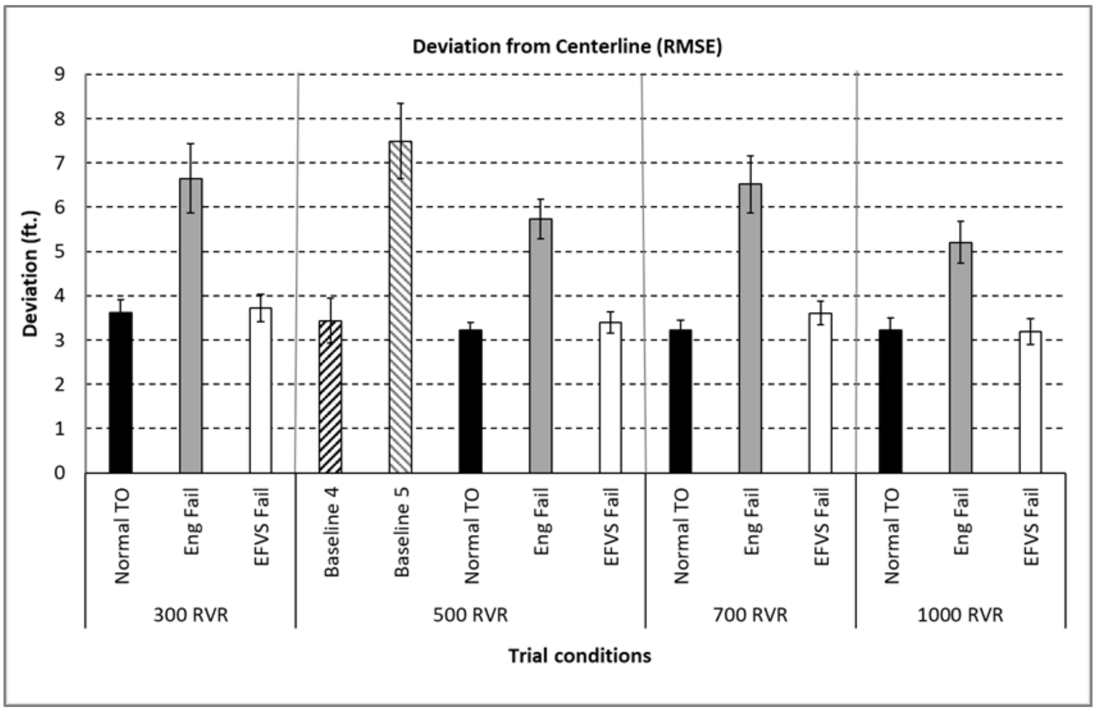
Comparisons 1, 2, and 4 are reasonable and direct, as are 8 and 9. Other comparisons are between conditions that are as similar as possible with a key difference defining them. Comparison 3, however, was the closest one possible for NO EDGE LIGHTING because there was, by intent, some kind of edge lighting present in ALL of the other RVR conditions (300 feet RVR, always HIRL; 500 and 700 feet RVR, HIRL or MIRL). Because the HUD EFVS was always on excepting in the baseline conditions, comparison 3 contains two factors working against one another to some degree. In 700 feet RVR, the EFVS is on and so are edge lights. As such, the lower visibility has two things, which may compensate for it—edge lighting and an EFVS image. In the 1000 feet RVR condition, there are neither edge lights nor EFVS image, but the visibility is very good comparatively. A no-difference finding here would only allow one to say that edge lighting AND EFVS combined with no centerline lights were at least as good as operating in 1000 feet RVR without edge lights, centerline lights, or an EFVS image, and thus the lack of difference could as easily be attributed, alternately, to better visibility in the 1000 feet RVR condition.

Additionally, one would have needed to see effects in the main analysis of 500 and 700 feet RVR conditions that implied something was at work there. Specifically, we would have needed to see a consistent main effect of edge lighting or a consistent two-way interaction between edge lighting and EFVS on/off. Across the 12 results in the main analysis (3 dependent variables for normal takeoff, EFVS-fail-continue takeoff, engine fail, and normal/EFVS-continue comparison), main effects appeared for only the EFVS-fail-continue task for edge lighting for RMSe deviation from centerline [$F(1, 9) = 8.64$, $p = 0.017$] and mean deviation [$F(1, 9) = 12.278$, $p = 0.007$], with very small mean differences (2 or so feet). The largest mean difference between conditions in the two-way interactions was only 2 feet (not operationally significant). This was similar for the two-way interactions between edge lighting and EFVS on/off, with similar extremely small, and not operationally significant, mean differences. These results were NOT present for the other tasks (normal and engine failure) and, given the sheer number of tests that were run (total specified previously) given the complexity of the design, they are considered to be largely artifacts. As such, comparison 3 is not reported here.

Figure 6 presents a quick overview of relevant performance (RMSE deviation from centerline; a measure of variability influenced by magnitude as it weights the larger scores more) by the four visibilities (300, 500, 700, and 1000 feet RVR) and the three tasks. Baseline 4, the normal takeoff without EFVS that was performed in 500 feet RVR (with HIRL and centerline lights), produced a value that was not significantly different from normal takeoffs with the EFVS under any other visibility condition or the EFVS failure, with continued takeoff, for conditions without centerline lights and with MIRL.

Figure 6

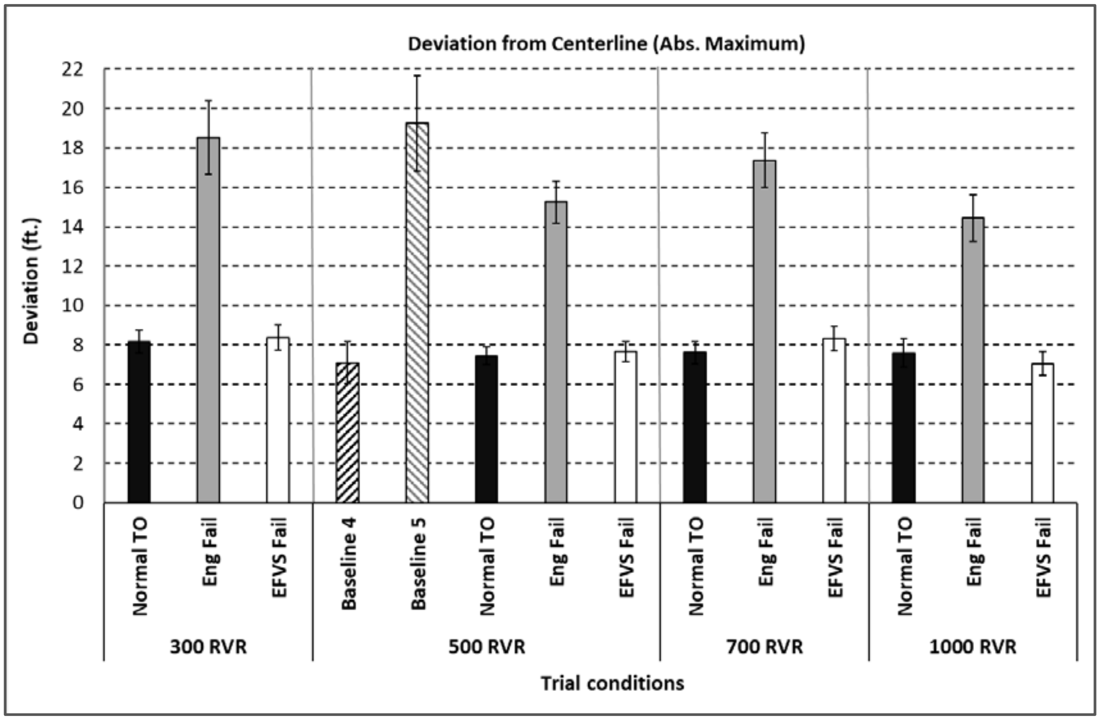
RMSe Deviation from Centerline by Task versus Baseline Performance



It is most informative to look at the baselines at 500 feet RVR versus the EFVS conditions at 300 feet RVR and see that performance for centerline tracking was no worse at 300 feet RVR with the EFVS on than it was at 500 feet RVR with the EFVS off (Baseline). In addition, precisely the same pattern appears in Figure 7, where the maximum absolute deviation from centerline is shown. Thus, what appeared to be equivalent performance to that in the baseline conditions (500 feet RVR) was obtained at a lower visibility (300 feet RVR), suggesting that the presence of EFVS can support authorized operations at that visibility, supported by the equivalence tests between these conditions.

Figure 7

Absolute Maximum Deviation from Centerline by RVR and Task versus Baseline



Comparison 4 addressed the compensatory nature of EFVS for absence of centerline lighting during engine-failure rejected takeoffs (5_H_N_ENG). Here, the performances in 5_H_N_ENG and Baseline 5, representing the current authorization, were *not* equivalent. It is clear, from Figures 6 and 7, that there appears to be a performance benefit to EFVS during engine-failure rejected takeoffs at 500 feet RVR; the crews were better able to maintain runway centerline tracking when EFVS was present and a lighted runway centerline was not, as compared when EFVS was turned off but a lighted centerline was present. Based on this result, it would appear that EFVS effectively compensated for the absence of runway centerline lighting during low visibility (500 feet RVR) takeoff operations in which an engine failure occurred. It is worth noting in Figures 6 and 7 that performance on the three tasks at 1000 feet RVR with EFVS but without any runway lighting did not appear to be demonstrably different from performance at 500 feet RVR, with EFVS, with runway edge lighting, and with no centerline lighting.

The conclusions drawn here are supported by the equivalence tests performed for the various pairings, in which the results indicated equivalence between the reference Baseline performances and the associated experimental trial results (Comparisons 1 and 2) or a performance benefit with EFVS over Baseline conditions (Comparison 4). Further details of the eight workable comparisons (excluding Comparison 3) are presented in the following section.

Equivalence Test Procedure and Outcomes

The possible outcomes of the test procedure (see Lakens, 2017, for the details of selecting appropriate bounds for the comparisons) are shown in Table 2. The test consists of two parts. In the first, one attempts to determine if the two distributions being compared fall within the same upper and lower bounds (equivalence). In the second, a conventional t test is conducted to see if the distributions of scores are statistically different. Of the four possible outcomes, only one results in a conclusion of equivalence. Two others leave the outcome undetermined, and the fourth indicates that the samples are different from one another statistically.

Table 2

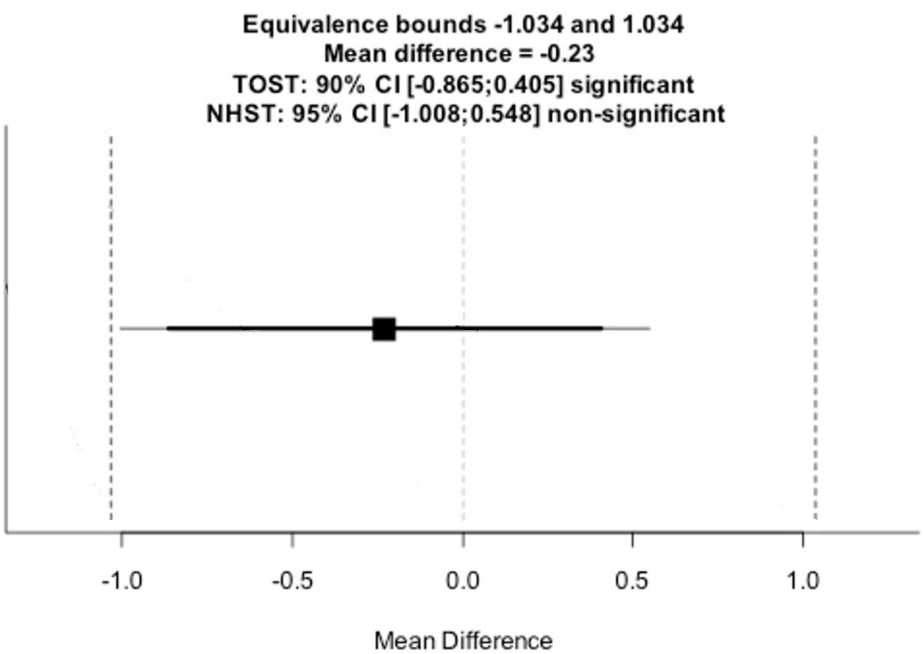
Possible Outcomes of the Equivalence Test Procedure

Test 1 Outcome	Test 2 Outcome	Resulting conclusion
Statistically Significant	Not Significant	*Samples Equivalent*
Statistically Significant	Statistically Significant	Undetermined
Not Significant	Not Significant	Undetermined
Not Significant	Statistically Significant	Samples Different

Figure 8 presents a graphical example of the equivalence test paradigm/results from the Baseline 4 versus Baseline 2 comparison, Absolute Mean deviation from centerline. One can see the mean represented by the black square and the 90% and 95% confidence limits represented by the overlaid horizontal lines. The vertical dotted lines to the far left and right indicate the equivalence boundaries. Both of the confidence intervals fall within the boundaries (significant result of p = 0.021), and the null-hypothesis t-test is not significant (p = 0.529), indicating that the two samples are deemed to be equivalent.

Figure 8

Graphical Representation of Equivalence Boundaries and Confidence Intervals



Summarizing the results for the equivalence tests in a count of them by category (Table 3), we can see that there were 12 rated equivalent, 9 rated undetermined, and 2 rated not equivalent. In the table, the equivalences are equally distributed across the three performance measures, as, approximately, are the undetermined findings. The non-equivalent conclusions only show up twice, once in absolute mean and once in RMS error, and both in the same trial comparison. It is worth keeping in mind that characteristics of each measure when considering what each implies as well as the magnitude of the means differences between the conditions, all of which were quite small (related to operational significance). Absolute mean deviation measures how far, on the average and without directional sign, the aircraft was from the centerline throughout the trial. RMS error registers variability over time and weights larger excursions more than smaller excursions. Absolute maximum deviation registers the farthest the aircraft deviated from centerline during a trial. The complete details of the 8 comparisons for equivalence are presented in Tables 4 through 7. Means and standard deviations are provided in Table 4 and the results of the statistical comparisons are provided in Tables 5, 6, and 7, which will be the references for the discussion following.

Table 3

Frequency-Count Summary of Results, by Performance Measure, for the Equivalence Tests of Deviation from Centerline

	Outcome		
Deviation Measure	Equivalent	Undetermined	Not Equivalent
Absolute Mean	4	3	1
RMS Error	4	3	1
Absolute Maximum	4	4	0

In examining absolute mean deviations for Baseline 4 and Baseline 2 (see Table 5), we find that the first test for both samples within confidence limits is significant ($p = 0.021$) and the null-hypothesis test is not ($p = 0.529$), meaning that one can consider the performance equivalent in the two samples. Thus, one possible assumption would be that absence of the centerline lighting in this specific case was offset by presence of the EFVS image. The same principle holds for the other comparisons. Comparison 4 (engine-failure trials) results are rather unique in that for two of the comparisons, the performance results are NOT equivalent and, in fact, performance was better with the EFVS without centerline lights, and in the third comparison it is "undetermined."

Table 4

Comparison Number and Description, Deviation Measure, Mean (Feet), Standard Deviation (SD), and Absolute Difference between Means for Equivalence Tests

Comparison #/ description	Dev. Measure	Mean 1	SD 1	Mean 2	SD 2	Abs. Diff.
1) Baseline 4 (1) vs. Baseline 2 (2)	Absolute Mean	2.60	1.23	2.83	1.89	0.23
	RMSe	3.43	1.76	3.75	2.56	0.32
	Absolute Max	7.10	3.70	8.08	5.90	0.98
2) Baseline 4 (1) vs. 3_H_N_NCL_Norm (2)	Absolute Mean	2.60	1.23	1.94	0.82	0.66
	RMSe	3.43	2.83	2.91	1.02	0.52
	Absolute Max	7.10	3.70	8.15	2.04	1.05
4) Baseline 5 (1) vs. 5_H_N_ENG (2)	Absolute Mean	5.10	1.81	3.57	1.19	1.53
	RMSe	7.49	2.93	5.29	2.05	2.20
	Absolute Max	19.24	8.42	14.77	6.27	4.47
5) Baseline 4 (1) vs. 10_N_N_Norm (2)	Absolute Mean	2.60	1.23	2.45	1.20	0.15
	RMSe	3.43	1.76	3.19	1.60	0.24
	Absolute Max	7.10	3.70	6.48	3.99	0.62
6) Baseline 5 (1) vs. 10_N_N_ENG (2)	Absolute Mean	5.10	1.81	3.80	1.85	1.30
	RMSe	7.49	2.93	5.72	2.66	1.77
	Absolute Max	19.24	8.43	16.48	5.82	2.76
7) 7_M_N_EVF (1) vs. 10_N_N_EVF (2)	Absolute Mean	2.77	2.11	2.28	1.45	0.49
	RMSe	3.64	2.75	2.89	1.69	0.75
	Absolute Max	7.15	5.80	5.68	2.57	1.47
8) 3_H_N_NCL_Norm (1) vs. 3_N_H_NCL_EVF (2)	Absolute Mean	1.94	0.82	2.18	0.73	0.24
	RMSe	2.90	1.02	3.46	1.15	0.56
	Absolute Max	8.16	2.05	10.24	3.94	2.08
9) 5_H_N_Norm (1) vs. 5_H_N_EVF (2)	Absolute Mean	2.54	1.15	2.37	1.67	0.17
	RMSe	3.26	1.49	3.10	2.04	0.16
	Absolute Max	6.60	3.88	6.50	4.07	0.10

Table 5

Result of Statistical Equivalence Tests for Comparisons 1, 2, and 4.

Comparison #/ description	Deviation Measure	Test (Conf. interval)	Equiv. bounds	Conf. limits	t df	p	Result
1) Baseline 4 vs. Baseline 2	Absolute Mean	TOST (90%)	±1.034	-0.865 to 0.504	11	0.021	Equivalent
		NHST (95%)		-1.008 to 0.548	11	0.529	
	RMSe	TOST (90%)	±1.293	-1.116 to 0.472	11	0.025	Equivalent
		NHST (95%)		-1.295 to 0.651	11	0.481	
	Absolute Maximum	TOST (90%)	±2.548	-2.547 to 0.518	11	0.049	Equivalent
		NHST (95%)		-2.9 to 0.934	11	0.283	
2) Baseline 4 vs. 3_H_N_NCL_Norm	Absolute Mean	TOST (90%)	±1.192	-1.391 to 0.073	11	0.109	Undetermined
		NHST (95%)		-1.556 to 0.238	11	0.134	
	RMSe	TOST (90%)	±1.599	-1.508 to 0.454	11	0.037	Equivalent
		NHST (95%)		-1.73 to 0.676	11	0.356	
	Absolute Maximum	TOST (90%)	±3.706	-1.218 to 3.33	11	0.030	Equivalent
		NHST (95%)		-1.731 to 3.843	11	0.422	
4) Baseline 5 vs. 5_H_N_ENG	Absolute Mean	TOST (90%)	±1.485	-2.446 to -0.624	11	0.539	**Not Equivalent**
		NHST (95%)		-2.652 to -0.418	11	0.012	
	RMSe	TOST (90%)	±2.367	-3.654 to -0.748	11	0.420	**Not Equivalent**
		NHST (95%)		-3.981 to -0.421	11	0.020	
	Absolute Maximum	TOST (90%)	±7.274	-8.938 to -0.01	11	0.142	Undetermined
		NHST (95%)		-9.945 to 0.997	11	0.099	

Note: Baseline 4 = 500 feet RVR, HIRL on, EFVS off, centerline lighting on, normal takeoff
Baseline 2 = 500 feet RVR, HIRL on, EFVS on, centerline lighting off, normal takeoff
3_H_N_NCL_Norm = 300 feet RVR, HIRL on, EFVS on, centerline lighting off, normal takeoff
Baseline 5 = 500 feet RVR, HIRL on, EFVS off, centerline lighting on, engine failure (reject)
5_H_N_ENG = 500 feet RVR, HIRL on, EFVS on, centerline lighting off, engine failure (reject)

Examining results for Comparison 5, Baseline 4 current authorization (no EFVS at 500 feet RVR) versus 1000 feet RVR no lights but EFVS on (see Table 6), we see that performance was deemed equivalent for 2 out of the 3 performance measures (absolute mean error and RMS error; not for absolute maximum error, where neither test was significant; thus “undetermined”). For that overall effect, then, one can likely safely assume that the crews’ performances were more similar than not. Given this result, one might be safe in concluding that performance while operating at 1000 feet RVR without the benefit of runway lighting infrastructure but with EFVS was not measurably different from operating at 500 feet RVR with the full benefit of runway lighting.

Comparison 6 (see Table 5) falls just on the other side of the balance point, where two of the measures come up “undetermined” and one comes up “equivalent.” It is interesting to note that the mean differences of the undetermined outcomes are both less than 2 feet, and the equivalent outcome (RMSe) less than 3.0, suggesting that the differences are not likely to be operationally significant.

Comparison 7 comes up undetermined on all three measures, so that we cannot say with any authority that the performances with a failure of the EFVS near V1, one in 1000 feet RVR without infrastructure and the other in 700 feet RVR with MIRL are comparable or that they are necessarily different (again, the differences are all extremely small).

Table 6

Results of Statistical Equivalence Tests for Comparisons 5, 6, and 7

Comparison #/ description	Deviation Measure	Test (Conf. interval)	Equiv. bounds	Conf. limits	t df	p	Result
5) Baseline 4 vs. 10_N_N_Norm	Absolute Mean	TOST (90%)	±0.514	-0.465 to 0.165	11	0.031	Equivalent
		NHST (95%)		-0.536 to 0.236	11	0.414	
	RMSe	TOST (90%)	±0.657	-0.643 to 0.163	11	0.045	Equivalent
		NHST (95%)		-0.734 to 0.254	11	0.291	
	Absolute Maximum	TOST (90%)	±1.187	-1.348 to 0.108	11	0.095	Undetermined
		NHST (95%)		-1.513 to 0.273	11	0.153	
6) Baseline 5 vs. 10_N_N_ENG	Absolute Mean	TOST (90%)	±2.063	-2.566 to -0.034	11	0.151	Undetermined
		NHST (95%)		-2.851 to 0.251	11	0.093	
	RMSe	TOST (90%)	±2.872	-3.533 to -0.007	11	0.143	Undetermined
		NHST (95%)		-3.93 to 0.39	11	0.099	
	Absolute Maximum	TOST (90%)	±7.758	-7.521 to 2.001	11	0.043	Equivalent
		NHST (95%)		-8.595 to 3.075	11	0.319	
7) 7_M_N_EVF vs. 10_N_N_EVF	Absolute Mean	TOST (90%)	±0.862	-0.039 to 1.019	11	0.116	Undetermined
		NHST (95%)		-0.158 to 1.138	11	0.121	
	RMSe	TOST (90%)	±1.235	-0.008 to 1.508	11	0.137	Undetermined
		NHST (95%)		-0.179 to 1.679	11	0.107	
	Absolute Maximum	TOST (90%)	±3.436	-0.639 to 3.579	11	0.061	Undetermined
		NHST (95%)		-1.114 to 4.054	11	0.235	

Note: Baseline 4 = 500 feet RVR, HIRL on, EFVS off, centerline lighting on, normal takeoff
10_N_N_Norm = 1000 feet RVR, EFVS on, centerline and runway edge lighting off, normal takeoff
Baseline 5 = 500 feet RVR, HIRL on, EFVS off, centerline lighting on, engine failure (reject)
10_N_N_ENG = 1000 feet RVR, EFVS on, centerline and runway edge lighting off, engine failure (reject)
7_M_N_EVF = 700 feet RVR, MIRL on, EFVS on, centerline lighting off, EFVS failure (continue)
10_N_N_EVF = 1000 feet RVR, EFVS on, centerline and runway edge lighting off, EFVS failure (continue)

Comparison 8 (see Table 7), comparing continued takeoffs in 300 feet RVR (normal versus EFVS fail/continue), also comes up with one equivalent result (absolute mean error) and two undetermined, again suggesting that we are not able to state, comprehensively, that the results are all equivalent. Again, the mean differences are incredibly small, and likely of no operational consequence whatsoever. The same comparison at 500 feet RVR (Comparison 9, Table 7) produced ALL equivalent results (all three measures, so that we can say with some authority that those two operations produced equivalent performance.

Table 7

Result of Statistical Equivalence Tests for Comparisons 8 and 9.

Comparison #/ description	Measure	Test (Conf. interval)	Equiv. bounds	Conf. limits	t df	p	Result
8) 3_H_N_NCL_Norm vs. 3_N_H_NCL_EVF	Absolute Mean	TOST (90%)	±0.629	-0.626 to 0.146	11	0.049	Equivalent
		NHST (95%)		-0.713 to 0.233	11	0.288	
	RMSe	TOST (90%)	±0.816	-1.053 to -0.051	11	0.182	Undetermined
		NHST (95%)		-1.166 to 0.062	11	0.073	
	Absolute Maximum	TOST (90%)	±3.158	-4.019 to -0.142	11	0.170	Undetermined
		NHST (95%)		-4.456 to 0.295	11	0.080	
9) 5_H_N_Norm vs. 5_H_N_EVF	Absolute Mean	TOST (90%)	±0.918	-0.399 to 0.729	11	0.018	Equivalent
		NHST (95%)		-0.526 to 0.856	11	0.609	
	RMSe	TOST (90%)	±1.000	-0.457 to 0.77	11	0.016	Equivalent
		NHST (95%)		-0.596 to 0.909	11	0.656	
	Absolute Maximum	TOST (90%)	±2.259	-1.295 to 1.478	11	0.009	Equivalent
		NHST (95%)		-1.607 to 1.791	11	0.908	

Note: 3_H_N_NCL_Norm = 300 feet RVR, HIRL on, EFVS on, centerline lighting off, normal takeoff
3_N_H_NCL_EVF = 300 feet RVR, HIRL on, EFVS on, centerline lighting off, EFVS failure (continue)
5_H_N_Norm = 500 feet RVR, HIRL on, EFVS on, centerline lighting off, normal takeoff
5_H_N_EVF = 500 feet RVR, HIRL on, EFVS on, centerline lighting off, EFVS failure (continue)

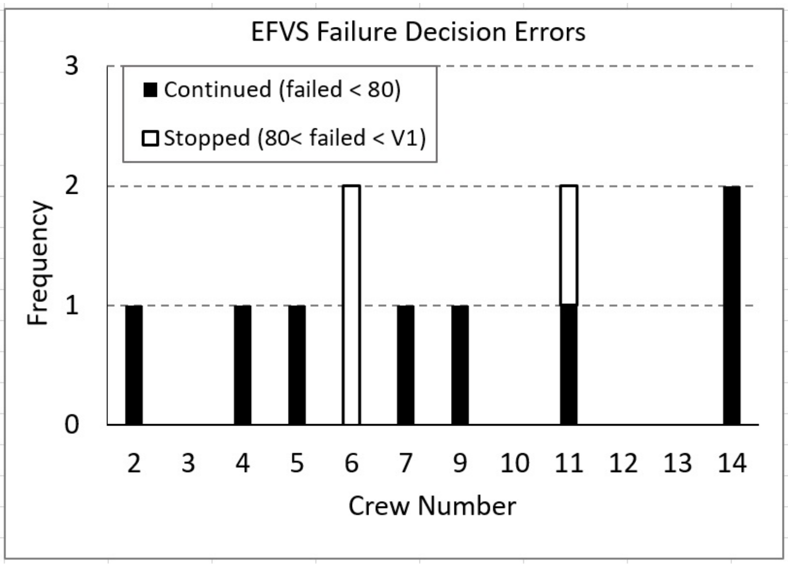
Decision Errors

EFVS failures were of two types, and the crew had to differentiate between them by the indicated speed at which they occurred. The originally incorporated failure occurred just below V1 and the instruction was for the crew to continue the takeoff if and when this happened. The supplemental-trial failure was one where the EFVS failed just below 80 kts, a situation where the HUD EFVS manufacturer has provided guidance recommending that the takeoff be rejected. Thus, the crew was required to make a continue/reject decision based upon when the failure occurred.

Per crew, there were 14 EFVS failures just below V1 and 4 EFVS failures at 75 kts that were part of the experiment design. As such, the incidence of decision errors shown in Figure 9 is relatively low. The majority of the crews who erred in the “continue” direction did so on the first “reject” trial. Note that the “continued” error was far more prevalent than the “stopped” error, and this was consistent with the crews’ attitudes of wanting to continue the takeoff unless there was an engine failure below V1. Their expressed opinions were that they did not consider the loss of the EFVS to be a significant or flight-terminating condition.

Figure 9

EFVS-Failure Decision Errors by Crew and Type



Workload

Data collected after every takeoff trial were examined to determine if any significant effect of the independent variables could be seen in the subjective measures of workload. Nonparametric (more appropriate to the data) analyses were conducted. No statistically significant differences were found as a function of any of the manipulated variables for the FOs’ ratings of workload. This was consistent with the FOs’ indications that their task, as normally performed, was unaffected by EFVS on the captain’s side and little affected/influenced by EFVS on their side (head down), despite them indicating that they thought it was a useful back-up to the primary display in the HUD.

For the captains' workload ratings, specific comparisons of interest and their associated results based on the nonparametric Wilcoxon Signed Rank Tests are provided (see Table 8). It is important to note from the outset that although nonparametric analyses were conducted, the results—significant or not significant—inform as to the reliability of the study results, but not necessarily operational significance. Operational relevance is best determined by a holistic approach that considers the results of the analysis, magnitude of the effect, and context of the operation (e.g., length and width of the runway, risk associated with the operation, inherent task difficulty, etc.). Here, the Pearson r correlation is used as the parameter of the effect size, which provides an objective and standardized measure of the magnitude of the observed effect. The effect size provides an indication as to the strength of the relationship between the experimental manipulation (e.g., presence or absence of EFVS) and perceived workload. According to Cohen (1992), an r of ±0.1 to 0.3 represents a small strength of association, ±0.3 to 0.5 represents a medium strength of association, and ±0.5 to 1.0 represents a large strength of association.

1) Is perceived workload during normal takeoffs at 500 feet RVR influenced by EFVS and centerline lighting?
    a. Baseline 2 (500 feet RVR, HIRL on, EFVS on, centerline lighting off) versus
    b. Baseline 4 (500 feet RVR, HIRL on, EFVS off, centerline lighting on)

The results of the Baseline 2 versus Baseline 4 comparison suggest that at 500 feet RVR, there was no significant difference in experienced workload as a result of the absence of runway centerline lighting when EFVS was present ($p > 0.05$ for visual, mental, physical, and time pressure). Further, the Pearson r values, representing the effect size, suggested that the strength of association between the manipulated variables (here, EFVS and centerline lighting) and perceived workload was not large ($r < 0.50$). This is consistent with the comparison of performance data for these conditions.

2) Does EFVS offset perceived workload during reduced visibility normal takeoff operations without centerline lighting?
    a. 3_H_N_NCL_Norm (300 feet RVR, HIRL on, EFVS on, centerline lighting off) versus
    b. Baseline 4 (500 feet RVR, HIRL on, EFVS off, centerline lighting on)

There were no significant differences in perceived workload when comparing 3_H_N_NCL_Norm to Baseline 4 ($p > 0.05$ for visual, mental, physical, and time pressure). Measures of the strength of association between the experimental variables (RVR, centerline lighting, EFVS) and perceived workload were small ($r < 0.3$). These results extend those of workload Comparison 1 to suggest that EFVS may successfully compensate for runway centerline lighting—in terms of the captains' perceived workload and performance metrics based on previously discussed equivalence testing—even when the OTW visibility was reduced from 500 feet RVR to 300 feet RVR during normal takeoff operations.

3) Are there any differences in perceived workload between engine failure reject and EFVS failure reject operations?
    a. 5_H_N_ENG (500 feet RVR, HIRL on, EFVS on, centerline lighting off, Engine failure reject) versus
    b. 5_H_R_EVF_75 (500 feet RVR, HIRL on, EFVS on, centerline lighting off, EFVS failure reject)

Here, the direct comparison involved two types of equipment failure operations—both requiring that the captain reject the takeoff and safely stop the aircraft on the runway. Airline pilots train for engine failure conditions on a routine basis, and thus, the decision criteria are well-learned and rehearsed. In contrast, the evaluation pilots experienced EFVS failures for the first time during the study, and were asked to use newly learned decision rules (failure < 80 kts reject; failure > 80 kts continue) to complete the task.

Results from the Wilcoxon Signed Rank Tests suggested that there was no difference in perceived workload between engine failure reject and EFVS failure reject takeoff operations (p >

0.05 for visual, mental, physical, and time pressure). Further, effect size measures for each workload dimension were less than 0.5 (Pearson's r), suggesting that there was not a strong relationship between the type of failure (EFVS or Engine) and perceived workload. This suggests that the newly encountered flight operations, in which an EFVS failure occurred during takeoff, were perceived as no more demanding than the comparator engine failure takeoff operation.

4) Does EFVS offset perceived workload during engine failure conditions at 500 feet RVR without centerline lighting?
    a. 5_H_N_ENG (500 feet RVR, HIRL on, EFVS on, centerline lighting off, engine failure reject) versus
    b. Baseline 5 (500 feet RVR, HIRL on, EFVS off, centerline lighting on, engine failure reject)

The results from the Wilcoxon Signed Rank Test were not statistically significant ($p >$ 0.05 for visual, mental, physical, and time pressure), though there was a strong relationship between the manipulated variables (EFVS and centerline lighting) and visual workload ($r = -0.55$) and mental workload ($r = -0.56$). This suggests a strong relationship between the presence of EFVS and perceived visual and mental workload during engine failure operations, with higher workload associated with takeoff trials in which EFVS was absent (even though centerline lighting was present).

Together with the flight performance results discussed in the equivalence testing section of this report, it would appear that having EFVS during an engine failure on takeoff is associated with lower mental and visual workload, and better runway centerline tracking performance, though perhaps not of the magnitude to be operationally relevant.

5) Are there any differences in perceived workload between normal takeoffs and EFVS failure continue takeoffs at 300 feet RVR?
    a. 3_H_N_NCL_EVF (300 feet RVR, HIRL on, EFVS on, centerline lighting off, EFVS failure continue) versus

b. 3_H_N_NCL_Norm (300 feet RVR, HIRL on, EFVS on, centerline lighting off, normal takeoff)

EFVS failure continue takeoffs were perceived as more demanding than normal takeoffs at 300 feet RVR. In this comparison, neither condition included runway centerline lighting. For example, for takeoffs with an EFVS failure, visual workload ($p = 0.010$), mental workload ($p = 0.005$), and workload associated with time pressure ($p = 0.030$) were rated as significantly higher, based on the median as a measure of central tendency, than ratings associated with normal takeoffs (Figure 10). Additionally, the strength of association between type of takeoff operation (normal or EFVS failure continue) and perceived workload was large ($r > 0.5$) for each of the workload domains (Table 8).

6) Are there any differences in perceived workload between normal takeoffs and EFVS failure continue takeoffs at 500 feet RVR?
    a. 5_H_N_EVF (500 feet RVR, centerline lighting off, HIRL on, EFVS on, EFVS failure continue) versus
    b. 5_H_N_Norm (500 feet RVR, centerline lighting off, HIRL on, EFVS on, normal takeoff)

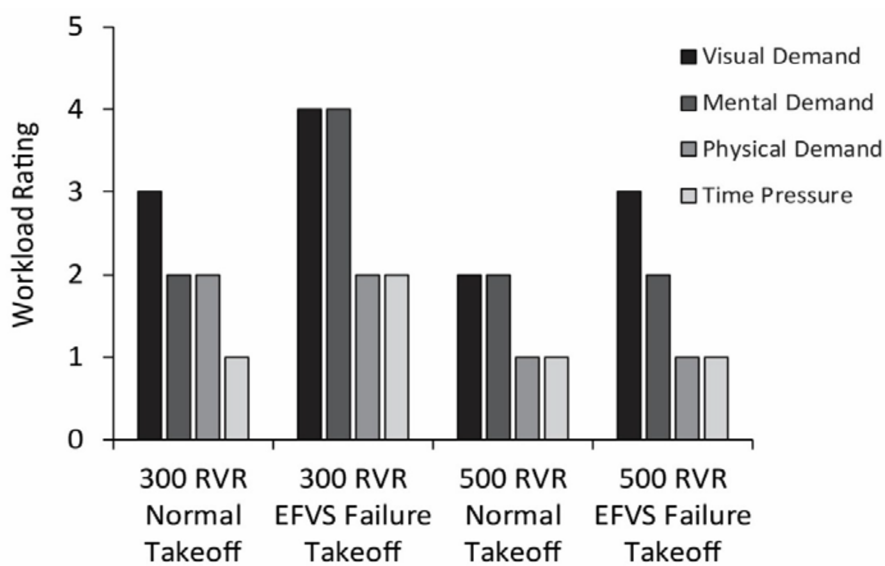
Workload Comparison 6 is considered an extension of Workload Comparison 5, but this time evaluating workload between normal takeoffs and EFVS failure continue takeoffs at 500 feet RVR, as opposed to the more restrictive 300 feet RVR (Workload Comparison 5).

When the OTW visibility was 500 feet RVR, the evaluation pilots perceived takeoffs in which an EFVS failure occurred above 80 kts without runway centerline lighting as more physically demanding than normal takeoffs in the same conditions ($p = 0.025$). Further the strength of the relationship between type of takeoff operation (normal or EFVS failure continue) and perceived physical workload was large ($r = 0.065$). The median value for physical workload associated with EFVS failure conditions was 2 (on a scale of 0 to 5), while the median value for normal operations was 1—a difference that would reasonably be considered not of operational importance.

There were no significant differences between the type of takeoff operation (EFVS failure continue and normal takeoffs) and workload associated with visual, mental, or time pressure ($p > 0.05$), and the effect sizes associated with this relationship were classified as small or medium ($r < 0.50$).

Figure 10

Subjective Workload Ratings for Normal and EFVS Failure Takeoffs at 300 Feet RVR and 500 Feet RVR



Note: Values Plotted are the Median Responses.

Table 8

Results of Wilcoxon Signed Rank Tests for Subjective Workload

Question	Workload Comparison	Measure	Median 1	Median 2	T	*p*	r
1	Baseline 2 versus Baseline 4	Visual	2	2	10.5	0.141	-0.4
		Mental	2	2	8.0	0.257	-0.33
		Physical	1	2	9.0	0.655	0.13
		Time	1	1	7.5	1.000	0.00
2	3_H_N_NCL_Norm versus Baseline 4	Visual	3	2	23.0	0.470	0.21
		Mental	2	2	25.0	0.739	0.10
		Physical	2	2	12.0	0.739	0.10
		Time	1	1	6.0	0.655	-0.13
3	5_H_N_ENG versus 5_H_R_EVF_75	Visual	2	3	3.0	0.096	-0.48
		Mental	3	3	9.0	0.655	0.13
		Physical	3	3	12.5	0.157	0.41
		Time	3	2	18.0	0.096	0.48
4	5_H_N_ENG versus Baseline 5	Visual	2	3	4.0	0.059	-0.55**
		Mental	3	4	10.0	0.052	-0.56**
		Physical	3	3	7.0	0.206	-0.37
		Time	3	3	5.0	0.480	-0.20
5	3_N_H_NCL_EVF versus 3_H_N_NCL_Norm	Visual	4	3	52.5	0.010*	0.74**
		Mental	4	2	63.5	0.005*	0.81**
		Physical	2	2	25.0	0.054	0.56**
		Time	2	1	21.0	0.020*	0.67**
6	5_H_N_EVF versus 5_H_N_Norm	Visual	3	2	29.0	0.112	0.46
		Mental	2	2	22.0	0.165	0.40
		Physical	2	1	15.0	0.025*	0.65**
		Time	1	1	2.0	0.655	0.13

*Note: * denotes statistical significance at the p < 0.05 level.*
*** denotes a large effect size of r > 0.50, based on Cohen (1992).*

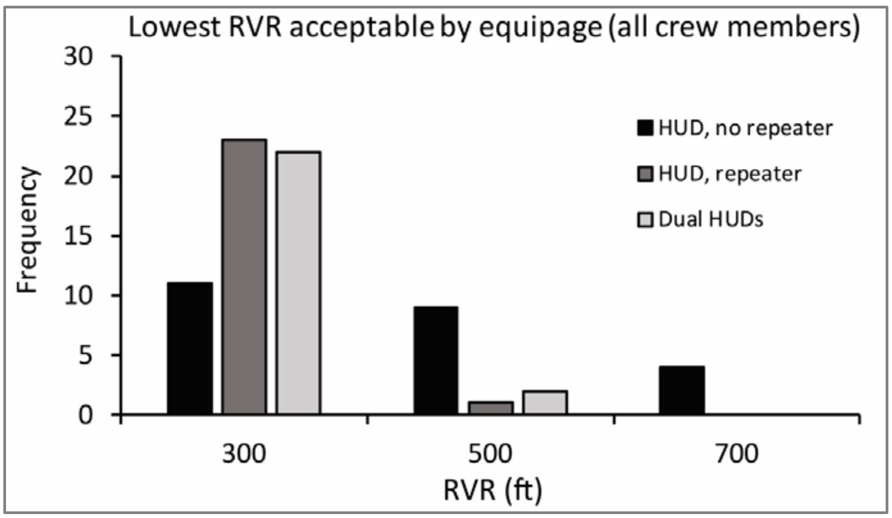
Post-Task Questionnaire

When asked about the lowest RVR acceptable for takeoff in the post-task questionnaire (Appendix H), unsurprisingly, EFVS technology was viewed as more helpful at lower visibility (300 feet RVR) compared to relatively higher visibility (500 and 700 feet RVR) conditions. In

Figure 11, it is clear that with visibilities as low as 300 feet RVR, the majority of pilots preferred EFVS displayed on a HUD for the captain, with a repeater head-down display for the FO, with the secondary preference being EFVS dual-HUDs. By increasing the RVR to 500 and 700 feet, pilots either found EFVS to be unnecessary, or that EFVS for the captain only would be acceptable.

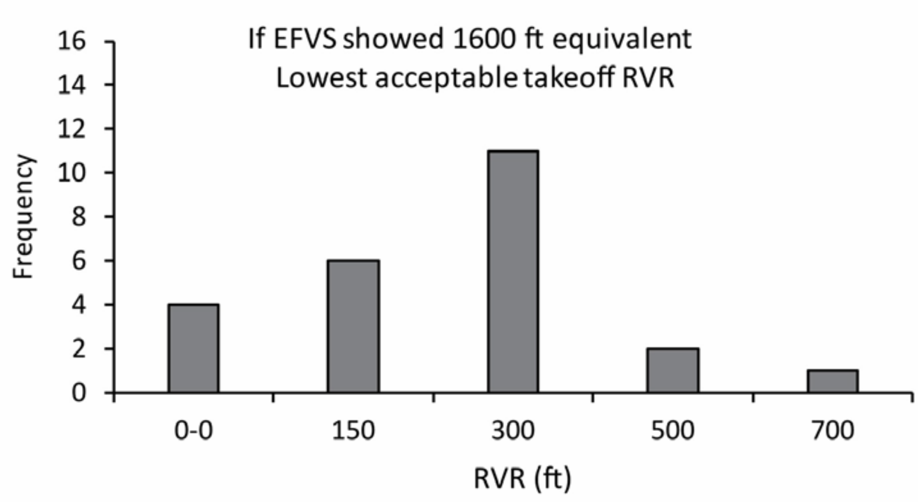
Figure 11

Frequency of choice of lowest RVR that would be acceptable by equipage for all 24 participants



When asked about the lowest acceptable RVR for takeoff if provided an EFVS HUD with the equivalent visibility of 1600 feet RVR, the majority of pilots felt comfortable taking off at 300 feet RVR (Figure 12). However, it should be noted that many pilots (n = 10) reported believing they would feel comfortable taking off at either 0 or 150 feet RVR despite not having experienced these conditions during the experiment, illustrating the perceived visual and safety advantage of EFVS during low visibility takeoffs.

Figure 12
Lowest Acceptable Takeoff RVR if EFVS Showed Equivalent of 1600 Feet RVR



Preference for EFVS training medium ranked flight-simulator experience highest (4.8 out of 5) with computer second (2.9), followed by internet (2.4), classroom (2.2), video (1.8) and handbook (0.9). Regarding EFVS helpfulness during the takeoff, 91% of respondents rated the display as helpful in accomplishing the task. Both captains and FOs rated the painted runway centerline as being a major contributor to maintaining track using the EFVS, and captains rated the EFVS in the HUD also to be a large contributor to successful task completion. EFVS imagery was also rated as a major contributor in maintaining positional awareness (a separate question from the specific question about the painted centerline).

Conclusions

No clear safety issues were observed with any EFVS-presenting configurations and it appeared that the use of EFVS produced performance consistent with that required for successful operations as low as 300 feet RVR, including cases where there was no centerline lighting (but HIRL was present). Equivalence tests indicated that, in many cases, performance with the EFVS in the absence of some features of airport infrastructure was equivalent to performance without the EFVS in conditions that represented current authorizations. There were also cases where the differences were “undetermined” as far as equivalence but were so small that they were likely not of operational significance, an assessment that should be made separately from the statistical evaluation of the performance differences.

Additionally, there appeared to be a performance benefit to EFVS when an engine failure occurred during takeoff, even when runway centerline lighting was absent. Workload was not rated as excessive or markedly different from the Baseline conditions, and captains were, in the majority, positive about the contributions the imagery made to conducting low-visibility operations. These results suggest that EFVS can be used in place of some airport infrastructure during low-visibility operations, thus potentially increasing the number of airports that may be accessible during reduced-visibility conditions. This, in combination with recent results from low-visibility taxi evaluations (Beringer et al., 2019) and approach-to-landing evaluations (synthetic vision; Beringer et al., 2018) for transport-category aircraft, suggest that it is possible to augment the entire range of low-visibility operations and increase accessibility of a number of airports with lesser infrastructure through the use of these types of display and imaging systems.

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Appendix A

Condition Specifications

Table A 1

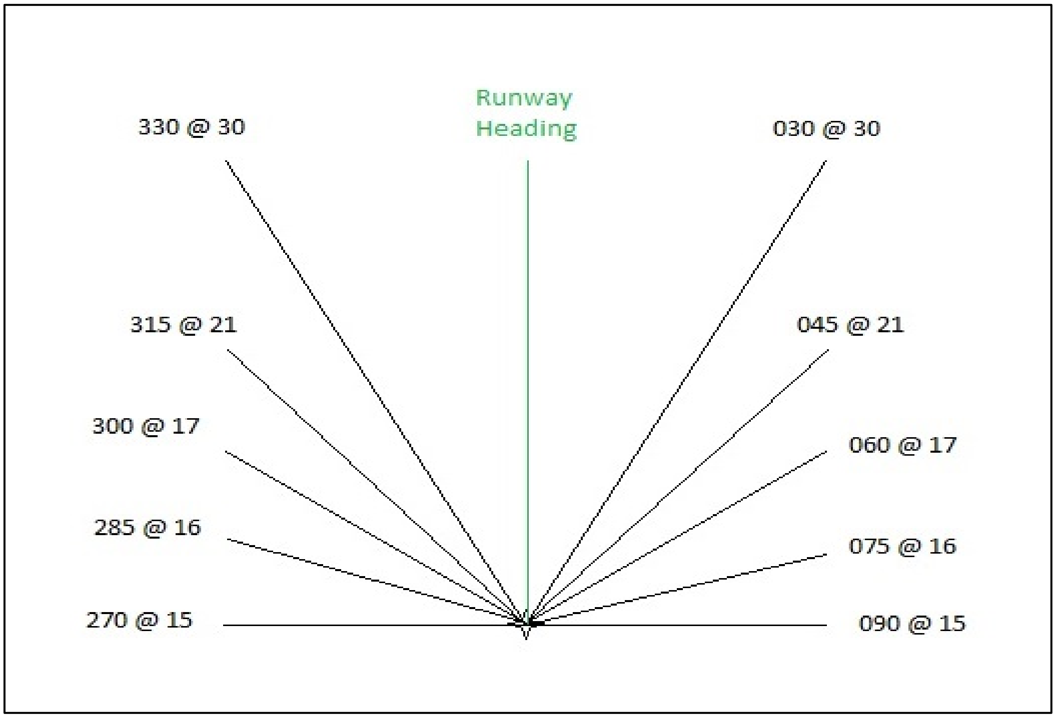
Specification of Experimental Conditions, All Trials and Conditions Excepting Training

			variable	varible	variable	variable	fixed	fixed	fixed	fixed				
Cond. #	Condition label	Cond code	RVR	HIRL/MIRL	EVFS repeater	Task	CLL	RWY width	EVFS	Ambient L.	Rel X-Wind	Rel wind details	Comments (1)	Comments (2)
							Var							
1	3_H_N_CL_Norm	3111	300	HIRL	off	Normal T/O	on	150	on	Night	15L	315 @ 21		300 Sup 1 (old label)
2	3_H_N_CL_ENG	3112	300	HIRL	off	<V1 E-fail reject	on	150	on	Night	15R	045 @ 21	Left Eng fail	300 Sup 2 (old label)
3	3_H_N_CL_EVF	3113	300	HIRL	off	<V1 EVFS fail reject	on	150	on	Night	15L	270 @ 15		300 Sup 3 (old label)
33	3_H_R_CL_Norm	3211	300	HIRL	on	Normal T/O	on	150	on	Night	15R	060 @ 17		
34	3_H_R_CL_ENG	3212	300	HIRL	on	<V1 E-fail reject	on	150	on	Night	15L	315 @ 21	Right Eng fail	
35	3_H_R_CL_EVF	3213	300	HIRL	on	<V1 EVFS fail	on	150	on	Night	15R	075 @ 16		
42	3_H_N_NCL_Norm	3121	300	HIRL	off	Normal T/O	off	150	on	Night	15R	045 @ 21		
43	3_H_N_NCL_ENG	3122	300	HIRL	off	<V1 E-fail reject	off	150	on	Night	15L	300 @ 17	Right Eng fail	
44	3_H_N_NCL_EVF	3123	300	HIRL	off	<V1 EVFS fail	off	150	on	Night	15R	090 @ 15		
45	3_H_R_NCL_Norm	3221	300	HIRL	on	Normal T/O	off	150	on	Night	15L	300 @ 17		
46	3_H_R_NCL_ENG	3222	300	HIRL	on	<V1 E-fail reject	off	150	on	Night	15R	060 @ 17	Left Eng fail	
47	3_H_R_NCL_EVF	3223	300	HIRL	on	<V1 EVFS fail	off	150	on	Night	15L	315 @ 21		
4	5_H_R_Norm	1111	500	HIRL	on	Normal T/O	off	150	on	Night	15R	045 @ 21		
5	5_H_R_ENG	1112	500	HIRL	on	<V1 E-fail reject	off	150	on	Night	15L	315 @ 21	Right Eng fail	
6	5_H_R_EVF	1113	500	HIRL	on	<V1 EV fail	off	150	on	Night	15R	075 @ 16		
7	5_H_N_Norm	1121	500	HIRL	off	Normal T/O	off	150	on	Night	15L	285 @ 16		
8	5_H_N_ENG	1122	500	HIRL	off	<V1 E-fail reject	off	150	on	Night	15R	059 @ 17	Left Eng fail	
9	5_H_N_EVF	1123	500	HIRL	off	<V1 EV fail	off	150	on	Night	15L	270 @15		
10	5_M_R_Norm	1211	500	MIRL	on	Normal T/O	off	150	on	Night	15L	315 @ 21		
11	5_M_R_ENG	1212	500	MIRL	on	<V1 E-fail reject	off	150	on	Night	15R	090 @ 15	Left Eng fail	
12	5_M_R_EVF	1213	500	MIRL	on	<V1 EV fail	off	150	on	Night	15L	300 @ 17		
13	5_M_N_Norm	1221	500	MIRL	off	Normal T/O	off	150	on	Night	15R	075 @ 16		
14	5_M_N_ENG	1222	500	MIRL	off	<V1 E-fail reject	off	150	on	Night	15L	285 @ 16	Right Eng fail	
15	5_M_N_EVF	1223	500	MIRL	off	<V1 EV fail	off	150	on	NIght	15R	045 @ 21		
16	7_H_R_Norm	2111	700	HIRL	on	Normal T/O	off	150	on	Night	15L	300 @ 17		
17	7_H_R_ENG	2112	700	HIRL	on	<V1 E-fail reject	off	150	on	Night	15R	045 @ 21	Left Eng fail	
18	7_H_R_EVF	2113	700	HIRL	on	<V1 EV fail	off	150	on	Night	15L	285 @ 16		
19	7_H_N_Norm	2121	700	HIRL	off	Normal T/O	off	150	on	Night	15R	090 @ 15		
20	7_H_N_ENG	2122	700	HIRL	off	<V1 E-fail reject	off	150	on	Night	15L	300 @ 17	Right Eng fail	
21	7_H_N_EVF	2123	700	HIRL	off	<V1 EV fail	off	150	on	Night	15R	090 @ 15		
22	7_M_R_Norm	2211	700	MIRL	on	Normal T/O	off	150	on	Night	15R	059 @ 17		
23	7_M_R_ENG	2212	700	MIRL	on	<V1 E-fail reject	off	150	on	Night	15L	270 @15	Right Eng fail	
24	7_M_R_EVF	2213	700	MIRL	on	<V1 EV fail	off	150	on	Night	15R	059 @ 17		
25	7_M_N_Norm	2221	700	MIRL	off	Normal T/O	off	150	on	Night	15L	270 @15		
26	7_M_N_ENG	2222	700	MIRL	off	<V1 E-fail reject	off	150	on	Night	15R	075 @ 16	Left Eng fail	
27	7_M_N_EVF	2223	700	MIRL	off	<V1 EV fail	off	150	on	Night	15L	315 @ 21		
36	10_N_R_Norm	10_R_norm	1000	All off	on	Normal T/O	off	150	on	Night	15R	075 @ 16		
37	10_N_R_ENG	10_R_ENG	1000	All off	on	<V1 E-fail reject	off	150	on	Night	15L	330 @ 30	Right Eng fail	
38	10_N_R_EVF	10_R_EVF	1000	All off	on	<V1 EV fail	off	150	on	Night	15R	030 @ 30		
39	10_N_N_Norm	10_N_norm	1000	All off	off	Normal T/O	off	150	on	Night	15L	300 @ 17		
40	10_N_N_ENG	10_N_EVG	1000	All off	off	<V1 E-fail reject	off	150	on	Night	15R	060 @ 17	Left Eng fail	
41	10_N_N_EVF	10_N_EVF	1000	All off	off	<V1 EV fail	off	150	on	Night	15L	285 @ 16		
28	Base 1	B1	500	HIRL	off	Normal T/O	off	150	on	Night	15L	270 @15	Beginning of order	Track learning/sequence effects
29	Base 2	B2	500	HIRL	off	Normal T/O	off	150	on	Night	15L	270 @15	Middle of order	Track learning/sequence effects
30	Base 3	B3	500	HIRL	off	Normal T/O	off	150	on	Night	15L	270 @15	End of order	Track learning/sequence effects
31	Base 4 current 1	A1	500	HIRL	off	Normal T/O	on	150	off	Night	15R	300@17		Anchor for current authorization
32	Base 5 current 2	A2	500	HIRL	off	<V1 E-fail reject	on	150	off	NIght	15R	090 @ 15	Left Eng fail	Anchor for current authorization
48	3_H_R_CL_EVF_75	3214	300	HIRL	on	<80 kts EV fail reject	on	150	on	Night	15R	075 @ 16		
49	3_H_R_NCL_EVF_75	3224	300	HIRL	on	<80 kts EV fail reject	off	150	on	Night	15L	315 @ 21		
50	5_H_R_EVF_75	1114	500	HIRL	on	<80 kts EV fail reject	off	150	on	Night	15R	075 @ 16		
51	7_H_R_EVF_75	2114	700	HIRL	on	<80 kts EV fail reject	off	150	on	Night	15L	285 @ 16		

EF = Engine Failure
EVF = EFVS Failure

Figure A 1

Distribution of Winds Used in the Capacity of a Sampling Variable

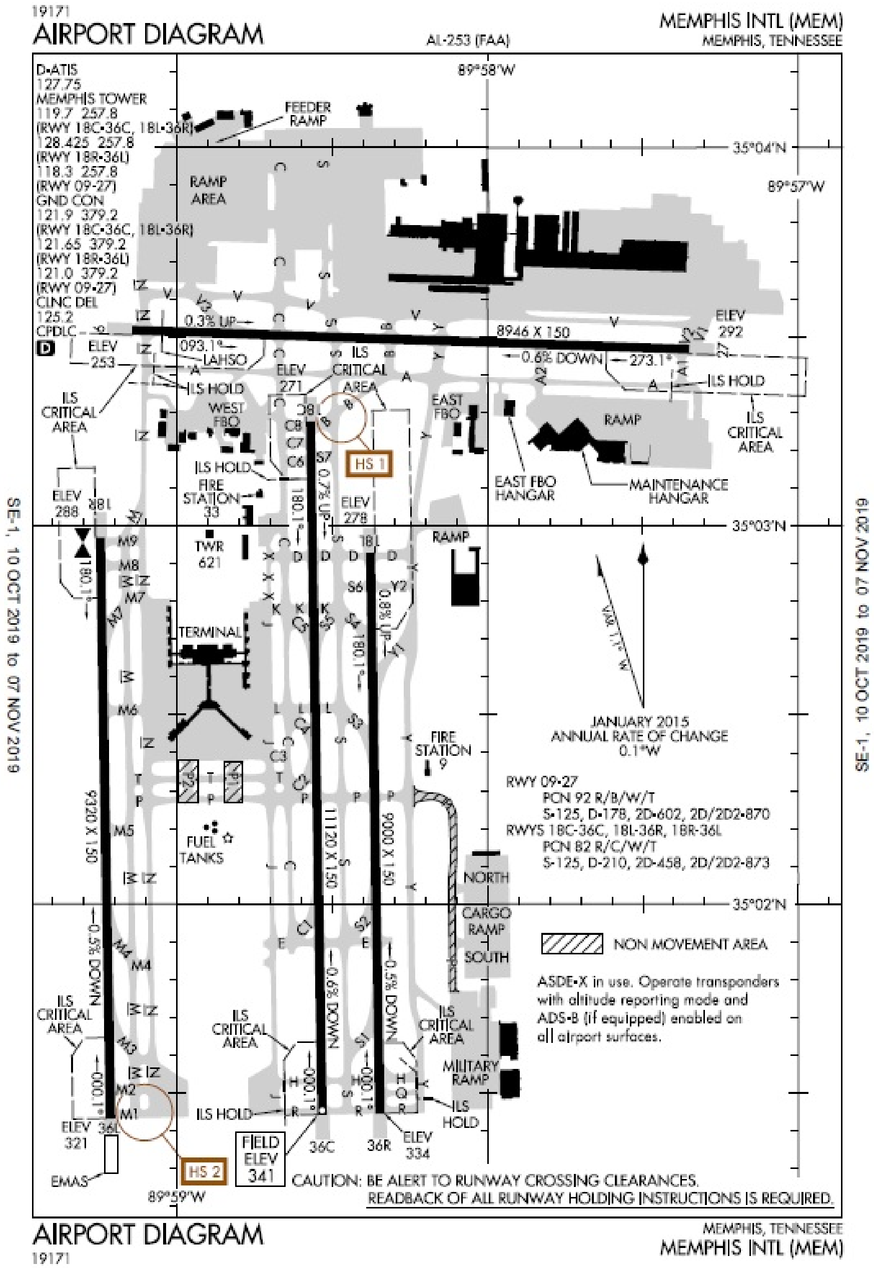


Appendix B

Airport Surface Diagram

Figure B 1

Airport Surface Diagram for Memphis International Airport (KMEM)



Appendix C

Analysis Summary Tables for Absolute Maximum Deviation from Centerline

Table C 1

Descriptive Statistics for Absolute Maximum Deviation from Centerline, Normal Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON	6.6	3.6	12
500 RVR_MIRL_EFVSOFF	8.0	2.3	12
500 RVR_HIRL_EFVSON	8.4	1.9	12
500 RVR_HIRL_EFVSOFF	6.6	3.8	12
700 RVR_MIRL_EFVSON	8.4	3.8	12
700 RVR_MIRL_EFVSOFF	6.5	4.1	12
700 RVR_HIRL_EFVSON	6.1	4.1	12
700 RVR_HIRL_EFVSOFF	9.2	2.9	12

Table C 2

GLM Analysis Results for Core Factorial, Absolute Maximum Deviation from Centerline, Normal Takeoff

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	.832	1	.832	.390	.545
Error (RVR)	23.470	11	2.134		
Edge Lights	.940	1	.940	.300	.595
Error (Edge Lights)	34.463	11	3.133		
EFVS	.734	1	.734	.160	.697
Error (EFVS)	50.386	11	4.581		
RVR * Edge Lights	.014	1	.014	.007	.935
Error (RVR*Edge Lights)	21.881	11	1.989		
RVR * EFVS	3.995	1	3.995	.617	.449
Error (RVR*EFVS)	71.270	11	6.479		
Edge Lights * EFVS	4.245	1	4.245	1.068	.323
Error (Edge Lights*EFVS)	43.709	11	3.974		
RVR * Edge Lights * EFVS	103.788	1	103.788	5.156	.044

Error (RVR*Edge Lights*EFVS)	221.433	11	20.130		

Table C 3

Descriptive Statistics for Absolute Maximum Deviation from Centerline, EFVS Fail, Continue Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500RVR_MIRL_EFVSON	7.2	3.0	10
500RVR_MIRL_EFVSOFF	7.9	2.8	10
500RVR_HIRL_EFVSON	7.9	3.5	10
500RVR_HIRL_EFVSOFF	5.8	2.7	10
700 RVR_MIRL_EFVSON	9.9	2.8	10
700 RVR_MIRL_EFVSOFF	5.9	3.8	10
700 RVR_HIRL_EFVSON	5.2	2.4	10
700 RVR_HIRL_EFVSOFF	9.6	3.4	10

Table C 4

GLM Analysis Results for Core Factorial, Absolute Maximum Deviation from Centerline, EFVS Fail, Continue Takeoff

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	4.217	1	4.217	2.231	.169
Error (RVR)	17.012	9	1.890		
Edge Lights	6.518	1	6.518	1.903	.201
Error (Edge Lights)	30.821	9	3.425		
EFVS	.883	1	.883	.434	.527
Error (EFVS)	18.313	9	2.035		
RVR * Edge Lights	.195	1	.195	.093	.767
Error (RVR*Edge Lights)	18.909	9	2.101		
RVR * EFVS	4.409	1	4.409	1.451	.259
Error (RVR*EFVS)	27.353	9	3.039		
Edge Lights * EFVS	39.833	1	39.833	7.537	.023
Error (Edge Lights*EFVS)	47.567	9	5.285		
RVR * Edge Lights * EFVS	155.619	1	155.619	5.629	.042
Error (RVR*Edge Lights*EFVS)	248.794	9	27.644		

Table C 5

Descriptive Statistics for Comparison of Absolute Maximum Deviation from Centerline for Normal and EFVS-Fail-Continue Takeoffs.

Descriptive Statistics

Variable levels/task	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON EFVS Continue TO	7.2	3.0	10
500 RVR_MIRL_EFVSON Normal TO	5.6	2.6	10
500 RVR_MIRL_EFVSOFF EFVS Continue TO	7.9	2.8	10
500 RVR_MIRL_EFVSOFF Normal TO	7.5	1.8	10
500 RVR_HIRL_EFVSON EFVS Continue TO	7.9	3.5	10
500 RVR_HIRL_EFVSON Normal TO	8.1	1.9	10
500 RVR_HIRL_EFVSOFF EFVS Continue TO	5.8	2.7	10
500 RVR_HIRL_EFVSOFF Normal TO	5.6	1.7	10
700 RVR MIRL_EFVSON EFVS Continue TO	9.9	2.8	10
700 RVR MIRL_EFVSON Normal TO	8.1	3.8	10
700 RVR_MIRL_EFVSOFF EFVS Continue TO	5.9	3.8	10
700 RVR_MIRL_EFVSOFF Normal TO	5.8	2.8	10
700 RVR_HIRL_EFVSON EFVS Continue TO	5.2	2.4	10
700 RVR_HIRL_EFVSON Normal TO	5.3	2.5	10
700 RVR_HIRL_EFVSOFF EFVS Continue TO	9.6	3.4	10
700 RVR_HIRL_EFVSOFF Normal TO	8.6	2.5	10

Table C 6

GLM Analysis Results for Comparison of Absolute Maximum Deviation from Centerline for Normal and EFVS-Fail-Continue Takeoffs

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	4.283	1	4.283	1.876	.204
Error (RVR)	20.543	9	2.283		
Edge Lights	1.501	1	1.501	.426	.531
Error (Edge Lights)	31.744	9	3.527		
EFVS	.178	1	.178	.088	.773
Error (EFVS)	18.107	9	2.012		
Task	14.624	1	14.624	1.836	.208
Error (Task)	71.692	9	7.966		
RVR * Edge Lights	.039	1	.039	.012	.916

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
Error (RVR*Edge Lights)	29.592	9	3.288		
RVR * EFVS	7.831	1	7.831	1.141	.313
Error (RVR*EFVS)	61.753	9	6.861		
Edge Lights * EFVS	29.542	1	29.542	7.875	.021
Error (Edge Lights*EFVS)	33.764	9	3.752		
RVR * Edge Lights * EFVS	277.001	1	277.001	6.955	.027
Error (RVR*Edge Lights*EFVS)	358.446	9	39.827		
RVR * Task	.696	1	.696	.713	.420
Error (RVR*Task)	8.790	9	.977		
Edge Lights * Task	5.690	1	5.690	1.533	.247
Error (Edge Lights*Task)	33.399	9	3.711		
RVR * Edge Lights * Task	.676	1	.676	.682	.430
Error (RVR*Edge Lights*Task)	8.917	9	.991		
EFVS * Task	.823	1	.823	.172	.688
Error (EFVS*Task)	43.077	9	4.786		
RVR * EFVS * Task	.029	1	.029	.010	.924
Error (RVR*EFVS*Task)	26.991	9	2.999		
Edge Lights * EFVS * Task	12.182	1	12.182	2.011	.190
Error (Edge Lights*EFVS*Task)	54.511	9	6.057		
RVR * Edge Lights * EFVS * Task	.997	1	.997	.296	.600
Error (RVR*Edge Lights*EFVS*Task)	30.348	9	3.372		

Table C 7

Descriptive Statistics for Absolute Maximum Deviation from Centerline for Engine Failure, Rejected Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON	14.9	4.9	11
500 RVR_MIRL_EFVSOFF	14.1	5.4	11
500 RVR_HIRL_EFVSON	12.3	6.8	11
500 RVR_HIRL_EFVSOFF	13.3	3.9	11
700 RVR_MIRL_EFVSON	14.3	7.5	11
700 RVR_MIRL_EFVSOFF	16.5	4.8	11
700 RVR_HIRL_EFVSON	17.6	11.8	11
700 RVR_HIRL_EFVSOFF	15.2	9.4	11

Table C 8
GLM Analysis Results for Absolute Maximum Deviation from Centerline for Engine Failure, Rejected Takeoff

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	114.051	1	114.051	3.180	.105
Error (RVR)	358.696	10	35.870		
Edge Lights	2.641	1	2.641	.054	.821
Error (Edge Lights)	490.335	10	49.034		
EFVS	.003	1	.003	.000	.991
Error (EFVS)	233.386	10	23.339		
RVR * Edge Lights	41.769	1	41.769	2.407	.152
Error (RVR*Edge Lights)	173.504	10	17.350		
RVR * EFVS	.264	1	.264	.023	.884
Error (RVR*EFVS)	116.866	10	11.687		
Edge Lights * EFVS	11.110	1	11.110	.509	.492
Error (Edge Lights*EFVS)	218.227	10	21.823		
RVR * Edge Lights * EFVS	57.473	1	57.473	1.740	.217
Error (RVR*Edge Lights*EFVS)	330.254	10	33.025		

Appendix D

Analysis Summary Tables for Root-mean-squared Error Deviation from Centerline

Table D 1

Descriptive Statistics for Root-Mean-Squared Error Deviation from Centerline, Normal Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON	3.2	1.7	12
500 RVR_MIRL_EFVSOFF	2.9	.5	12
500 RVR_HIRL_EFVSON	3.3	.9	12
500 RVR_HIRL_EFVSOFF	3.2	1.4	12
700 RVR_MIRL_EFVSON	2.9	1.1	12
700 RVR_MIRL_EFVSOFF	3.3	2.0	12
700 RVR_HIRL_EFVSON	2.	1.8	12
700 RVR_HIRL_EFVSOFF	3.5	1.3	12

Table D 2

GLM Analysis Results for Root-Mean-Squared Error Deviation from Centerline, Normal Takeoff

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	7.699E-5	1	7.699E-5	.000	.990
Error(RVR)	4.713	11	.428		
Edge Lights	.523	1	.523	.564	.468
Error (Edge Lights)	10.197	11	.927		
EFVS	.468	1	.468	.586	.460
Error (EFVS)	8.789	11	.799		
RVR * Edge Lights	.028	1	.028	.068	.799
Error (RVR*Edge Lights)	4.537	11	.412		
RVR * EFVS	2.876	1	2.876	2.742	.126
Error (RVR*EFVS)	11.536	11	1.049		
Edge Lights * EFVS	.254	1	.254	.339	.572
Error (Edge Lights*EFVS)	8.235	11	.749		
RVR * Edge Lights * EFVS	.000	1	.000	.000	.997
Error (RVR*Edge Lights*EFVS)	75.196	11	6.836		

Table D 3

Descriptive Statistics for Root-Mean-Squared Error Deviation from Centerline, EFVS Failure, Continue Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON	3.7	1.8	10
500 RVR_MIRL_EFVSOFF	3.3	.9	10
500 RVR_HIRL_EFVSON	3.1	1.1	10
500 RVR_HIRL_EFVSOFF	2.7	1.2	10
700 RVR_MIRL_EFVSON	3.7	1.0	10
700 RVR_MIRL_EFVSOFF	3.1	2.1	10
700 RVR_HIRL_EFVSON	2.6	1.6	10
700 RVR_HIRL_EFVSOFF	3.7	1.2	10

Table D 4

GLM Analysis Results for Root-Mean-Squared Error Deviation from Centerline, EFVS Failure, Continue Takeoff

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	.261	1	.261	.523	.488
Error (RVR)	4.493	9	.499		
Edge Lights	3.966	1	3.966	8.640	.017
Error (Edge Lights)	4.132	9	.459		
EFVS	.102	1	.102	.274	.613
Error (EFVS)	3.357	9	.373		
RVR * Edge Lights	.403	1	.403	.652	.440
Error (RVR*Edge Lights)	5.559	9	.618		
RVR * EFVS	2.120	1	2.120	4.124	.073
Error (RVR*EFVS)	4.627	9	.514		
Edge Lights * EFVS	3.517	1	3.517	6.187	.035
Error (Edge Lights*EFVS)	5.116	9	.568		
RVR * Edge Lights * EFVS	3.731	1	3.731	.410	.538
Error (RVR*Edge Lights*EFVS)	81.889	9	9.099		

Table D 5

Descriptive Statistics for Comparison of Root-Mean-Squared Deviation from Centerline for Normal and EFVS-Fail-Continue Takeoffs

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON Normal TO	2.9	1.5	10
500 RVR_MIRL_EFVSON EFVS Continue TO	3.7	1.8	10
500 RVR_MIRL_EFVSOFF Normal TO	2.9	.5	10
500 RVR_MIRL_EFVSOFF EFVS Continue TO	3.3	.9	10
500 RVR_HIRL_EFVSON Normal TO	3.2	.9	10
500 RVR_HIRL_EFVSON EFVS Continue TO	3.1	1.1	10
500 RVR_HIRL_EFVSOFF Normal TO	3.1	1.1	10
500 RVR_HIRL_EFVSOFF EFVS Continue TO	2.7	1.2	10
700 RVR_MIRL_EFVSON Normal TO	2.7	1.1	10
700 RVR_MIRL_EFVSON EFVS Continue TO	3.7	1.0	10
700 RVR_MIRL_EFVSOFF Normal TO	3.1	1.6	10
700 RVR_MIRL_EFVSOFF EFVS Continue TO	3.1	2.1	10
700 RVR_HIRL_EFVSON Normal TO	2.6	1.4	10
700 RVR_HIRL_EFVSON EFVS Continue TO	2.6	1.6	10
700 RVR_HIRL_EFVSOFF Normal TO	3.5	1.4	10
700 RVR_HIRL_EFVSOFF EFVS Continue TO	3.7	1.2	10

Table D 6

GLM Analysis Results for Comparison of Root-Mean-Squared Deviation from Centerline for Normal and EFVS-Fail-Continue Takeoffs

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	.062	1	.062	.117	.740
Error(RVR)	4.747	9	.527		
Edge Lights	.451	1	.451	.692	.427
Error (Edge Lights)	5.867	9	.652		
EFVS	.392	1	.392	1.489	.253
Error (EFVS)	2.370	9	.263		
Task	2.344	1	2.344	3.550	.092
Error (Task)	5.941	9	.660		
RVR * Edge Lights	.049	1	.049	.061	.811
Error (RVR*Edge Lights)	7.328	9	.814		

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR * EFVS	4.156	1	4.156	2.976	.119
Error (RVR*EFVS)	12.568	9	1.396		
Edge Lights * EFVS	2.808	1	2.808	2.923	.122
Error (Edge Lights*EFVS)	8.647	9	.961		
RVR * Edge Lights * EFVS	3.330	1	3.330	.217	.652
Error (RVR*Edge Lights*EFVS)	138.134	9	15.348		
RVR * Task	.224	1	.224	1.310	.282
Error (RVR*Task)	1.541	9	.171		
Edge Lights * Task	4.601	1	4.601	5.498	.044
Error (Edge Lights*Task)	7.531	9	.837		
RVR * Edge Lights * Task	.456	1	.456	1.670	.229
Error (RVR*Edge Lights*Task)	2.457	9	.273		
EFVS * Task	1.163	1	1.163	1.485	.254
Error (EFVS*Task)	7.045	9	.783		
RVR * EFVS * Task	.000	1	.000	.001	.974
Error (RVR*EFVS*Task)	3.415	9	.379		
Edge Lights * EFVS * Task	.954	1	.954	1.839	.208
Error (Edge Lights*EFVS*Task)	4.668	9	.519		
RVR * Edge Lights * EFVS * Task	.822	1	.822	3.799	.083
Error (RVR*Edge Lights*EFVS*Task)	1.947	9	.216		

Table D 7

Descriptive Statistics for Root-Mean-Squared Deviation from Centerline for Engine Failure, Rejected Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON	6.5	4.3	12
500 RVR_MIRL_EFVSOFF	5.8	2.4	12
500 RVR_HIRL_EFVSON	5.2	3.3	12
500 RVR_HIRL_EFVSOFF	5.2	2.0	12
700 RVR_MIRL_EFVSON	5.8	4.0	12
700 RVR_MIRL_EFVSOFF	6.5	2.9	12
700 RVR_HIRL_EFVSON	7.0	5.8	12
700 RVR_HIRL_EFVSOFF	6.5	5.0	12

Table D 8

GLM Analysis Results for Root-Mean-Squared Deviation from Centerline for Engine Failure, Rejected Takeoff

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	14.647	1	14.647	1.662	.224
Error (RVR)	96.933	11	8.812		
Edge Lights	.628	1	.628	.068	.799
Error (Edge Lights)	101.549	11	9.232		
EFVS	.379	1	.379	.084	.777
Error (EFVS)	49.588	11	4.508		
RVR * Edge Lights	13.352	1	13.352	3.078	.107
Error (RVR*Edge Lights)	47.719	11	4.338		
RVR * EFVS	1.228	1	1.228	.626	.446
Error (RVR*EFVS)	21.587	11	1.962		
Edge Lights * EFVS	.285	1	.285	.177	.682
Error (Edge Lights*EFVS)	17.767	11	1.615		
RVR * Edge Lights * EFVS	5.229	1	5.229	.511	.490
Error (RVR*Edge Lights*EFVS)	112.628	11	10.239		

Appendix E

Analysis Summary Tables for Mean Deviation from Centerline

Table E 1

Descriptive Statistics for Mean Deviation from Centerline, Normal Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON	2.5	1.3	12
500 RVR_MIRL_EFVSOFF	1.9	.5	12
500 RVR_HIRL_EFVSON	2.3	.7	12
500 RVR_HIRL_EFVSOFF	2.5	1.1	12
700 RVR_MIRL_EFVSON	2.0	.8	12
700 RVR_MIRL_EFVSOFF	2.64	1.6	12
700 RVR_HIRL_EFVSON	2.3	1.4	12
700 RVR_HIRL_EFVSOFF	2.4	1.1	12

Table E 2

GLM Analysis Results for Mean Deviation from Centerline, Normal Takeoff

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
RVR	.002	1	.002	.006	.941
Error (RVR)	2.961	11	.269		
Edge Lights	.386	1	.386	.556	.472
Error (Edge Lights)	7.645	11	.695		
EFVS	.210	1	.210	.475	.505
Error (EFVS)	4.874	11	.443		
RVR * Edge Lights	.159	1	.159	.533	.481
Error (RVR*Edge Lights)	3.288	11	.299		
RVR * EFVS	1.882	1	1.882	3.038	.109
Error (RVR*EFVS)	6.815	11	.620		
Edge Lights * EFVS	.041	1	.041	.080	.783
Error (Edge Lights*EFVS)	5.662	11	.515		
RVR * Edge Lights * EFVS	2.226	1	2.226	.446	.518

Error (RVR*Edge Lights*EFVS)	54.888	11	4.990		

Table E 3

Descriptive Statistics for Mean Deviation from Centerline, EFVS Failure, Continue Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON	2.8	1.4	10
500 RVR_MIRL_EFVSOFF	2.3	.8	10
500 RVR_HIRL_EFVSON	2.1	.7	10
500 RVR_HIRL_EFVSOFF	2.	1.0	10
700 RVR_MIRL_EFVSON	2.7	.8	10
700 RVR_MIRL_EFVSOFF	2.4	1.5	10
700 RVR_HIRL_EFVSON	2.1	1.3	10
700 RVR_HIRL_EFVSOFF	2.5	.8	10

Table E 4

GLM Analysis Results for Mean Deviation from Centerline, EFVS Failure, Continue Takeoff

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
RVR	.084	1	.084	.269	.617
Error (RVR)	2.802	9	.311		
Edge Lights	2.741	1	2.741	12.278	.007
Error (Edge Lights)	2.009	9	.223		
EFVS	.273	1	.273	.912	.364
Error (EFVS)	2.695	9	.299		
RVR * Edge Lights	.327	1	.327	.852	.380
Error (RVR*Edge Lights)	3.455	9	.384		
RVR * EFVS	.586	1	.586	2.746	.132
Error (RVR*EFVS)	1.920	9	.213		
Edge Lights * EFVS	1.313	1	1.313	4.461	.064
Error (Edge Lights*EFVS)	2.648	9	.294		
RVR * Edge Lights * EFVS	.117	1	.117	.019	.895
Error (RVR*Edge Lights*EFVS)	56.607	9	6.290		

Table E 5

Descriptive Statistics for Comparison of Mean Deviation from Centerline for Normal and EFVS-Fail-Continue Takeoffs

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON_Normal TO	2.2	1.1	10
500 RVR_MIRL_EFVSON_EFVS Continue TO	2.8	1.4	10
500 RVR_MIRL_EFVSOFF_Normal TO	1.9	.5	10
500 RVR_MIRL_EFVSOFF_EFVS Continue TO	2.3	.8	10
500 RVR_HIRL_EFVSON_Normal TO	2.3	.8	10
500 RVR_HIRL_EFVSON_EFVS Continue TO	2.1	.7	10
500 RVR_HIRL_EFVSOFF_Normal TO	2.5	.9	10
500 RVR_HIRL_EFVSOFF_EFVS Continue TO	2.0	1.0	10
700 RVR_MIRL_EFVSON_Normal TO	1.9	.8	10
700 RVR_MIRL_EFVSON_EFVS Continue TO	2.7	.8	10
700 RVR_MIRL_EFVSOFF_Normal TO	2.4	1.3	10
700 RVR_MIRL_EFVSOFF_EFVS Continue TO	2.4	1.5	10
700 RVR_HIRL_EFVSON_Normal TO	2.1	1.1	10
700 RVR_HIRL_EFVSON_EFVS Continue TO	2.1	1.3	10
700 RVR_HIRL_EFVSOFF_Normal TO	2.4	1.2	10
700 RVR_HIRL_EFVSOFF_EFVS Continue TO	2.5	.8	10

Table E 6

GLM Analysis Results for Comparison of Mean Deviation from Centerline for Normal and EFVS-Fail-Continue Takeoffs

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	.005	1	.005	.018	.898
Error (RVR)	2.678	9	.298		
Edge Lights	.275	1	.275	1.112	.319
Error (Edge Lights)	2.225	9	.247		
EFVS	.069	1	.069	.722	.418

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
Error (EFVS)	.861	9	.096		
Task	.929	1	.929	3.505	.094
Error (Task)	2.384	9	.265		
RVR * Edge Lights	.008	1	.008	.014	.910
Error (RVR*Edge Lights)	5.021	9	.558		
RVR * EFVS	1.888	1	1.888	2.796	.129
Error (RVR*EFVS)	6.079	9	.675		
Edge Lights * EFVS	1.157	1	1.157	2.001	.191
Error (Edge Lights*EFVS)	5.203	9	.578		
RVR * Edge Lights * EFVS	.111	1	.111	.010	.921
Error (RVR*Edge Lights*EFVS)	96.722	9	10.747		
RVR * Task	.113	1	.113	.802	.394
Error (RVR*Task)	1.274	9	.142		
Edge Lights * Task	3.302	1	3.302	4.576	.061
Error (Edge Lights*Task)	6.494	9	.722		
RVR * Edge Lights * Task	.521	1	.521	3.324	.102
Error (RVR*Edge Lights*Task)	1.410	9	.157		
EFVS * Task	1.004	1	1.004	1.754	.218
Error (EFVS*Task)	5.150	9	.572		
RVR * EFVS * Task	.085	1	.085	.292	.602
Error (RVR*EFVS*Task)	2.622	9	.291		
Edge Lights * EFVS * Task	.297	1	.297	.925	.361
Error (Edge Lights*EFVS*Task)	2.889	9	.321		
RVR * Edge Lights * EFVS * Task	.667	1	.667	3.508	.094
Error (RVR*Edge Lights*EFVS*Task)	1.710	9	.190		

Table E 7

Descriptive Statistics for Mean Deviation from Centerline for Engine Failure, Rejected Takeoff

Descriptive Statistics

Variable levels	Mean	Std. Deviation	N
500 RVR_MIRL_EFVSON	4.5	3.0	12

500 RVR_MIRL_EFVSOFF	4.2	1.8	12
500 RVR_HIRL_EFVSON	3.7	2.3	12
500 RVR_HIRL_EFVSOFF	3.5	1.1	12
700 RVR_MIRL_EFVSON	4.2	3.0	12
700 RVR_MIRL_EFVSOFF	4.5	1.9	12
700 RVR_HIRL_EFVSON	4.6	3.8	12
700 RVR_HIRL_EFVSOFF	4.7	3.7	12

Table E 8

GLM Analysis Results for Mean Deviation from Centerline for Engine Failure, Rejected Takeoff

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source	Type III Sum of Squares	*df*	Mean Square	F	*p*
RVR	6.511	1	6.511	1.436	.256
Error (RVR)	49.867	11	4.533		
Edge Lights	1.453	1	1.453	.362	.560
Error (Edge Lights)	44.146	11	4.013		
EFVS	.002	1	.002	.001	.977
Error (EFVS)	28.860	11	2.624		
RVR * Edge Lights	6.418	1	6.418	2.593	.136
Error (RVR*Edge Lights)	27.224	11	2.475		
RVR * EFVS	1.263	1	1.263	1.910	.194
Error (RVR*EFVS)	7.278	11	.662		
Edge Lights * EFVS	.005	1	.005	.005	.948
Error (Edge Lights*EFVS)	12.051	11	1.096		
RVR * Edge Lights * EFVS	.223	1	.223	.031	.864
Error (RVR*Edge Lights*EFVS)	79.668	11	7.243		

Appendix F

Summary of Learning Effects across Baseline Trials for Deviation from Centerline

Table F 1

Mean, Standard Deviations (Mean / SD), F-statistics, and p-values for 3 Deviation-From-Centerline Measures for Distributed Baselines to Monitor Learning Effects.

Performance measure	Baseline 1	Baseline 2	Baseline 3	F (2,22)	*p*
Absolute Mean	2.81 / 1.52	2.83 / 1.89	2.48 / 1.56	1.58	.228
RMSe	3.73 / 1.99	3.75 / 2.56	3.28 / 2.09	1.64	.216
Absolute Maximum	7.72 / 3.65	8.03 / 5.90	6.89 / 4.72	.893	.424

Appendix G

Pilot Experience Questions

P# _______________ Date: ____________

1. **Pilot participating as:** ❑ Pilot Flying ❑ Pilot Monitoring

2. **What ratings do you hold currently?**

❑ Airline Transport Pilot (ATP)	❑ Instrument Rating
❑ Certified Flight Instructor (CFI)	❑ Multi-Engine
❑ Certified Flight Instructor – Instrument (CFII)	❑ Private Pilot
❑ Commercial	❑ Other

3. **Current flight crew position:** ❍ Captain ❍ First Officer ❍ Other

   If other, please specify: ____________________

4. **Have you used an enhanced flight vision system (EFVS) as displayed through a Heads-Up Display (HUD) in <u>actual</u> operations?** ❍ Yes❍ No

   If you answered yes, please answer the following questions:

   a. Approximate date of last use: __________
   b. What make and model EFVS did you use? __________
   c. Approximately how many hours of flying time have you logged using EFVS? ________
   d. During what phases of flight have you used EFVS? (please estimate percentages)
      Taxi ______ Take-off _______ Cruise______ Descent______
      Approach _______ Landing_______

5. **Have you used an enhanced flight vision system (EFVS) as displayed on a Head-Down Display (HDD, on the instrument panel) in <u>actual</u> operations?** ❍ Yes ❍ No

   If you answered yes, please answer the following questions:

   e. Approximate date of last use: __________
   f. Approximately how many hours of flying time have you logged using HDD EFVS? ________
   g. During what phases of flight have you used HDD EFVS? (please estimate percentages)
      Taxi ______ Take-off _______ Cruise______ Descent______
      Approach _______ Landing_______

6. **Years of CAT-III experience:** _________

7. **Please estimate your hours under the following conditions:**

   Total flight hours: _____________

Flight hours in the past month: _____________

Low-visibility takeoffs (number) between 1600 ft and 600 ft RVR: _____________

Appendix H

Post-test Questions

Pilot Opinion Interview Questions (Captain)

(EFVS for takeoff credit)

The following questions pertain to your use of certain display features in the simulator and to your willingness to perform takeoffs with and without these features in the real aircraft. Please circle the letter of your choice when appropriate or use the labeled scales on the other questions to circle a response that applies to each statement in this section.

1) What is the least equipage that you would be comfortable with for performing low-visibility takeoffs at RVRs less than 1000 feet?

   a. EFVS on left-seat HUD, no repeater for First Officer (FO)

   b. EFVS on left-seat HUD with head-down repeater for FO

   c. EFVS on dual HUDs

2) What is the lowest RVR that you would be willing to accept for takeoff for each of the following aircraft-equipage (Cpt and FO) conditions given the EFVS performance in today's simulation?

   First, circle the lowest RVR value that you would accept with that line's equipage. **Second,** mark in the parentheses to the right your ordered preference for the equipage as 1 (first), 2 (second), and 3 (third). If you cannot rank order them or feel that they are not different enough in terms of safety/performance to be ranked, circle "NR" for "No Ranking."

   a. EFVS on left-seat HUD, no repeater for First Officer (FO) _______ NR

   RVR: 1000 700 500 300

   -

   b. EFVS on left-seat HUD with head-down repeater for FO

   RVR: 1000 700 500 300 _______ NR

   c. EFVS on dual HUDs

   RVR: 1000 700 500 300 _______ NR

3) What is the minimum airport infrastructure that you believe you would need at each value of RVR to conduct takeoffs safely (given today's experience in the simulator) **WITHOUT EFVS**? For each value of RVR on the left side of the table, circle below which parts of airport infrastructure that you believe **you** would need to have. Circle only one type of edge lighting. This is for your crew position without regard to the First Officer's position. You may circle as many or as few as you want in each row for each value of RVR.

	Infrastructure (airport and/or flightdeck)	
RVR	Centerline Lights	Edge lights
300 feet	CLL	MIRL / HIRL
500 feet	CLL	MIRL / HIRL
700 feet	CLL	MIRL / HIRL
1000 feet	CLL	MIRL / HIRL

4) What is the minimum airport infrastructure that you believe you would need at each value of RVR to conduct takeoffs safely (given today's experience in the simulator) **WITH EFVS**? For each value of RVR on the left side of the table, circle below which parts of airport infrastructure that you believe **you** would need to have. Circle only one type of edge lighting. This is for your crew position without regard to the First Officer's position. You may circle as many or as few as you want in each row for each value of RVR.

	Infrastructure (airport and/or flightdeck)	
RVR	Centerline Lights	Edge lights
300 feet	CLL	MIRL / HIRL
500 feet	CLL	MIRL / HIRL
700 feet	CLL	MIRL / HIRL
1000 feet	CLL	MIRL / HIRL

5) The current authorizations for low-visibility takeoffs without EFVS require the ability to see some feature or light 1600 feet distant ahead of the aircraft. If the sensor image (regardless of type of sensor; i.e., infrared, millimeter wave, etc.) in the HUD and/or on the head-down display could consistently show features/lights at 1600 feet ahead of the aircraft, what would be your personal limit on the lowest actual RVR you could accept for takeoff if the authorization did not specify a lower limit?

   a. 700 Feet
   b. 500 feet
   c. 300 feet
   d. 150 feet
   e. 0-0 conditions

6) Brightness/contrast: Please mark on the scale where you felt that each of these factors was, for you, for the EFVS image in the HUD, for each of the two factors.

   f. Brightness - too dim…………….....…just right……………….too bright

      1 2 3 4 5

   g. Contrast - faded into …………........…...ok…………………..obscured
      out-the-window (OTW)

      1 2 3 4 5

7) Field of view in the HUD: I thought the field of view for EFVS in the HUD was –
   Too narrow…………………ok………………..….too wide

   1 2 3 4 5

8) Training: What forms of training would you want to see for HUD-based EFVS? Please rank order the following from 1 (most desired) to 6 (least desired)

	Ranking
Handbook (paper or electronic)	
Computer-based instruction	
Internet (on web site)	

Video (tape or DVD)	
Classroom	
Hands-on in flight simulator	

9) Did the HUD EFVS facilitate your ability to take off under the visibility conditions presented?

   Not at all……………..Moderately…………….Significantly

   1 2 3 4 5

10) Given your experience with EFVS in the HUD, please rate the EFVS picture for perceived overall reliability/accuracy and possible contributions to safety on the following scales:

EFVS – the EFVS image

	Poor	Below average	Above average	Excellent
Reliability/accuracy				
Safety contribution				

If you placed any ratings in the “Poor” or “Excellent” categories, please expand on which feature was responsible for that rating and why you rated it that way. Your explanation is crucial to our understanding the actual way in which pilots use these systems. How you use these systems will translate directly into how the FAA’s flight test evaluates future SVS systems.

Supplemental Questions (Pilot Flying): Operational concerns, position awareness and runway alignment, communication.

1. Did you have or do you anticipate any operational concerns about the use of EFVS for takeoff in low visibility when operating the B737? Are there generalizations for other size aircraft that you are comfortable offering based on this exercise in a B737?

2. Given that there were several instrumentation configurations used for the takeoffs, please consider the following topics regarding the takeoff operations performed in the simulator.
    a. Do you think the repeater display the FO used in some trials was helpful? (yes / no)

        i. If 'yes,' which form of display would you prefer the FO to have?

            1. EFVS in HUD on FO side of cockpit.
            2. The head-down display used in this study.
            3. No preference; either would suffice.

        ii. If 'no,' what was your reasoning for your answer?

            1. Didn't feel it was necessary.
            2. Believed there should be one person looking out without the EFVS (same principle as having one pilot in night-vision goggles and one out).

<u>Position awareness</u>

3. Did you feel that you had sufficient information to verify your position on the runway and to take off effectively?
    a. Without the EFVS in HUD (yes / no)
    b. With the EFVS in HUD (yes / no)
4. How much did each of the following contribute to your positional awareness (in percent; must total 100)?
    a. Without the HUD EFVS (when it failed)
        i. Direct observation [out the windscreen only] of runway infrastructure (to include looking THROUGH the HUD at the outside world). ________%
        ii. Other information available in the cockpit. ________%
        iii. FO's verbal sharing of information ________%
    b. WITH the HUD EFVS
        i. Direct observation of the runway infrastructure ________%
        ii. The imagery on the HUD EFVS ________%
        iii. FO's verbal sharing of information ________%

iv. Other information available in the cockpit ________%

5. Did you feel that you needed any additional airport infrastructure, when using the HUD EFVS, to aid you in establishing your position awareness? If so, list in order of preference. [You may not know particular technical equipage names, but please give a general description of what would improve position awareness]

6. Did you feel that you needed any additional cockpit resources (information systems, displays, guidance indicators) to aid you in establishing your position on the runway? If so, list in order of preference.

<u>Runway Alignment</u>

7. Rate in general, on a 3-point scale, the following pieces of infrastructure as to their relative contributions in helping you maintain alignment with the runway centerline. Place in the parentheses a **<u>3</u> for a large contribution, <u>2</u> for a moderate contribution, and <u>1</u> for a small contribution**. In addition, **please place an X after the one that was most important** for maintaining alignment if you felt contributions were similar in some cases but that one stood out above the others.
   a. Painted runway centerline ________
   b. Edge lighting ________
   c. EFVS in HUD ________
   d. Other runway features ________ (please list)

<u>Communication</u>

8. How effectively do you believe information was communicated between you and the FO as a function of the FO having an EFVS repeater (head-down) display in place of the nav display?

   a. The same as when there was only the HUD EFVS on my side.
   b. Better with the FO having a repeater display.
   c. Worse with the FO having a repeater display.

Pilot Opinion Interview Questions (First Officer)

(EFVS for takeoff credit)

The following questions pertain to your use of certain display features in the simulator and to your willingness to perform takeoffs with and without these features in the real aircraft. Please circle the letter of your choice when appropriate or use the labeled scales on the other questions to circle a response that applies to each statement in this section.

1) What is the least equipage that you would be comfortable with for performing low-visibility takeoffs at RVRs less than 1000 feet?

    a. EFVS on left-seat HUD, no repeater for First Officer (FO)

    b. EFVS on left-seat HUD <u>with head-down repeater for FO</u>

    c. EFVS on dual HUDs

2) What is the lowest RVR that you would be willing to accept for takeoff for each of the following equipage conditions <u>given the EFVS performance in today's simulation</u>?

    <u>First,</u> circle the lowest RVR value that you would accept with that line's equipage. **<u>Second,</u>** mark in the parentheses to the right your ordered preference, as FO, for the equipage as 1 (first), 2 (second), and 3 (third). If you cannot rank order them or feel that they are not different enough in trms of safety/performance to be ranked, circle "NR" for "No Ranking."

    a. EFVS on left-seat HUD, no repeater for First Officer (FO) _______ NR

        RVR: 1000 700 500 300

    b. EFVS on left-seat HUD <u>with head-down repeater</u> for FO

        RVR: 1000 700 500 300 _______ NR

    c. EFVS on dual HUDs

        RVR: 1000 700 500 300 _______ NR

3) What is the <u>minimum</u> airport ilnfrastructure that you believe you would need at each value of RVR to conduct takeoffs safely (given today's experience in the simulator) **<u>WITHOUT EFVS</u>**? For each value of RVR on the left side of the table, circle below which parts of airport infrastructure that you believe **<u>you</u>** would need to have. Circle only

one type of edge lighting. This is for your crew position without regard to the Captain's position. You may circle as many or as few as you want in each row for each value of RVR.

	Infrastructure (airport and/or flightdeck)	
RVR	Centerline Lights	Edge lights
300 feet	CLL	MIRL / HIRL
500 feet	CLL	MIRL / HIRL
700 feet	CLL	MIRL / HIRL
1000 feet	CLL	MIRL / HIRL

4) What is the minimum airport iInfrastructure that you believe you would need at each value of RVR to conduct takeoffs safely (given today's experience in the simulator) **WITH EFVS**? For each value of RVR on the left side of the table, circle below which parts of airport infrastructure that you believe **you** would need to have. Circle only one type of edge lighting. This is for your crew position without regard to the Captain's position. You may circle as many or as few as you want in each row for each value of RVR.

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500 feet	CLL	MIRL / HIRL
700 feet	CLL	MIRL / HIRL
1000 feet	CLL	MIRL / HIRL

5) The current authorizations for low-visibility takeoffs without EFVS require the ability to see some feature or light 1600 feet distant ahead of the aircraft. If the sensor image (regardless of type of sensor; i.e., infrared, millimeter wave, etc.) in the HUD and/or on the head-down display could consistently show features/lights at 1600 feet ahead of the

aircraft, what would be your personal limit on the lowest actual RVR you could accept for takeoff if the authorization did not specify a lower limit?

a. 700 Feet
b. 500 feet
c. 300 feet
d. 150 feet
e. 0-0 conditions

6) Brightness/contrast: Please rate on the scale how you perceived the following on the head-down EFVS image.

a. Brightness - too dim…………..… ……….just right………………..too bright

1	2	3	4	5

b. Contrast - Not sufficient to…………........ok…………………..Excellent differentiate features

1	2	3	4	5

7) Field of view in the head-down display: I thought the field of view for EFVS in the HDD was –

Too narrow……………………ok…………………too wide

1	2	3	4	5

8) Training: What forms of training would you want to see for head-down EFVS use? Please rank order the following from 1 (most desired) to 6 (least desired)

	Ranking
Handbook (paper or electronic)	
Computer-based instruction	
Internet (on web site)	
Video (tape or DVD)	
Classroom	

Hands-on in flight simulator	

9) Did the head-down repeater of the EFVS facilitate your ability to assist, as FO, during the take off under the visibility conditions presented?

Not at all……………..Moderately…………….Significantly

1 2 3 4 5

10) If you were performing the takeoff as FO (pilot flying), would the head-down EFVS be sufficient or would you prefer to use a HUD-based EFVS image?
    a. HDD ok
    b. Would prefer HUD on right side of cockpit

11) Given your experience with the EFVS head-down display (as FO), please rate the EFVS picture/image for perceived overall reliability/accuracy and possible contributions to safety on the following scales:

	Poor	Below average	Above average	Excellent
Reliability/accuracy				
Safety contribution				

If you placed any ratings in the “Poor” or “Excellent” categories, please expand on which feature was responsible for that rating and why you rated it that way. Your explanation is crucial to our understanding the actual way in which pilots use these systems. How you use these systems will translate directly into how the FAA’s flight test evaluates future SVS systems.

Supplemental Questions (Pilot Monitoring): Operational concerns, position awareness and runway alignment, communication.

1. Did you have or do you anticipate any operational concerns about the use of EFVS for takeoff in low visibility when operating the B737? Are there generalizations for other size aircraft that you are comfortable offering based on this exercise in a B737?

2. Given that you had an EFVS repeater (head down) HUD for some of the takeoffs, please consider the following topics regarding the takeoff operations performed in the simulator.
    a. Do you think that the repeater display you used in some trials was helpful? (yes / no)
        i. If 'yes,' which form of display would you prefer to have?
            1. EFVS in HUD on FO side of cockpit.
            2. The head-down display used in this study.
            3. No preference; either would suffice.
        ii. If 'no,' what was your reasoning for your answer?
            1. Didn't feel it was necessary.
            2. Believed there should be one person looking out without the EFVS (same principle as having one pilot in night-vision goggles and one out).

<u>Position awareness</u>

3. Did you feel that you had sufficient information to verify your position on the runway and to take off effectively?
    a. Without the EFVS repeater display (yes / no)
    b. With the head-down repeater display (yes / no)

4. When you had the EFVS repeater on your side of the flight deck, how often did you visually refer to it (estimate)?
    a. Not at all
    b. Infrequently
    c. Roughly half of the time
    d. Frequently
    e. Constantly

5. How much did each of the following contribute to your positional awareness (in percent; must total 100)?

a. Without the head-down EFVS
    i. Direct observation [out the windscreen only] of runway infrastructure. ______%
    ii. Other information available in the cockpit. ________%
    iii. Captain's verbal sharing of information ________%
b. WITH the head-down EFVS display
    i. Direct observation of the runway infrastructure ________%
    ii. The imagery on the EFVS repeater ________%
    iii. Captain's verbal sharing of information ________%
    iv. Other information available in the cockpit ________%

6. Did you feel that you needed any additional airport infrastructure, when using the head-down EFVS, to aid you in establishing your position awareness? If so, list in order of preference. [You may not know particular technical equipage names, but please give a general description of what would improve position awareness]

7. Did you feel that you needed any additional cockpit resources (information systems, displays, guidance indicators) to aid you in establishing your position on the runway? If so, list in order of preference.

Runway Alignment

8. Rate in general, on a 3-point scale, the following pieces of infrastructure as to their relative contributions in helping you monitor (if you did so) alignment with the runway centerline. Place in the parentheses a **3 for a large contribution, 2 for a moderate contribution, and 1 for a small contribution**. In addition, **please place an X after the one that was most important** for maintaining alignment if you felt contributions were similar in some cases but that one stood out above the others.
    a. Painted runway centerline _______
    b. Edge lighting _______
    c. Other runway features _______ (please list)
    d. Not applicable. Monitored other information; Captain's responsibility to maintain alignment unless severe departure detected.

Communication

9. How effectively do you believe information was communicated between you and your Captain as a function of you having an EFVS repeater (head-down) display in place of the nav display?
    a. The same as when there was only the HUD EFVS on the Captain's side.
    b. Better with me having a repeater display.
    c. Worse with me having a repeater display.