

2020

Evaluating the effect of sensor limitations in flight vision systems on pilot performance

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**Evaluating the effect of sensor limitations in flight
vision systems on pilot performance**

by

Ramanathan Annamalai

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
Michael C. Dorneich, Major Professor
Cameron Mackenzie
Peng Wei

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2020

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TABLE OF CONTENTS

	Page
LIST OF FIGURES.....	v
LIST OF TABLES	viii
NOMENCLATURE.....	ix
ACKNOWLEDGMENTS.....	x
ABSTRACT.....	xi
CHAPTER 1. INTRODUCTION.....	1
1.1 Statement of Authorship	1
1.2 Objective	1
1.3 Equivalent Vision Operations	2
1.4 Problem Statement	3
1.4.1 Human Factors Implications.....	3
1.4.2 Sensor Limitations	4
1.5 Research Questions	6
1.6 Benefits	7
1.7 Approach.....	8
1.8 Thesis Roadmap.....	8
CHAPTER 2. RELATED WORKS.....	9
2.1 Sensor-based Flight Vision Systems.....	9
2.2 FAA Policies and Operation Requirements	10
2.3 Human Factors Issues	13
2.3.1 Pilot Performance	13
2.3.2 Workload	15
2.3.3 Attention Allocation	15
2.3.4 Situation Awareness	16
2.3.5 Decision Making.....	16
2.4 Sensor Capabilities and Limitations.....	17
2.4.1 Forward Looking Infrared Sensors (FLIR).....	18
2.4.2 Millimeter Wave Rader	20
2.4.3 Light Detection and Ranging (LIDAR)	21
2.4.4 Multispectral Sensors.....	21
CHAPTER 3. METHOD.....	24
3.1 Hypothesis.....	24
3.2 Participants.....	25
3.3 Tasks	25
3.4 Independent Variables.....	26
3.4.1 Visibility	26
3.4.2 Sensor Information Quality	27

3.5 Dependent Variables	30
3.5.1 Attention Allocation	31
3.5.2 Pilot Performance (Approach)	31
3.5.3 Pilot Performance (Landing)	32
3.5.4 Workload and Situation Awareness Assessment.....	33
3.5.5 Decision-Making	33
3.6 Experimental Design.....	34
3.7 Experimental Procedure	35
3.8 Testing Environment.....	36
3.9 Data Analysis Plan	37
CHAPTER 4. RESULTS	39
4.1 Pilot Performance (Approach)	39
4.1.1 Glideslope RMS.....	39
4.1.2 Localizer RMS	41
4.1.3 Sink Rate.....	44
4.1.4 Approach Airspeed	46
4.2 Pilot Performance (Landing).....	48
4.2.1 Distance away from Centerline.....	48
4.2.2 Distance away from Touchdown Markers.....	49
4.2.3 Vertical Speed at Touchdown.....	50
4.3 Overall Workload.....	51
4.4 Situation Awareness.....	52
4.5 Decision Making	53
4.5.1 Successful Decision to Land.....	53
4.5.2 Decision Height	55
4.5.3 Retrospective Interview on Decision Making	57
4.6 Attention Allocation.....	58
4.6.1 First Fixation.....	58
4.6.2 Altitude difference between First Cue Availability and First Fixation	59
4.6.3 Heat Maps	60
4.6.4 Total Scan Distribution.....	61
4.6.5 Transitions between HUD/OTW and PFD	66
4.7 IFR Experience.....	67
4.8 Summary Statistics.....	68
CHAPTER 5. DISCUSSION	71
5.1 Hypothesis 1	71
5.1.1 Approach and Landing Performance	71
5.1.2 Situation Awareness	72
5.1.3 Decision Making.....	72
5.1.4 Workload	72
5.2 Hypothesis 2.....	73
5.3 Hypothesis 3.....	74
5.4 Observations based on Attention Allocation.....	74
5.5 Observations within Sensor Information Quality	75

CHAPTER 6. CONCLUSION	76
6.1 Summary	76
6.2 Contributions	76
6.3 Limitations	77
6.4 Future Work	77
REFERENCES	78
APPENDIX. IRB STUDY MATERIALS FOR PILOT STUDY	82

LIST OF FIGURES

	Page
Figure 1. Enhanced Flight Vision System, Image from (AC 90-106A, FAA, 2017).....	10
Figure 2. Type I EFVS Operation (EFVS to 100 ft above touchdown zone (TDZ)),.....	11
Figure 3. Type II EFVS Operation (EFVS to Touchdown and Rollout),	11
Figure 4. IR sensor imagery, Image from (Thorsten, 2019).....	18
Figure 5. Thermally reversed IR sensor imagery, Image from (Thorsten, 2019)	19
Figure 6. RVR Levels.....	26
Figure 7. Simulated display at three levels of Sensor Information Quality: no sensor output (top), poor sensor output (middle), and good sensor output (bottom). Each image was captured at 100 ft AGL.	28
Figure 8. Simulated display in 1000 and 600 RVR.....	29
Figure 9. Counterbalancing of the six unique combinations of conditions (three levels of Sensor Information Quality and two levels of Visibility).....	35
Figure 10. Experiment Procedure.....	35
Figure 11. Testing Environment.....	37
Figure 12. Glideslope RMS for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error).....	39
Figure 13. Glideslope Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	41
Figure 14. Localizer RMS for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error).....	42
Figure 15. Localizer Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	43
Figure 16. Sink Rate for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error).....	44
Figure 17. Sink Rate Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	45

Figure 18. Approach Airspeed for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	46
Figure 19. Approach Airspeed Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error).....	47
Figure 20. Distance from Centerline for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	48
Figure 21. Distance from Touchdown Zone for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error).....	50
Figure 22. Vertical Speed at Touchdown for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error).....	51
Figure 23. Overall Workload for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	52
Figure 24. Overall Situation Awareness for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	53
Figure 25. Successful Decision to Land for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	54
Figure 26. Decision Height for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error).....	55
Figure 27. Decision Height Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error).....	57
Figure 28. First Fixation on cue, measured from AGL for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)	59
Figure 29. The difference in altitude between first availability and first fixation for two levels of visibility and three levels of sensor information quality	60
Figure 30. Heat Maps for all IV Combinations.....	61
Figure 31. Distribution of Pilot's Scan for IFR Segment for the combination of six IVs	63
Figure 32. Distribution of Pilot's Scan for Transition Segment for the combination of six IVs ...	64
Figure 33. Distribution of Pilot's Scan for VFR Segment for the combination of six IVs.....	65
Figure 34. Distribution of Pilot's Scan for Total Scan duration for six IV combinations (Error bars represent the standard error).....	66

Figure 35. Total Transition among PFD and HUD/OTW for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error) 67

Figure 36. Pilot's IFR Experience 68

LIST OF TABLES

	Page
Table 1. Dependent Variables	30
Table 2. Landing Decision Table	34
Table 3. Landing Decision exceedances for two levels of visibility and three levels of sensor information quality.....	54
Table 4. Summary Statistics for Dependent Variables.....	68
Table 5. Exceedance Summary (%)	70
Table 6. Bowker's Test Summary	70

NOMENCLATURE

EFVS	Enhanced Flight Vision System
EVO	Equivalent Vision Operations
HUD	Heads-up Display
OTW	Outside the window
IFR	Instrument Flight Rules
VFR	Visual Flight Rules
IAP	Instrument Approach Procedure
FAA	Federal Aviation Authority
SA	Situation Awareness
HF	Human Factors
GA	General Aviation
DA/DH	Decision Altitude/Decision Height
FPM	Feet Per Minute
RMS	Root Mean Square
PFD	Primary Flight Display
AGL	Above ground level
MMWR	Millimeter Wave Radar
FLIR	Forward Looking Infrared
LiDAR	Light Detection and Radiation
PAPI	Precision Approach Path Indicators
RTL	Runway Threshold Line

ACKNOWLEDGMENTS

I would like to thank my graduate advisor and guru, Dr. Michael Dorneich for guiding and supporting me throughout my master's program. Also, I would like to thank the rest of my committee members, Dr. Cameron Mackenzie, and Dr. Peng Wei for supporting my thesis work. Without my parents, this journey is not possible for me. Especially my mother, for her encouragement to pursue my master's program in the U.S.

Also, I would like to thank my friends in Iowa for their encouragement, positivity, and tremendous support throughout my master's program. Finally, I want to express my gratitude to faculties and staff at the IMSE Department, pilot participants who took part in my study, and ACSL colleagues for making my time at Iowa State University a wonderful experience.

ABSTRACT

Sensor-based flight vision systems enable approaches to altitudes closer to the runway that would otherwise be precluded due to low visibility ceilings. These systems have the potential to augment the safety in flight operations and enable improved crew performance irrespective of the visibility conditions. The sensor-based flight vision system utilizes imaging sensors capable of penetrating through obscuring weather conditions, thereby providing forward vision of the runway environment in real-time for display on a heads-up display (HUD). As the use of sensor-based flight vision system is likely to increase in general aviation operations due to recent FAA policy revision, it is necessary to evaluate the associated human performance implications, especially during off-nominal conditions. Most of the previous studies were primarily limited to nominal cases and the assessment on off-nominal cases was limited only to HUD failures though the sensors integrated to these systems can produce degraded sensor output concerning atmospheric conditions. So, the objective of this thesis is to evaluate the human factors implications in using the flight vision system displaying poor sensor output. A pilot-in-the-loop experiment was conducted in a fixed-base flight simulator modeled with the sensor-based flight vision system. Evaluation pilots flew six different experimental trials with two visibility levels (i.e. 600ft RVR and 1000ft RVR) and three levels of sensor information quality (i.e. none, poor, and good sensor output). Measures of performance include approach and landing performance, attention allocation, workload, and decision-making. The experiment results indicated that the pilot's landing performance and decision making were negatively impacted by poor sensor output. Neither workload nor situation awareness was impacted. Attention allocation results show that pilots had utilized the precision approach path indicator (PAPI) and runway threshold line (RTL) for touchdown operations and fixating on RTL was critical to avoid incorrect landing decisions.

CHAPTER 1. INTRODUCTION

1.1 Statement of Authorship

Portions of Chapter 1-3 of this thesis work has appeared in Annamalai, Dorneich, and Tokadli (2019). Güliz Tokadli has contributed to the initial experimental design of the pilot study, contributed to the questionnaire design, and obtaining IRB approval for the pilot study. Ramanathan Annamalai performed the literature review, designed the flight simulations, developed the experimental design, conducted the pilot study, conducted the data analysis and results interpretation, and authored the conference paper. All these above-mentioned tasks were performed under the guidance of Dr. Michael Dorneich.

1.2 Objective

Sensor-based flight vision systems utilize sensor-based information to present pilots with an enhanced view of the outside environment in degraded visual conditions. Such systems enable aircraft approaches to continue to altitudes closer to the runway that would otherwise be allowed due to low visibility and ceilings. These imaging sensors produce images of the forward scene of external topography. The use of such systems can enable all-weather approaches and landings, irrespective of the visibility conditions. In 2016, the FAA revised its existing policy on conducting approaches using these sensor-based flight vision systems, such as Enhanced Flight Vision Systems (EFVS); allowing pilots to land solely utilizing the resulting imagery displayed. The expected use of a sensor-based flight vision system is likely to increase in general aviation (GA) operations due to this policy revision (FAA, 2016). It is necessary to evaluate the associated human factors implications, especially during off-nominal conditions. Previous studies were primarily limited to nominal cases, and the only off-nominal cases tested were limited to HUD failures (Arthur et al., 2013; Kramer et al., 2014; Etherington et al., 2015). The thesis explores the human factors

implications of sensor limitations when using sensor-based flight vision systems, specifically the impact on pilot performance.

1.3 Equivalent Vision Operations

General Aviation (GA) flight operation includes business, sightseeing, freight services, search and rescue, medical evacuation, and encompasses 370,000 aircraft ranging from gliders to corporate business jets to million pilots worldwide. Almost 80% of the aviation accidents occur in GA operation, with a fatality rate of 6.51 per 100,000 flight hours and 645 fatalities annually (NTSB, 2014). In the United States, the average annual cost associated with GA accidents ranges from 1.5 to 4.5 Billion USD per annum. Bad weather is the primary instigating factor for GA accidents, accounting for 23% of fatalities (15,439 of 58,687) and 70% of flight delays (Fultz and Ashley, 2013).

Low ceilings and low visibility are the leading contributing factors in GA accidents (with 27% of overall fatalities). Low visibility and low ceilings impact the pilot's ability to develop and maintain situation awareness to ensure the continuation of safe, efficient air and ground operations. Moreover, small GA aircrafts are not equipped with advanced onboard technologies to support crew performance due to their cost, size, and power constraints. In a typical low visibility operation, pilots must be able to observe the runway marking at the mandated decision height to continue the approach. In other words, they must be able to transition from Instrument Flight Rules (IFR) to Visual Flight Rules (VFR) at the proscribed decision height to descend under Instrument Approach Procedure (FAA, 2005). If the crew is not able to obtain the appropriate visual cues, i.e. sight of runway elements such as centerline markings, runway lights, etc. from the established decision height (DH), the crew must initiate the missed approach or go-around procedure.

The U.S. air transportation seeks to improve the safety and reliability in the Part 91 GA Operations through technologies that enable equivalent vision operation (EVO) (Joint Planning and

Development Office, 2008). Successful implementation of EVO is challenged by the installation of advanced equipment within the cockpit or the development of airport infrastructure. Implementation of EVO requires precise navigation, surveillance, and precision guidance systems for the “all-weather” approach and landing. The sensor-based flight vision system is designed to detect the runway element using real-time imaging sensors such as millimeter-wave radar (MMWR), forward-looking infrared (FLIR), and Light detection and ranging (LiDAR) to provide an enhanced vision of the forward topography irrespective weather conditions. This forward vision technology aid in flight operations for commercial, business, and GA purposes. The sensor information is processed, and the enhanced forward scene is conformally presented on a heads-up display (HUD) overlaid with flight symbols (flight path vector, airspeed, headings, pitch, and altitude). In 2016, the FAA has revised its existing regulations on one of the sensor-based flight vision system called Enhanced Flight Vision System (EFVS) and mandated additional requirements within CFR §91.176 that enables pilots to perform the touchdown and rollout operations, relying solely on the sensor imagery (FAA, 2017). Overall, the potential to augment flight safety and improve crew performance as these systems provide the equivalent visual cues needed to operate in low visibility conditions (Etherington, Kramer, Severance, Bailey, Williams & Harrison, 2015).

1.4 Problem Statement

1.4.1 Human Factors Implications

Between 2004 and 2016, NASA has conducted several flight tests and simulator-based studies to evaluate various aspects of sensor-based flight vision systems for nominal and off-nominal cases. These studies could be grouped into several human factors issues such as pilot performance, workload, situation awareness, decision making, and attention allocation. With respect to nominal cases, EFVS has shown to increased pilot performance with no negative impacts. Moreover, EFVS did not impose any workload concerns and it did not negatively impact pilot

decision making. For off-nominal cases, a simulation-based study raised some concerns with the pilot's situation awareness with respect to loss of HUD information and obstacle detection using flight vision system (Kramer et al., 2013). Pilot's attention distribution between the HUD/OTW and PFD when using sensor-based flight vision systems could negatively impact the pilot's situation awareness. Overall, previous studies on flight vision systems for off-nominal cases did not investigate any human performance implications related to sensor limitations. Most of the previous works on flight vision systems were conducted on actual flights and due to safety concerns, these limitations were not explored.

1.4.2 Sensor Limitations

Flight vision systems utilize primarily three types of sensors. They are as follows:

- **MMWR:** Millimeter Wave Radar (MMWR) could be a passive imaging system, utilizing a camera that detects energy, but active systems are more suitable for flight use. The ideal range resolution for MMW radar is from 0.25 meters up to 3 meters, with 3° to 4° of angular resolution (Abou-Jaoude, 2003).
- **LIDAR:** Light detection and ranging (LIDAR) system is an active sensing system, utilizing a pulsed laser to illuminate a target and the return from that laser is detected by a sensor. LIDAR has a very high precision (a few mm to a few cms) compared with other sensors, but relatively short-range (< 1km) at the power levels that would be approved for flight use.
- **FLIR:** Forward Looking Infrared is a passive sensor, widely used in military and civil aircraft to enhance visibility as it provides good contrast under night, fog, and haze conditions, and is one of the inexpensive sensor technologies for aviation purpose

(Todd, Hester, & Summers, 1992). FLIR cameras can have ranged over 10km and have a wider field of views.

In some cases, dual-sensor technology is employed where pilots utilize the combined outputs of two sensors (i.e. MMWR and IR sensor) to identify the runway terrain (Kramer et al., 2016).

Each of these sensors has limitations that could produce poor or low-resolution sensor imagery concerning specific atmospheric conditions. MMWR sensors works well for most of the operationally relevant atmospheric conditions, but the images are not as high resolution as natural vision (Etherington et al., 2015). For MMWR sensors, the low-resolution sensor imagery is due to atmospheric attenuations, when operated at or below 60 GHz frequencies (Skolnik, 2008). Flight vision systems displaying low-resolution output are likely to impact the crew's decision making and performance during landing phases of flight as the runway is indistinguishable for touchdown and rollout operation.

The infrared sensor works on the temperature difference of a target object. In the case of flight vision systems, IR sensors measure the surface temperature of the runway and its surrounding area to differentiate between them. During the day, the runway/taxiways can be hotter than the surrounding ground. At night, the runway can be colder than the surrounding ground. Thermal reversal is the moment when the temperature differential reverses between the runway and the surrounding ground (Yang and Hansmen, 1994). When the surface temperature of the runway is close or equal to its surrounding area, IR sensors cannot distinguish between the two surfaces. This limitation within the IR sensor adds concerns during landing phases such as touchdown on surrounding grass, running into obstacles, and steep landings. Other important sensor-based issues will be discussed in detail under the background section.

Though sensor-based flight vision systems have demonstrated improvements in pilot performance, resulted in lower workload levels and better decision making, most of these studies were performed for nominal cases and minimal exploration was done on the off-nominal side. This motivates a dedicated study to evaluate the associated human performance implications in using flight vision systems during off-nominal cases associated with degraded sensor output. Thus, the objective of the thesis is to investigate the human performance implications (i.e. pilot's approach and landing performance, decision-making, workload, situation awareness, and attention allocation) on collaborating with sensor-based flight vision systems displaying degraded sensor imagery.

1.5 Research Questions

This thesis specifically examines the impact of degraded sensor imagery (such as that due to thermal reversals) in the IR-based vision system on pilot performance (approach and landing), attention allocation, workload, situation awareness, and decision making. The following research questions are proposed.

1. *What is the effect on pilot's decision to land due to degraded sensor imagery in flight vision systems?*

Degraded sensor imagery could pose a challenge for pilots to distinguish among the runway and surrounding. The level of reliance on sensor-based imaging systems may or may not be affected, either appropriately or inappropriately, when pilots make the decision to go-around vs. proceed with the landing. A comparison of the decision height for the flight vs. height at which pilots made their decision are key parameters to be identified.

2. *What are the impacts of degraded sensor imagery on the pilot approach and landing performance?*

Previous studies have reported that sensor-based flight vision systems have improved pilot performance. This is a two-way comparison between having a sensor-based system and not having a sensor-based system. This question would be an extension of the baseline test to evaluate performance among three cases; an appropriate sensor-based flight vision system, sensors output impacted with the thermal reversal, and normal out-of-the-window view.

3. *How the pilot's workload and situation awareness are impacted by utilizing flight vision systems displaying degraded sensor imagery?*

Previous studies have reported that flight operations utilizing sensor-based systems have reported moderate, easily managed, workload with no situation awareness (SA) concerns (Kramer et al., 2011). Comparing the workload and SA levels among good and poor sensor output (degraded) cases will inform the degree to which pilots were challenged by sensor limitations.

1.6 Benefits

From 2004 to 2016, several studies have explored the effectiveness of sensor-based flight vision system for nominal cases (Arthur, Kramer, & Bailey, 2005; Bailey et al., 2010; Kramer et al., 2015; Kramer, Ellis, et al., 2014; Kramer et al., 2017). However, none of the studies have investigated the impact of sensor limitations in a flight vision system over pilot performance and decision making. This study is specifically exploring the potential impact of degraded sensor output due to phenomenon such as thermal reversal. Degraded sensor imagery might challenge the operator in differentiating the runway visually at the prescribed decision height. Furthermore, this study evaluates pilot performance at 1000 RVR and 600ft RVR. The 2016 rule change authorized operators to make use of EFVS to completely perform touchdown and landing operations irrespective of RVR levels. On successfully validating the study hypothesis, we could

- Derive insights on the impact of degraded sensor imagery over the pilot's attention allocation such as cue fixation, cue availability, landing decision altitude.

- Determine critical human factor issues (performance, workload or situation awareness) on utilizing flight vision system displaying degraded sensor output
- Provide recommendations on expected landing decisions to be taken at 600ft RVR on collaborating with flight vision systems displaying degraded sensor output

1.7 Approach

A pilot-in-the-loop study has been conducted to investigate the adverse effect of degraded sensor imagery in a sensor-based flight vision system over pilot performance during landing and approach. The simulations were designed to represent a flight vision system with HUD symbols as recommended by the FAA under AC 90-106A. General Aviation, IFR-rated, Pilots performed landing and approach tasks in a simulated environment. These tasks were designed for three varying levels of sensor image quality: No sensor output (no flight vision system), poor sensor output (degraded runway imagery), and good sensor output (fully functioning flight vision system). These three levels of sensor imagery were tested each at two varying levels of runway visibility range (RVR): 600ft and 1000ft. The outside-of-the-window (OTW) visibility levels were chosen to represent CAT II and CAT III flying conditions prescribed under IFR. The dependent variables are chosen to capture attention allocation, pilot landing & approach performance (as specified in Airmen Standards for Instrument approach), situation awareness, and workload.

1.8 Thesis Roadmap

Chapter 2 will discuss previous work relevant to the research questions. Chapter 3 will discuss the method of human-in-the-loop evaluation. Chapter 4 presents the results of the evaluation. Chapter 5 presents a discussion of the evaluation results. Chapter 6 presents a summary of the work, contributions, and suggestions for future work.

CHAPTER 2. RELATED WORKS

The objective of this study is to evaluate the human performance implications associated with using a flight vision system when impacted by sensor limitations. This study will evaluate the effects of utilizing flight vision systems with degraded or poor sensor imagery on a pilot's approach and landing performance, decision-making, workload, situation awareness, and attention allocation. This chapter describes the current state of the science in sensor-based flight vision systems as well as the associated human factors implications of their use. Moreover, this section discusses some sensor limitations which compromise the representational consistency of the resulting imagery displayed to pilots.

2.1 Sensor-based Flight Vision Systems

A flight vision system that has been operational for quite some time is Enhanced Flight Visions Systems (EFVS). EFVS uses onboard sensor systems to detect visual cues in the forward environment (Fig 1). The sensor information is processed and presented on a HUD to conformably display the sensor output overlaid for the pilot's out-of-the-window (OTW) view. The EFVS sensor produces an image of the outside scene which pilots use to develop a 3-D interpretation of the outside world (Korn, 2007). Before the introduction of EFVS, the pilot would fly an Instrument flight rules (IFR) approach (i.e., utilize their glideslope and localizer information to fly their aircraft). However, for a pilot to decide to land, they must transition from IFR to Visual flight rules (VFR) before a prescribed decision altitude (DA) / decision height (DH). Pilots must be able to visually identify cues such as runway elements to descend below DA/DH and proceed for landing.

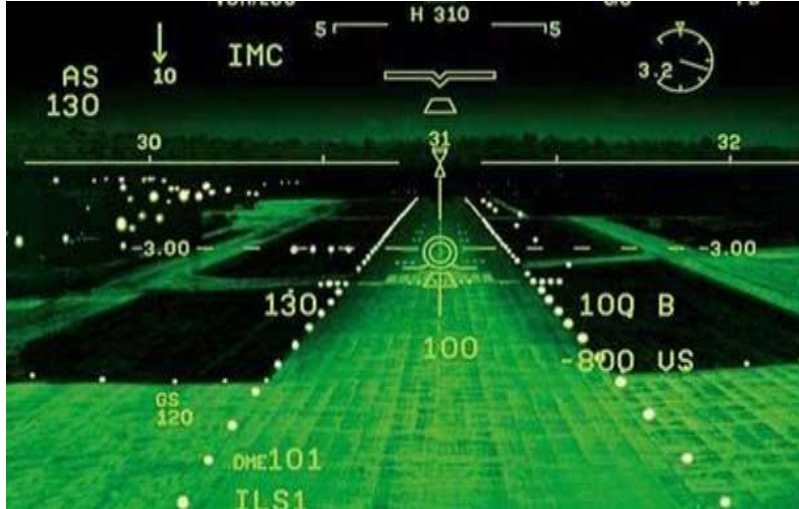


Figure 1. Enhanced Flight Vision System, Image from (AC 90-106A, FAA, 2017)

In a normal flight operation, the flight path segment from 1000ft to DH is called the *instrument segment* and from DH to touchdown is called the *visual segment*. EFVS is employed in the visual segment of an instrument approach where the pilot must acquire the visual cues needed to continue the approach. EFVS systems are aircraft-based and do not require airport infrastructure. EFVS offers an enhanced vision of the forward topography with the help of real-time imaging sensors such as millimeter-wave radar (MMWR), forward-looking infrared (FLIR), and light detection and ranging (LiDAR). EFVS is a head-up display (HUD) based guidance/navigation system, supports the pilot during low visibility approach and landing (AC 90-106A, FAA, 2017). The effectiveness of EFVS is determined by its visual advantage factor. The visual advantage factor is the ratio of the distance a pilot could see using an EFVS (enhanced flight visibility) compared to the distance the pilot can see without the use of the EFVS (flight visibility). Based on a NASA study, the visual advantage factor is ranged between 2 to 3 (Kramer et al., 2014)

2.2 FAA Policies and Operation Requirements

In 2004, the FAA amended Title 14 of the US Code of Federal Regulations (CFR) 91.176 to authorize operators conducting straight-in instrument approach procedures to operate below the

published Decision Altitude (DA)/Decision Height (DH) when using an FAA certified EFVS (Figure 2). This regulation permits pilots to make use of EFVS up to 100ft above touchdown.

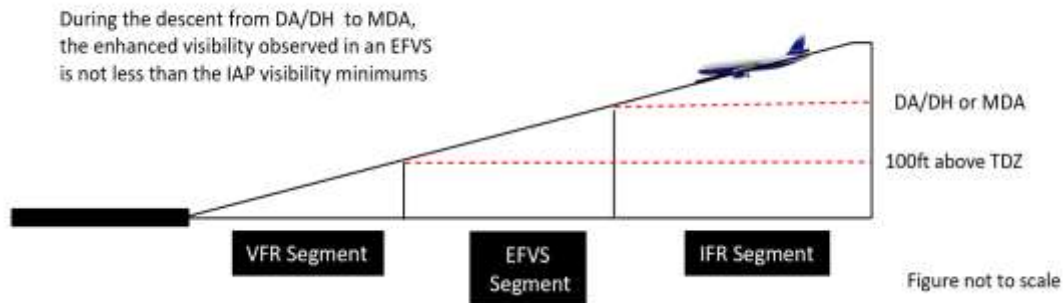


Figure 2. Type I EFVS Operation (EFVS to 100 ft above touchdown zone (TDZ)),
Image from (based on FAA, 2020)

In 2016, the FAA revised its existing regulations on EFVS and mandated additional requirements within CFR §91.176 that enables pilots to perform the touchdown and rollout operations (Figure 3Figure 2), relying solely on the EFVS sensor imagery (FAA, 2017).

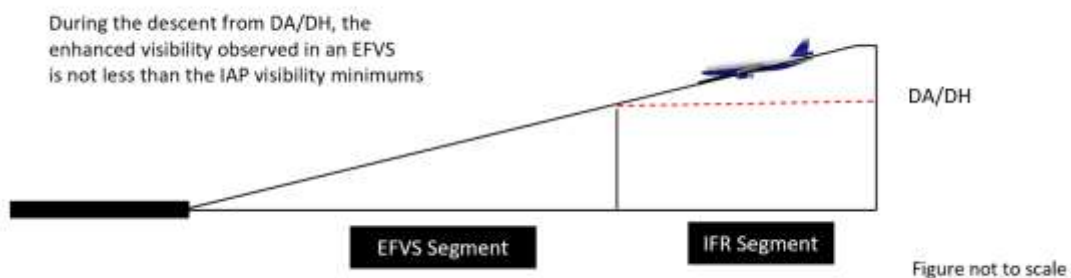


Figure 3. Type II EFVS Operation (EFVS to Touchdown and Rollout),
Image from (based on FAA, 2020)

The new regulation does not impose RVR minimum but rather limited to 1000 ft runway visual runway (RVR) as airworthiness and certification criteria to support EFVS operations below 1000 ft RVR have not been developed (Etherington, 2015). This revision enables the use of EFVS

in a wider range of operations in GA operations. Thus, EFVS has the potential to augment flight safety as it provides the equivalent visual cues needed to operate in low visibility conditions (Etherington, Kramer, Severance, Bailey, Williams & Harrison, 2015). The EFVS improves safety by enhancing situation and position awareness, allowing pilots to conduct a stabilized approach, and reducing the number of missed approaches. Moreover, the FAA revised its existing regulations and mandated additional requirements in §91.176 for EFVS that enables pilots to perform the touchdown and rollout operations, relying solely on the EFVS sensor imagery (FAA, 2017). This revision enables the use of EFVS in a wider range of operations, especially in GA operations.

Pilots are approved to use EFVS based on regulation laid out in §91.176 for flying straight-in approaches and, potentially, landing. According to §91.176,

EFVS must:

- Display the EFVS information aligned with and scaled to the external scene topography, along with flight information and other symbology as specified in §91.176, on a heads-up display.
- Display a flare prompt or flare cue for fixed-wing aircraft (only if using the EFVS to descend below 100 feet and complete the touchdown and rollout).

One of the important rules for EFVS operation is the visual requirements for approach and landing. The flight vision system should display similar required visual cues for the pilot during approach and landing as during an approach without EFVS. Those cues are specified in §91.176(a)(3), §91.176(b)(3) and are explained in AC 90-106 which requires that:

For Type 1 EFVS operation (descent below decision height or MDA), the following references must be visible using the EFVS:

- The approach light system (ALS); or

- The runway threshold, identified by the beginning of the runway landing surface, the threshold lights, or the runway end identifier lights; and
- The touchdown zone (TDZ), identified by the runway TDZ landing surface, the TDZ lights, the TDZ markings, or the runway lights

For Type II EFVS operation (descent below 100 feet above the TDZ to touchdown and rollout), at least one of the following must be visible using the EFVS:

- The runway threshold.
- The lights or markings of the threshold
- The runway touchdown zone landing surface; or
- The lights or markings of the touchdown zone.

2.3 Human Factors Issues

The Vehicle Systems and Safety Technologies (VSST) program organized by NASA's Aviation Safety Program, has designed and conducted numerous evaluation of interface technologies such as EFVS and SVS to increase the pilots' situation awareness and established training programs to recover from adverse events which might lead to catastrophic accidents (Lynda, Etherington, Severance, Bailey, 2016). Between 2004 and 2016, NASA has conducted several flight tests and simulator-based studies to evaluate various aspects of the sensor-based flight vision system. These studies focused on human factors and system performance issues such as pilot performance, visual advantage, operational feasibility, and workload for varying visibility conditions.

2.3.1 Pilot Performance

Several flight tests conducted by NASA have analyzed pilot performance measures such as landing vs. go-arounds (Kramer, Harrison, et al., 2014), lateral and vertical landing position

(Bailey et al., 2010; Kramer et al., 2015; Kramer, Ellis, et al., 2014; Kramer et al., 2017), sink rate (Kramer et al., 2015; Kramer et al., 2017), airspeed variations (Kramer et al., 2017), and flight path, localizer, and glideslope deviations (Arthur, Kramer, & Bailey, 2005; Kramer et al., 2015; Kramer et al., 2017). These studies were flight tests performed under nominal conditions and demonstrated improvements in pilot performance while using flight vision systems for conducting approach and landing operations. NASA has also tested a few off-nominal scenarios such as EFVS and HUD failure, insufficient enhanced flight visibility to land. Two EFVS and HUD failure run (one in 1000 ft RVR and one in 700 ft RVR) were conducted and crews were not informed of this event in advance. In the 1000 ft RVR EFVS failure condition, 11 of 12 crews inappropriately landed despite complete loss of the HUD symbology and FLIR imagery. For the 700 ft RVR EFVS failure condition, 10 of 12 crews inappropriately decided to land when HUD symbology and FLIR imagery failed below DH. In the post-experiment interview, the pilot's reported that despite EFVS HUD failure occurs, there was enough outside visibility to safely complete the landing. Likewise, for insufficient enhanced flight visibility on 700 ft RVR, 10 of the 12 flight crews made the inappropriate decision to land when EFVS-HUD did not provide enough visual flight references at the DH and 100 ft AGL. In post-experiment interviews, pilots reported that they have decided to land because they felt that they had enough information based on the visual cues provided before they reached the 100ft HAT decision height. Overall, the pilot lateral performance was impacted with respect to RVR in the presence of EFVS failure. However, other performance factors such as sink rate, touchdown position, or distance away from centerline were not impacted due to EFVS failure (Kramer et al., 2013).

2.3.2 Workload

Previous NASA studies on flight vision system did not report any major workload concerns (Kramer et al., 2014), (Arthur et al., 2013). But another flight test was conducted to test all-weather approach and landing using “ADVISE-PRO” (Advanced visual system for situation awareness enhancement – a prototype enhanced and synthetic vision system). The test result indicated a high workload on pilots while transitioning between HUD and outside of the window view (Korn, 2007).

2.3.3 Attention Allocation

Pilot’s attention allocation is a cognitive process of selectively focusing on certain flight information while ignoring other perceivable information to accomplish the tasks. Attention allocation is impacted by factors such as visual clutter (disorderly representation of heads-up symbology which leads to performance degradation and confusion), attention fixation (inattentiveness to outside scene events while focusing on heads up display elements) and field of view (visually observable area of HUD). The flight test conducted using Advice Pro investigated the pilot’s visual clutter and attention fixation (Korn, 2007). Results indicated that the pilot’s transition between HUD and outside of the window view impacted their attention fixation, landing performance, and decision-making. NASA has also explored the minimum field of view requirement for HUD in an EFVS system. Three different field-of-view were utilized for this study; wide-angle (48 deg), normal (23 deg), and telephoto (11 deg) resulted in an angular magnification factor of 0.34, 0.73, and 1.55 respectively (Bailey, Kramer, & Williams, 2010). The post-experiment assessment revealed that certain phases of flight became increasingly difficult and the pilot’s ability to control the flight was reduced with decreasing field-of-view. Data analysis also reveals that the display reduction or magnification of the HUD field of view has a significant effect on pilot performance. NASA also conducted a pilot-in-the-loop study with runway visibility range

(RVR) set at 500 ft with full dark conditions (Arthur, 2013). This study has investigated aspects such as HUD locations and parallax effects associated with utilizing flight vision systems. No significant performance, workload, or situation awareness was determined in the nominal HUD position. Also, participants reported that they were highly distracted when conformal symbology was not aligned with the OTW imagery.

2.3.4 Situation Awareness

A Rockwell-Collins simulator study investigated the impact on the pilot's performance and situation awareness due to an EFVS-HUD failure (Etherington et al., 2015). Results indicated that pilots did not perform a go-around when the HUD was intentionally failed by the experimenters well above decision height (DH). The crew ignored the failure messages displayed in the HUD. This suggests that the situational awareness of the pilot above and below the DH needs to be assessed for different flight vision systems and subsystem failure modes. When the auxiliary display was set at a 90-degree outboard to the flight crew, it causes degradation in workload, situation awareness, and reduced acceptability.

2.3.5 Decision Making

Flight tests conducted at Cambridge-Dorchester Airport (KCGE) using Kollsman Enhanced Vision System (EVS-I) infrared camera assessed pilot's cross-track and altitude deviation during the final approach to evaluate performance (McKinley, Heidhausen, Cramer, & Krone, 2008). Results confirmed the safety to conduct down-to-the-runway approaches except in one instance, the pilot briefly misjudged the runway at decision height as a taxiway. But the overall field pavement pattern has guided the pilot with alignment cues. This indicates the possibility of real-time misinterpretation of sensor imagery displayed to pilots. A NASA study also assessed pilot decision making when using a flight vision system. Specifically, pilots were evaluated on their

ability to correctly complete or abort an approach and landing, as well as successfully handle a runway incursion by a fire truck (Kramer et al., 2009). No significant effects on decision making were identified. A NASA study was conducted to assess the pilot's efficacy and decision making in utilizing sensor-based systems for non-normal operations (Prinzel, Lawrence, Kramer, Bailey, 2007). The non-normal scenario has two obstacles simulated on the runway, (i.e baggage cart and firetruck). Out of 12 flight crews, only one team was able to identify the baggage and all 12 of them have identified the fire truck. Eleven flight crews have proceeded to land despite a baggage cart was present on the runway. This indicates that the detection of small size object (baggage cart) was extremely difficult for pilots due to the low resolution of HUD.

Overall, it can be observed that the pilot's performance, workload, and situation awareness were least impacted during nominal cases. For off-nominal cases, the implications of the poor image quality or the resolution of the flight vision system's sensor output over pilot performance were not explored.

2.4 Sensor Capabilities and Limitations

This section discusses three different types of sensors integrated to flight vision system (forward-looking infrared (FLIR), millimeter wave radar (MMWR), light detection and ranging (LiDAR)), and multispectral sensors and the associated capabilities and limitations with each sensor type. The limitations result in a decrease in the information quality of the resulting imagery being displayed. According to the framework developed by Wang and Strong on information quality, there are four criteria for representing high-quality data, i) data should be intrinsically good, ii) contextually appropriate for the task, iii) clearly represented, and iv) accessible to the data consumer (Wang & Strong, 1996). In case of flight vision systems, it is appropriate to consider the

information quality of the representation of sensor output. This thesis explores how the representational information quality of the sensor imagery affects pilot performance.

2.4.1 Forward Looking Infrared Sensors (FLIR)

Forward Looking Infrared (FLIR) sensors detect the infrared radiation of the objects and motion of objects. In case of flight vision systems, they tend to be passive and utilizes a technique called the iHot spot technique. This technique considers the infrared radiation of the target object. In this case, the runway and its markings are the target object and it is differentiated from its surrounding grass area. The iHot spot technique would focus on the terrain with the higher thermal energy or assuming a great difference in thermal energy occurs between the runway and the surrounding area (Yilmaz, Shafique et al., 2003). This assumption enables IR sensor to eliminate unnecessary information being displayed to pilots view and highlight the slightly warmer runway terrain instead of a colder grass surrounding as shown in Figure 4 (Yilmaz, Shafique et al., 2003)

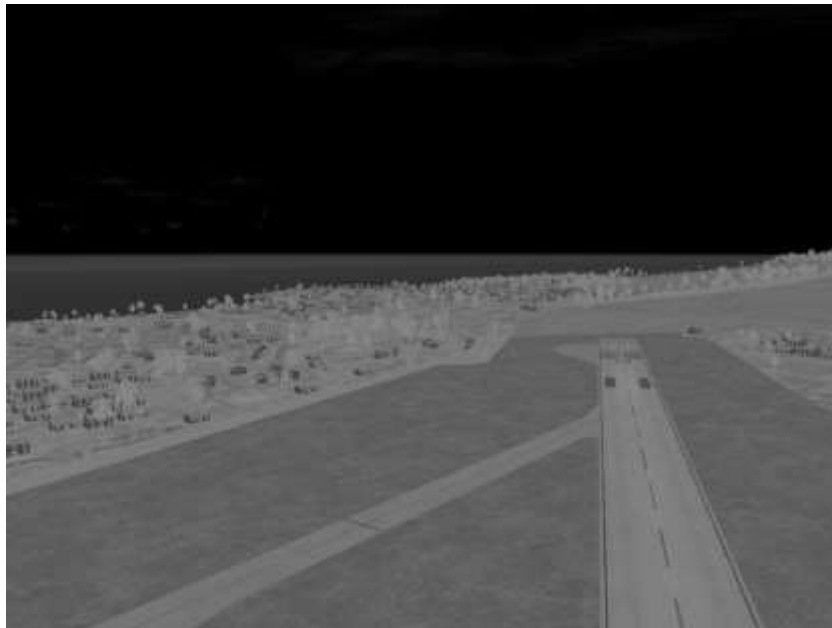


Figure 4. IR sensor imagery, Image from (Thorsten, 2019)

While IR functions well during smoke and haze, it has degraded performance in fog, rain, and snow as it can severely impact thermal imaging systems. Degradation occurs due to the scattering of light off droplets of water. The higher the density of droplets, the more the infrared signal is diminished (Beier and Gemperlin, 2004, Brooker, Birch et al., 2004, Etherington et al., 2015). Furthermore, sensor output based on temperature differences between the runway and the adjacent ground is subjected to thermal reversals. For instance, the runway image presented to the pilot during the day will show that the runway is hotter than the grass surrounding it. At night, this temperature differential is reversed as the runway is colder than the surrounding grass. Thermal reversal is the moment when the temperature differential reverses between the runway and its surrounding ground. When the surface temperature of the runway is close or equal to its surrounding area, IR sensors cannot distinguish between the two surfaces as shown in Figure 5. This could occur twice a day, during sunrise and sunset.



Figure 5. Thermally reversed IR sensor imagery, Image from (Thorsten, 2019)

This phenomenon could lead pilots to conduct a landing in the grass instead of the runway (i.e. touchdown on surrounding ground), running into obstacles, and steep landings (Yang and Hansmen, 1994).

2.4.2 Millimeter Wave Rader

Millimeter wave radar operates on the principle of electromagnetic emissions from a transmitter and detecting the return signal. The sensory imagery generated is a depiction of return signals scattered back from the ground. They are widely utilized for tracking objects and some basic imaging uses. The operating frequency of MMWR varies from 3 MHz to well over 300 GHz (Skolnik, 2008). With the atmospheric attenuation predominately occurring around 60 GHz, it is desirable to operate MMWR around 94 GHz or 76-77 GHz, as most MMW radars can see through some weather phenomena when operated at this frequency range (Yang and Hansen, 1994)

In case of flight vision systems, the MMWR sensor works well for most of the operationally relevant atmospheric conditions, but the images are not as high resolution as natural vision (Etherington et al., 2015). Also, an active MMW-radar yields information regarding the range and azimuth (viewing angle) of an object. This information can be transformed to obtain a perspective view of the outside world, but there is a lack of information about the object's height or vertical position. MMWR sensor is also inoperative at certain bandwidth where they would not produce any information at certain bandwidth (80 GHz for oxygen and 200 GHz for H₂O) during rain and fog as frequency absorption occurs (Foyle, Ahumada, Larimer, & Sweet, 1992). The performance of the MMWR sensor is generally measured through image contrast. Contrast is the ratio of the difference in signal between runway and background divided by the background signal, and thus the ratio varies from -1 to 1. The signal level refers to the amplitude of the calibrated sensor. If the signal level of runway and background has no significant difference (zero contrast), then flight

vision system cannot detect the runway; negative numbers indicate contrast of the runway is darker than the surrounding terrain; and larger positive numbers indicate contrast of the runway is brighter than the surrounding terrain (Burgess, Chang, Dunford, Hoh, Home, & Tucker, 1993). From a tower test on MMWR sensor performance (Burgess et al., 1993), it was determined that the acceptable contrast range for MMWR sensor imagery lies between -0.6 to -0.8 on a clear day and the contrast for unacceptable degraded sensor imagery is ranged between -0.2 to -0.6 on a foggy day. This is a clear limitation that the MMWR sensor is likely to produce degraded imagery on foggy conditions.

2.4.3 Light Detection and Ranging (LIDAR)

Light detection and ranging (LiDAR) is a sensor technology that utilizes a pulsed laser to illuminate the target object and the return light is detected by a sensor. In case of flight vision system, a series of laser scans over the external topography ensures a clear depiction of external terrain for pilots. Also, combining the detected outputs to the global positioning system provides an accurate representation of runway terrain (Campbell et al., 2003). LIDAR is widely used for high-resolution mapping applications and in automobiles to detect lane markings, there are few challenges associated with utilizing these sensors for flight vision systems. LiDAR is highly sensitive to aerosol and cloud particles which makes it ineffective for aviation purposes as adverse weather conditions, such as heavy clouds could highly compromise the sensor output (Sangam 2012). The operating range of LiDAR is very short (~ 2km) when operated at maximum levels. However, the range is not an important criterion on some approach and landing operations as pilots cannot see the runway on final approach until about a minute before landing (Yang 1994).

2.4.4 Multispectral Sensors

Multispectral imaging sensors operate on the principle of spectral imaging as it captures the image of an object to be detected within specific wavelengths ranges across the electromagnetic

spectrum. The spectral band of object detection ranges from the wavelength of 415 nm (blue-visible spectrum) to 12500 nm (ultra-violet spectrum). Due to its high range of operating bandwidth, multispectral imaging sensors are employed in diverse fields, like the military (target tracking), landmine and ballistic missile detection, weather forecasting (Goldberg, Stann, Gupta, 2003). In case of flight vision system, multispectral sensor systems utilize multiple sensors where each of them is tuned to a discrete, specific range of frequencies on the electromagnetic (EM) spectrum (Churchville, 2015). These sensors provide better flexibility of operation for all-weather conditions due to its high operating bandwidth. The multispectral imagery is also post-processed using computer vision technology where the resulting runway imagery is enhanced with objects distinguishability (Andreev & Lysenko, 2018). Multispectral sensors utilized today focus primarily on short-wave IR to detect the energy emitted from approach lighting systems. Long-wave IR is utilized to detect weak through multiple layers of the atmosphere. Moreover, the adoption of LED within the airport infield lights necessitates the addition of visible light sensors. Overall, short wave IR is sufficient to detect the required visual cues for conducting approach and landing. While the other sensors are utilized to provide imagery of the runway surrounding (Tiana, 2019).

With respect to weather phenomena, multispectral sensors are impacted by the amount and distribution of water molecules (moisture) present in the atmosphere. Fog is the most difficult phenomenon for the multispectral sensors to work with, followed by snow. Major issues with multispectral sensors include image synchronization and scan time. Each sensor has its own image and an associated scan rate. When the images are combined, they are subjected out of temporal synchrony (Foyle, Ahumada, Larimer, & Sweet, 1992). In case of multi-sensor integrated to flight vision system, sensor imagery will have varying resolution with different sized images. The elements displayed within EFVS such as runway, towers, lights, etc. are likely to be different from

the pilot's view. Some elements may or may not be displayed within EFVS and affect the object or situation recognition.

CHAPTER 3. METHOD

3.1 Hypothesis

The knowledge gaps identified from previous studies were translated into three experimental hypotheses. The hypotheses are as follows:

Poor sensor outputs displayed to pilots can create challenges when identifying runway and terrain (Korn, 2007; Burgess et al, 1993). The difficulty in runway identification can negatively impact pilot approach and landing performance and situation awareness. Moreover, if runway identification becomes difficult, the task difficulty may increase which may increase in pilot workload levels. This leads to the first experimental hypothesis:

H1: The use of sensor-based flight vision system displaying degraded sensor output will decrease the pilot's approach and landing performance, situation awareness, and increase workload when compared to the flight vision system with good sensor output

The pilot's utilization of sensor imagery displayed on the HUD is critical for low visibility approaches. For a sensor-based flight vision system having a constant visual advantage factor is important, and the availability of visual cues for pilot's view is delayed over lower visibility levels. If the cue availability is delayed, the utilization of HUD may eventually decrease. This leads to the second experimental hypothesis:

H2: The total time spent on HUD decreases with lower visibility levels.

The sensor-based flight vision system may increase the pilot's position awareness and reduce the number of incorrect landing decisions. As discussed in Chapter 2, weather phenomena impact sensors such as MMWR and IR, which can sometimes result in poor sensor output. On approaching the decision height, if pilots have difficulty identifying the runway or distinguishing

the runway from its surroundings, they would be uncertain of runway whereabouts and chances of making incorrect landing decisions may increase. This leads to the third experimental hypothesis:

H3: The number of incorrect decisions to land will increase with the use of sensor-based flight vision system displaying degraded sensor output when compared to flight vision system displaying good sensor output

3.2 Participants

A total of 26 IFR pilot participants were recruited for the study based on a power analysis of $\alpha=.05$ and $\beta=.80$. Participants have a minimum of 20 hours of Instrument flight hours experience. Participants averaged 1535.1 (range:100-11,500) total flight hours and had no previous experience with flight vision systems. Pilot participants were recruited from several sources such as university flying clubs, regional airports, flight schools, and aviation newsletters. Twenty-three participants were rated with single-engine land pilots and three participants had a multi-engine land experience on turboprop aircraft. Only two pilots had previous experience in utilizing a sensor-based flight vision system for landing and approach.

3.3 Tasks

Participants flew a Cessna Citation X aircraft during an approach and landing task. The scenario starts with the flight on autopilot mode and in-line with a runway 8 NM away. The flight begins from the fixed approach point (2500 ft AGL), and airspeed was set at 160 in KIAS with no flaps. The runway environment was set at the foggy condition with a constant ceiling height of 100 ft. All the approach and landings tasks are conducted on a simplified rendering of runway 05 of Des Moines International Airport (KDSM). All flight trials were conducted and evaluated under FAA Instrument Flight Rules. Once the participant acquires the glideslope and localizer indicator on their primary flight display (PFD), they should descent down utilizing them and proceed to the runway for landing. At or above the prescribed decision altitude (DA), participants should decide on

whether to proceed for landing. Participants could land the flight if they were able to visually identify the cues such as runway lights, runway ground, runway threshold line, runway edge lights, and precision approach indicator lights (PAPI) at or above DA. If they are not aligned with the runway or could not visually acquire the cues mentioned above, they should conduct a missed approach procedure. Once the participant completes the stabilized approach, he or she must proceed to the landing phase and complete the flight successfully. For the missed approach procedure, the participants were instructed to climb to 3100 ft. and hold.

3.4 Independent Variables

The independent variables of this study are Visibility and Sensor information quality. These variables are manipulated for each experimental trial to analyze several performance factors during the approach and landing phases of flight.

3.4.1 Visibility

Visibility levels were expressed as two different Runway Visual Range (RVR) levels: 600 ft and 1000 ft. RVR is defined as “the range over which the pilot of an aircraft on the centerline of a runway can see the runway surface markings or the lights delineating the runway or identifying its centerline” (FAA-Pilot Controller Glossary, 2014, pp. V-3). Figure 6 is a comparison of RVR levels, 600 ft, and 1000 ft on a runway environment.



a) 600 ft RVR



b) 1000 ft RVR

Figure 6. RVR Levels

3.4.2 Sensor Information Quality

Sensor Information Quality has three levels: a) No sensor output b) Poor sensor output and c) Good sensor output. For the Good sensor output, the expected sensor imagery of the runway was displayed in addition to all flight information from the HUD. The FAA approved 94 GHz MMWR sensor equipped EFVS model was utilized as a reference for designing the simulation of the flight vision system. The HUD symbology was designed as mandated in FAA advisory circular for EFVS (FAA Advisory Circular AC-90A, 2010). According to tower test results on MMWR sensor performance, the contrast for unacceptable degraded sensor imagery is ranged between -0.2 to -0.6 on a foggy day (Burgees, 1993). This result is utilized to design the poor sensor output condition as the contrast of the sensor imagery is altered to negative (-0.2) for the runway ground. Thus, participants were provided with a flight vision system displaying degraded sensor imagery. Figure 7 and Figure 8 represents the combination of visibility levels and sensor information quality, yielding six different conditions, respectively. For No sensor output, the pilots are not provided with any sensor-based flight vision output, but a HUD is provided as a guidance system with all essential flight symbology such as heading indicator, altitude indicator (AGL, and MSL), throttle indicator, airspeed indicator, and pitch ladder.

A visual advantage factor of 2.5 is chosen for modeling the enhanced visibility for HUD, based on Kramer (2014). For both poor and good sensor outputs independent variable (IV) cases, pilots could experience 2.5 times enhanced visibility on utilizing the HUD when compared to the OTW. So, pilots could have equivalent visibility of 2500ft RVR and 1500ft RVR for 1000ft RVR and 600ft RVR OTW visibility, respectively.

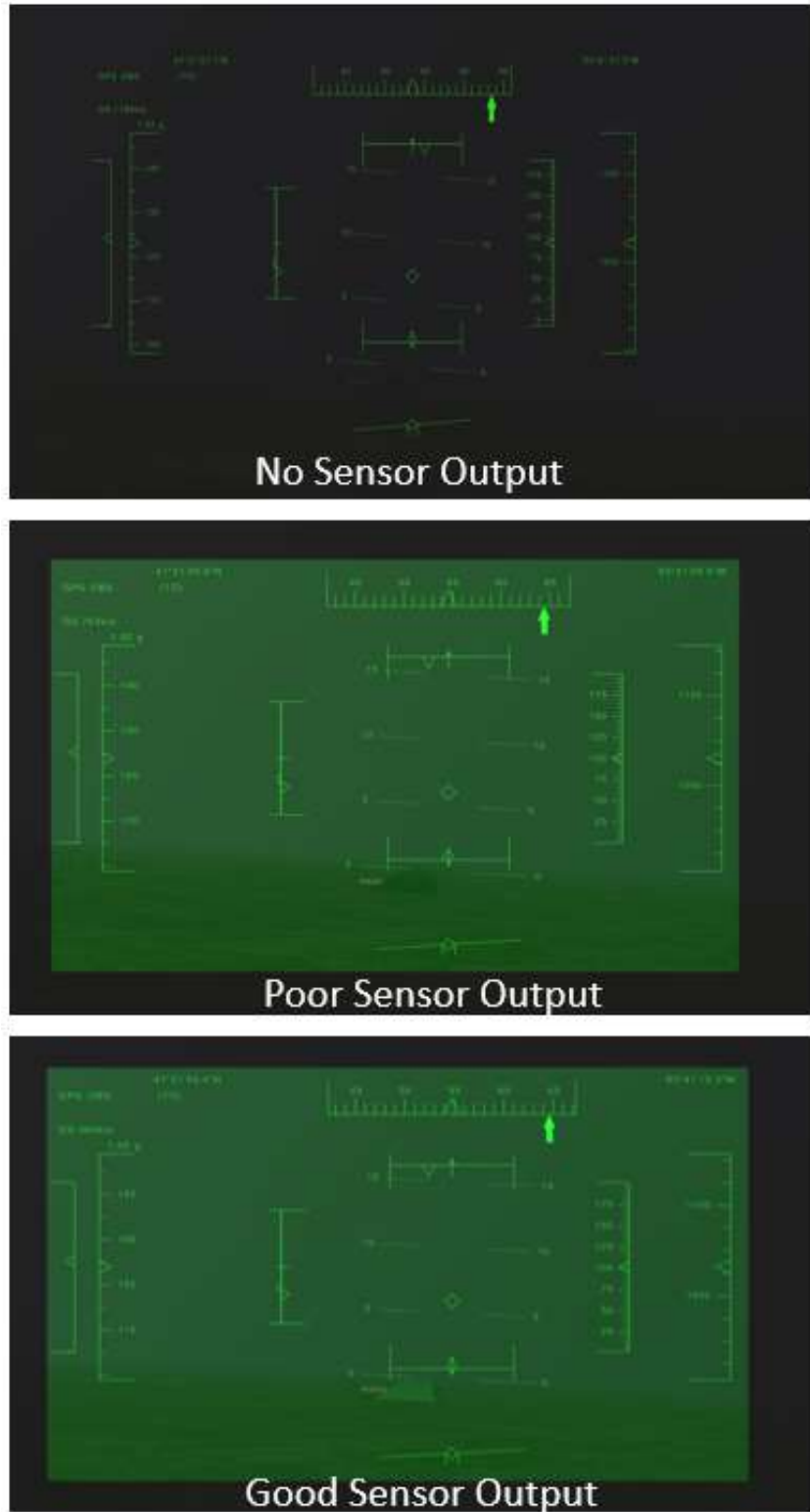


Figure 7. Simulated display at three levels of Sensor Information Quality: no sensor output (top), poor sensor output (middle), and good sensor output (bottom). Each image was captured at 100 ft AGL.



Figure 8. Simulated display in 1000 and 600 RVR (Red dotted circle indicates the runway environment). The runway is visible earlier in 1000 RVR (bottom figure) than in 600 RVR (top figure)

3.5 Dependent Variables

The dependent variables are the attention allocation, pilot performance, workload, and decision making during the approach and landing. Table 1 gives an overview of dependent variables, metrics, units, and data collection utilized in this study.

Table 1. Dependent Variables

Dependent Variables	Metrics	Units	Collection Method	Frequency
Attention Allocation	Time spent on PFD & HUD/OTW	Percentage	Eye Tracker Recordings	During Trial
	Number of PFD & HUD/OTW visits	Count		
	First Fixation	Feet above ground		
	First cue fixation vs first cue availability	Feet above ground		
Pilot Performance (Approach)	Glideslope Deviation	Measured in 1 scale deviation	Flight Sim Data	During trial
	Localizer Deviation			
	Sink Rate	Feet per minute (FPM)		
	Approach Airspeed	KIAS		
Pilot Performance (Landing)	Vertical speed at touchdown	Feet per minute (FPM)	Flight Sim Data	During trial
	Distance from centerline and touchdown location	Feet above ground		
Workload	NASA TLX	TLX: Likert Scale 0-21	Post-Task Questionnaire	After trial
Situation Awareness	SART techniques	SART: Likert Scale 1-7	Post-Task Questionnaire	After trial
Decision making	Altitude of Decision	Feet	Flight Sim Recordings	During trial
	Correct Decision	Count	Flight log and recordings	During Trial
	Retrospective Interview	Subjective Measure	Post Experiment Questionnaire	Post-experiment

3.5.1 Attention Allocation

Eye-tracking glasses were utilized to collect quantitative data on the participant's visual focus. To evaluate pilot's attention allocation, few important metrics such as the total scan duration within PFD and HUD/OTW, altitude difference between first availability and first fixation of decision cues, number of transition between PFD and OTW/HUD were utilized

- I. The total scan duration determines the time spent by participants across primary flight display (PFD), outside of the window, or the Heads-up display (HUD), non-area of interest zones. The assessment on total scan duration was categorized into three segments: IFR segment (from 1000ft AGL to 100ft DH), transition segment (from 100ft DH to 55ft TCH), and VFR segment (55ft to touchdown).
- II. Participants' first fixation of visual cues during each trial was compared against when that cue was first available. This analysis would provide critical information on altitude difference required for participants to fixate on any available visual cues before they have decided whether to land or go around.
- III. The number of pilot's gaze transitions between PFD and HUD/OTW during the trials was also assessed.

Overall, these evaluations would inform us of how the participant's visual attention has impacted their performance and decision making.

3.5.2 Pilot Performance (Approach)

For instrument approaches, the FAA (2017) defines evaluation criteria to analyze pilot performance for instrument flight ratings. For evaluating approach performance, the metrics of glideslope deviation, localizer deviation, and vertical speed at touchdown were utilized.

- I. The vertical deviation (glideslope) and horizontal deviation (localizer) were measured on a scale of 0 to 1, with 1 being a full-scale deviation. As per FAA standards, $\frac{3}{4}$ of a full-scale deviation on the glideslope is considered as unacceptable, which is 0.75 on this scale. These metrics were evaluated against the FAA standards, maintaining a stabilized final approach from the 1000 ft AGL to touchdown.
- II. For approach airspeed, the pilots were required to maintain the desired approach airspeed of the aircraft ± 10 knots.
- III. The pilot's vertical speed of descent (sink rate) was assessed. According to FAA guidelines, pilots should not exceed a vertical sink of 1000 feet per minute.

3.5.3 Pilot Performance (Landing)

For evaluating landing performance, the vertical speed at touchdown (fps), the distance away from the centerline, and touchdown markers were collected and evaluated against FAA acceptable limits.

- I. Distance from touchdown marker is a measure of how far down the runway, the pilot has landed with respect to touchdown markers. Distance from touchdown markers is measured as an absolute value from the runway threshold line. For a dry runway with threshold crossing height (TCH) for the runway was 55 ft, the acceptable landing distance is for Cessna Citation X is 3300 ft.
- II. Distance away from the centerline is a measure of how far the pilot has traveled in the lateral direction for the runway centerline. The acceptable distance from the centerline is ± 75 ft distance from the runway centerline as the runway is 150ft wide and landing off the runway is not acceptable.

- III. Also, the pilot's vertical speed at touchdown is the sink rate between the runway threshold line to the touchdown zone. The desired touchdown sink rate should be at 1-3 fps which is 60-180 feet per minute (Siegel & Hansman, 2001).

3.5.4 Workload and Situation Awareness Assessment

Total workload and Situation Awareness data were collected using NASA-TLX (Hart, & Staveland, 1988) and SART techniques (Endsley, 1995), respectively. Participants have completed NASA-TLX and SART questionnaires at the end of each trial.

3.5.5 Decision-Making

The altitude at which the participants made the decision to land or go around was recorded. The decision to initiate a missed approach or proceed for landing should be made before or at the decision height/decision altitude (DH/DA) for a precision approach. During the trials, they were instructed to speak out when they decided to land or go around. Eye tracker data and the experimental log from the flight simulation software were reviewed to determine the altitude at which cues were first available, the altitude at which participants first fixated on them, and the altitude at which participants decided to land. The possible visual cues available were the runway threshold markings, PAPI lights, runway edge lights, and touchdown markers. The participant's correct decision whether to land may change depending on the combination of independent variables (visibility, sensor information quality) and the specifics of the flight path (altitude, glideslope and localizer deviation, the attitude of the aircraft). Table 2. Landing Decision Table describes the expected appropriate landing decision for each condition.

Table 2. Landing Decision Table

	No sensor Output	Good sensor output	Poor Sensor output
600 ft RVR	Not Authorized to land	Authorized to land	Depends upon the pilot's approach
1000 ft RVR	Depends upon the pilot's approach	Authorized to land	Authorized to land

For most conditions, the decision to land was clear cut based on the available cues. However, in cases of 1000 ft, RVR / none, and 600 ft RVR / poor sensor imagery, the successful decision to land was based on their approach path, which could alter what cues are available at the DH. In these two cases, if the pilots were able to see the visual cues from prescribed DA/DH, they are authorized to land. Each flight recording was reviewed to determine what the correct decision should have been given the pilot's altitude, distance from the airport, and visibility of cues. This is assessed when participants made their decision. Participants have also completed a post-experiment subjective questionnaire that asked them to rank each of their flight trials, describe the overall impact of the sensor-based flight vision system in pilot's decision making, and How their decision making would be impacted by utilizing a sensor-based flight vision system displaying poor sensor output.

3.6 Experimental Design

The experimental was a 2 (Visibility: 600 RVR, 1000 RVR) x 3 (Sensor state: good sensor output, poor sensor output, no sensor output) within-subjects design. Figure 9 represents the Latin-square table for counterbalancing six experiment trials.

Recurring Order

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7
Trial 1	600ft None	600ft Good	1000ft Poor	1000ft None	1000ft Good	600ft Poor	600ft None
Trial 2	1000ft None	600ft None	1000ft Good	600ft Poor	600ft Poor	1000ft None	1000ft None
Trial 3	600ft Good	600ft Poor	600ft None	1000ft Good	1000ft None	1000ft Good	600ft Good
Trial 4	1000ft Good	1000ft Good	1000ft None	600ft None	600ft Good	600ft Good	1000ft Good
Trial 5	600ft Poor	1000ft None	600ft Good	1000ft Poor	600ft None	1000ft Poor	600ft Poor
Trial 6	1000ft Poor	1000ft Poor	600ft Poor	600ft Good	1000ft Poor	600ft None	1000ft Poor

Figure 9. Counterbalancing of the six unique combinations of conditions (three levels of Sensor Information Quality and two levels of Visibility)

3.7 Experimental Procedure

All the participants (IFR pilots) were given a 45-minute briefing on the flight test details with a training session before the experimental flight. The duration of the experiment for each participant lasted from two to three hours. Figure 10 represents the experimental procedure in a flowchart

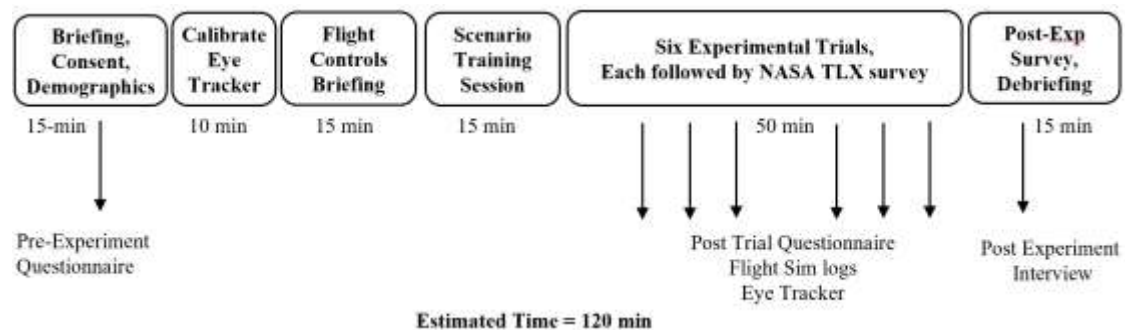


Figure 10. Experiment Procedure

The experimental procedure begins with participant briefing followed by informed consent, demographics survey, and eye-tracker setup. The participant was introduced to the flight simulator, followed by flight training. The training sessions consist of two approach and landing tasks: a) normal vision, instrument approach b) normal vision – instrument approach with HUD. The pilots

were given two phases of flight training. In phase I, participants was trained with the flight controls and displays with the flight simulator. In phase II, participants conducted instrument-based approaches from 8 NM to a runway environment. Participants were asked to conduct several training approaches and landing until they were confident in flying an instrument-based approach with the simulator. During the flight training, they were presented with the Heads-Up Display (HUD) but not trained with the sensor-based flight vision system. This is done to prevent any learning effect within the training. After successful training, participants were briefed about the experimental trials and explained about the sensor-based flight vision system. Each participant conducted six flight trials under every combination of the two independent variables as discussed in section 3.3 Tasks. After each trial, the participants completed a NASA TLX and SART based questionnaire in an electronic form to gather data on their workload levels and situation awareness of that trial. For each experimental trial, the flight was recorded, and participant eye-tracker data were collected. On completion of all trials, a post-experiment interview was conducted. In this session, a retrospective protocol was conducted by replaying the video recordings, and participants recalled the critical information used to making flight decisions. Finally, they were debriefed about their role in the experiment and thanked for their participation.

3.8 Testing Environment

The flight simulator was configured with Flight Gear (v 3.2 2018, Flight Gear, Canada), which is an open-source flight simulation software. Flight Gear software simulated 3D modeled HUD glass to represent a sensor-based flight vision system installed aircraft. The hardware configurations for this simulator facility include Saitek (Logitech, Switzerland) controls: Rudder-Pedals, Saitek Throttle Quadrant, 4-axis Yoke Controller, Saitek Radio Panels, Saitek Instrument

Panels. The forward view was depicted on an 82” TV screen, and two monitors support the pilot and co-pilot view of the flight deck displays (refer Figure 11)



Figure 11. Testing Environment

The Tobii eye-tracker glasses were utilized in this study to determine the attention allocation of pilots. Tobii Pro Glasses 2 (Tobii AB, Danderyd, Sweden) is a wearable eye-tracking device with a wireless live view function. The glasses are mainly utilized for its visual analysis capability and automated real-world mapping feature which enables us to streamline and map the eye tracker output, allowing immediate visualization of the quantified data.

3.9 Data Analysis Plan

Two-way within-subject ANOVA was performed for all quantitative dependent variables. A p -value ranging from 0.05 to 0.1 was categorized as marginally significant, values below 0.05 were categorized as significant, and values below .001 were categorized as highly significant (Gelman, 2013; Andrew, 2013). A pairwise Tukey's HSD comparison was performed for dependent variables. Cohen's d test was performed to compare the effect size between the means of independent variables. Nonparametric tests such as the test for homogeneity of variances (Levene's test) and test for normality and goodness of fit (W-Shapiro test) were also performed. Moreover, the pilot's landing and approach performance parameters such as glideslope and localizer deviations, sink rate, approach and landing speed, distance away from the touchdown

marker, and centerline were evaluated against the FAA standards. Chi-square and Bowker's test for symmetry of disagreement were performed to analyze the exceedances binominal data.

CHAPTER 4. RESULTS

4.1 Pilot Performance (Approach)

4.1.1 Glideslope RMS

Figure 12 illustrates the results for glideslope RMS for the combination of Sensor Information Quality and Visibility conditions. The data were normally distributed with homogenous variance. The main effect of Sensor Information Quality was not significant, $F(2,150) = 2.23, p = .11$. Also, the main effect of Visibility was not significant, $F(1,138) = 0.13, p = .71$. The interaction effect was significant, $F(5,150) = 2.23, p = .11$.

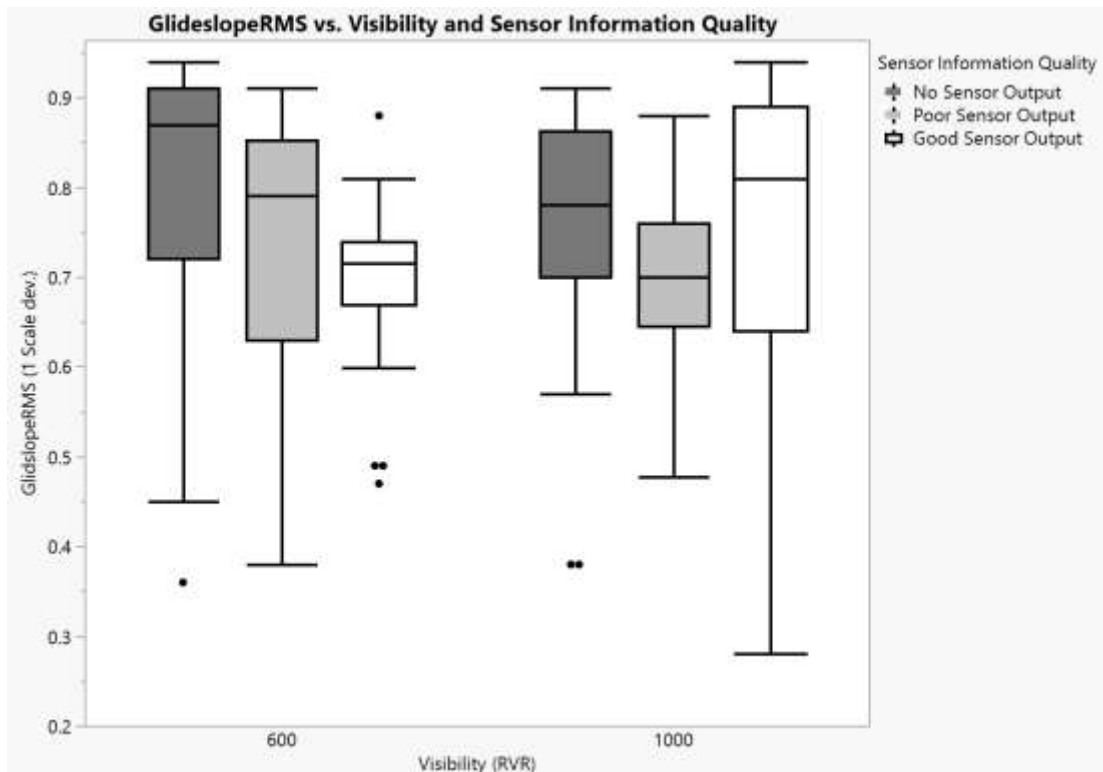


Figure 12. Glideslope RMS for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

The exceedance on glideslope RMS was observed in 75 approaches out of 156 trials conducted (i.e. 48.1%). Eighteen out of 52 approaches (i.e. 34.6%), conducted on good sensor output (both 600 ft and 1000 ft RVR) were observed with glideslope exceedances. Moreover, 34 out of 52 approaches (i.e. 65.3%), conducted on no sensor output, and 23 out of 52 approaches (i.e. 44.2%), conducted with poor sensor output resulted in glideslope exceedances. For Visibility, 40 out of 78 approaches (i.e. 51.2%) resulted in glideslope exceedances for 600ft RVR, and 35 out of 78 approaches (i.e. 44.8%) resulted in glideslope exceedances for 1000ft RVR.

Figure 13 illustrates the results for glideslope exceedances for the combination of Sensor Information Quality and Visibility conditions. Pairwise comparison indicated that no sensor output ($M = 65.3\%$, $SE = 8.8$) has significantly more exceedances compared to poor sensor output ($M = 44.2\%$, $SE = 13.1$, $\chi^2(1) = 5.26$, $p = .02$). Also, the no sensor output ($M = 65.3\%$, $SE = 8.8$) has significantly more exceedances compared to good sensor output ($M = 34.6\%$, $SE = 12.2$, $\chi^2(1) = 9.81$, $p = .002$). No significant differences were observed between good sensor output ($M = 34.6\%$, $SE = 12.2$) and poor sensor output ($M = 44.2\%$, $SE = 13.1$, $\chi^2(1) = 1.31$, $p = .25$). With respect to Visibility, no significant differences were observed between 600ft RVR ($M = 51.2\%$, $SE = 6.2$), and 1000ft RVR ($M = 44.9\%$, $SE = 4.4$, $\chi^2(1) = 0.61$, $p = .43$).

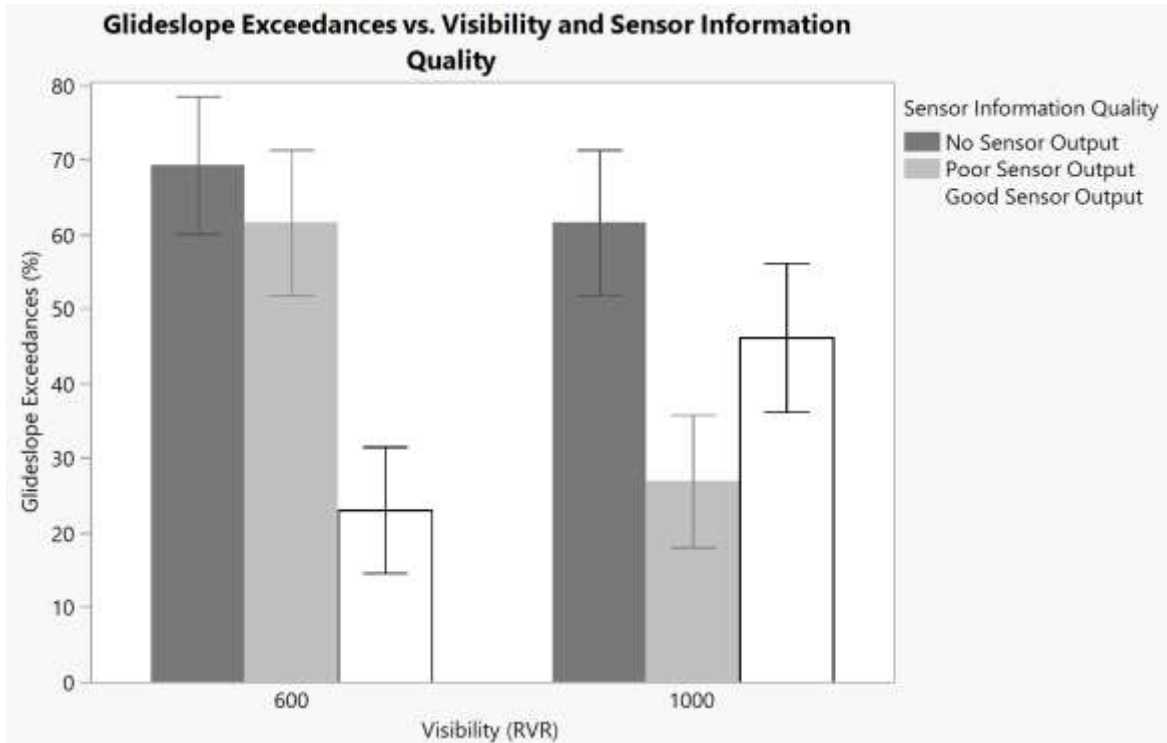


Figure 13. Glideslope Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.1.2 Localizer RMS

Figure 14 illustrates the results for localizer RMS for the combination of Sensor Information Quality and Visibility conditions. The data was normally distributed with non-homogenous variance. The main effect of Sensor Information Quality was highly significant, $F(2,150) = 6.56, p = .003$. Pairwise comparison showed that localizer RMS deviations in the no sensor output condition ($M = 0.50, SE = 0.04$) was significantly larger than the good sensor output condition ($M = 0.35, SE = 0.04, p = .003, d = 0.67$). Similarly, localizer RMS deviations in the poor sensor output ($M = 0.47, SE = 0.04, p = .003, d = 0.67$) was significantly larger than the good sensor output ($M = 0.35, SE = 0.04, p = .02, d = 0.6$). The main effect of Visibility was not significant, $F(1,150) = 0.001, p = .91$. The interaction effect was not significant, $F(5,150) = 1.59, p = .21$

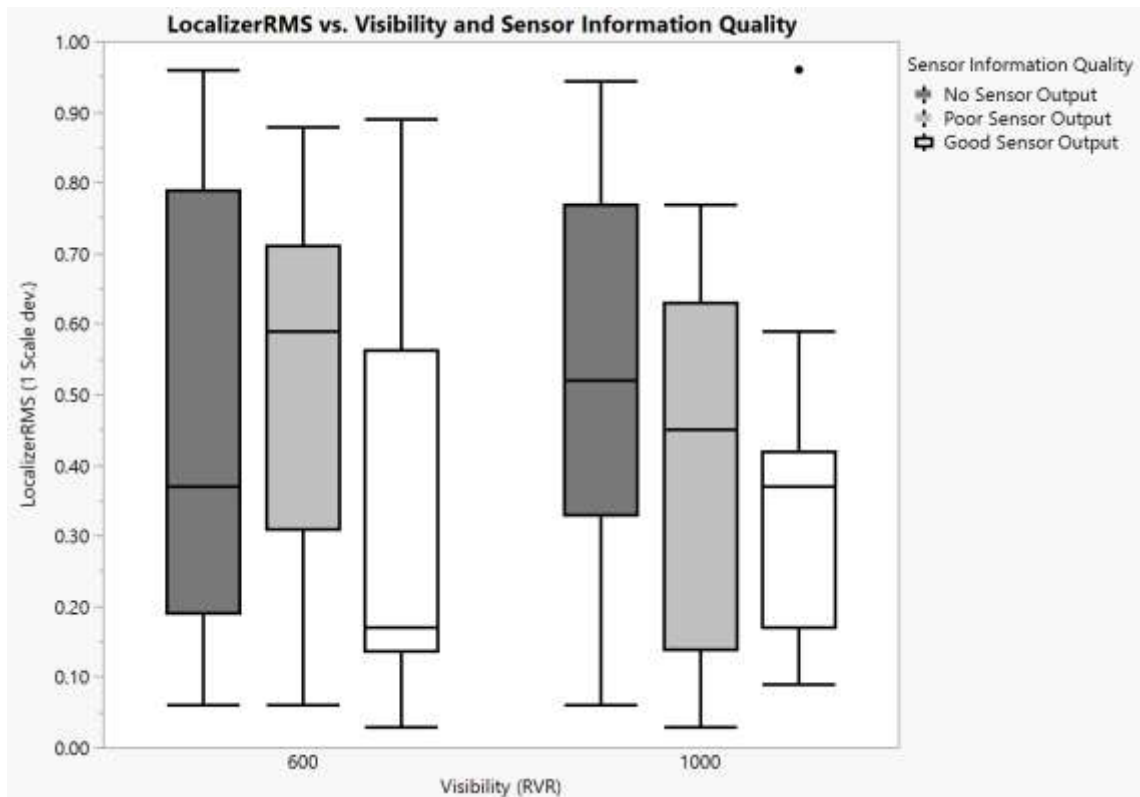


Figure 14. Localizer RMS for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

Similarly, horizontal deviation (localizer exceedances) is measured on a scale of 0 to 1, with 1 being a full-scale deviation. As per FAA standards, $\frac{3}{4}$ of a full-scale deviation on the localizer is considered as unacceptable, which is 0.75. From the trial data analyzed, the exceedance on localizer RMS was observed 27 times out of 156 trials, (i.e. 17.3%). 5 out of 52 approaches (i.e. 9.6%), conducted on good sensor output (both 600 ft and 1000 ft RVR) were observed with localizer exceedances. Moreover, 13 out of 52 approaches (i.e. 25.0%), conducted on no sensor output and 9 out of 52 approaches (i.e. 17.3%), conducted with poor sensor output has resulted in localizer exceedances. With respect to visibility, 16 out of 78 approaches (i.e. 20.5%) resulted in localizer exceedances for 600ft RVR, and 14 out of 72 approaches (i.e. 14.1%) resulted in localizer exceedances for 1000ft RVR.

Figure 15 illustrates the results on localizer exceedances for the combination of Sensor Information Quality and Visibility conditions. No significant differences were observed between good sensor output ($M = 9.6\%$, $SE = 6.3$) and poor sensor output ($M = 17.3\%$, $SE = 8.4$, $\chi^2(1) = 1.6$, $p = .20$). No significant differences were observed between no sensor output ($M = 25.0\%$, $SE = 8.1$) and poor sensor output ($M = 17.3\%$, $SE = 8.4$, $\chi^2(1) = 1.0$, $p = .31$). Pairwise comparison indicated that good sensor output ($M = 9.6\%$, $SE = 6.3$) has fewer exceedances no sensor output ($M = 25.0\%$, $SE = 8.1$, $\chi^2(1) = 3.55$, $p = .06$). With respect to Visibility, no significant differences were observed between 600ft RVR ($M = 20.5\%$, $SE = 6.2$) and 1000ft RVR ($M = 14.1\%$, $SE = 4.4$, $\chi^2(1) = 1.09$, $p = .21$).

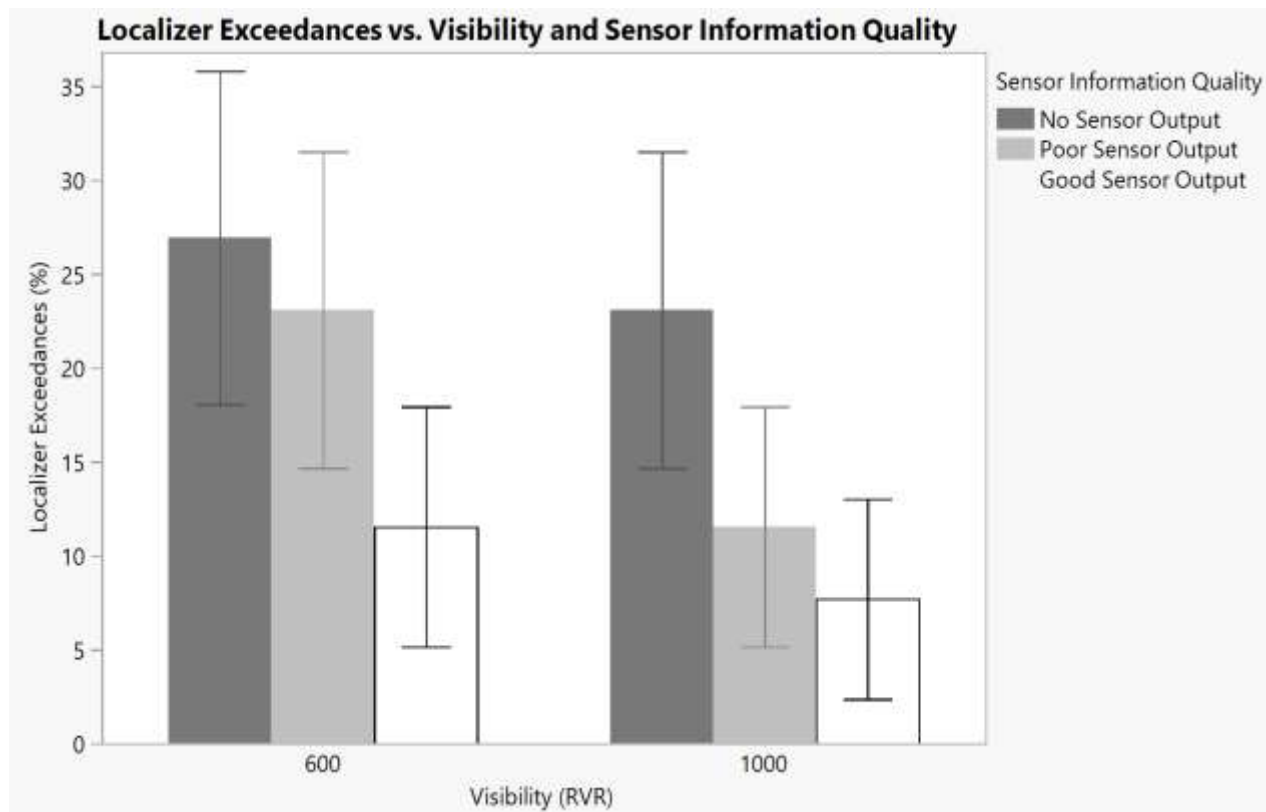


Figure 15. Localizer Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.1.3 Sink Rate

Figure 16 illustrates the results for the sink rate for the combination of Sensor Information Quality and Visibility conditions. The data were normally distributed with homogenous variance. The main effect of Sensor Information Quality was not significant, $F(2,150) = 1.99$, $p = .15$. The main effect of Visibility was also not significant, $F(1,150) = 0.21$, $p = .64$. The interaction effect was significant, $F(5,150) = 3.45$, $p = .004$.

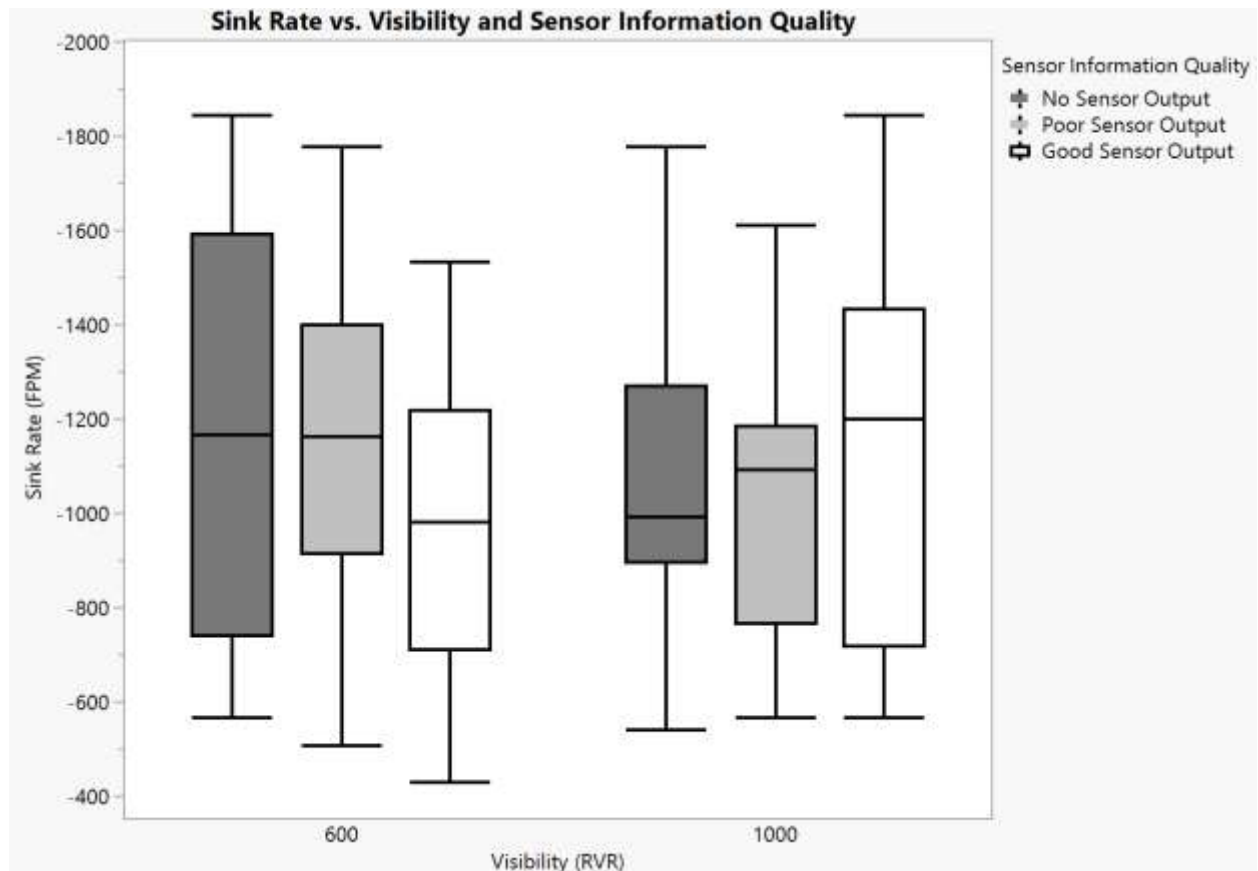


Figure 16. Sink Rate for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

From the trial data analyzed, the exceedance on the sink rate was observed 78 times out of 156 trials: (i.e. 50.0%). 26 out of 52 approaches (i.e. 50.0%), conducted on good sensor output (both 600 ft and 1000 ft RVR) were observed with sink rate exceedances. Moreover, 26 out of 52 approaches (i.e. 50.0%), conducted on no sensor output and 26 out of 52 approaches (i.e. 50.0%),

conducted with poor sensor output has resulted in exceedances. With respect to visibility, 39 out of 78 approaches (i.e. 50.0%) resulted in sink rate exceedances for 600ft RVR and 39 out of 78 approaches (i.e. 50.0%) resulted in sink rate exceedances for 1000ft RVR

Figure 17 illustrates the results on sink rate exceedances for the combination of Sensor Information Quality and Visibility conditions. No significant differences were observed between good sensor output ($M = 50.0\%$, $SE = 7.1$) and poor sensor output ($M = 50.0\%$, $SE = 7.1$, $\chi^2(1) = 0$, $p = .99$). No significant differences were observed between no sensor output ($M = 50.0\%$, $SE = 7.1$) and poor sensor output ($M = 50.0\%$, $SE = 7.1$, $\chi^2(1) = 0.53$, $p = .46$). No significant differences were observed among good sensor output ($M = 50.0\%$, $SE = 7.1$) and no sensor output ($M = 50\%$, $SE = 7.1$, $\chi^2(1) = 0.73$, $p = .39$). With respect to Visibility, no significant differences were observed at 600ft RVR ($M = 50.0\%$, $SE = 5.7$) or 1000ft RVR ($M = 50.0\%$, $SE = 5.7$, $\chi^2(1) = 0$, $p = .99$).

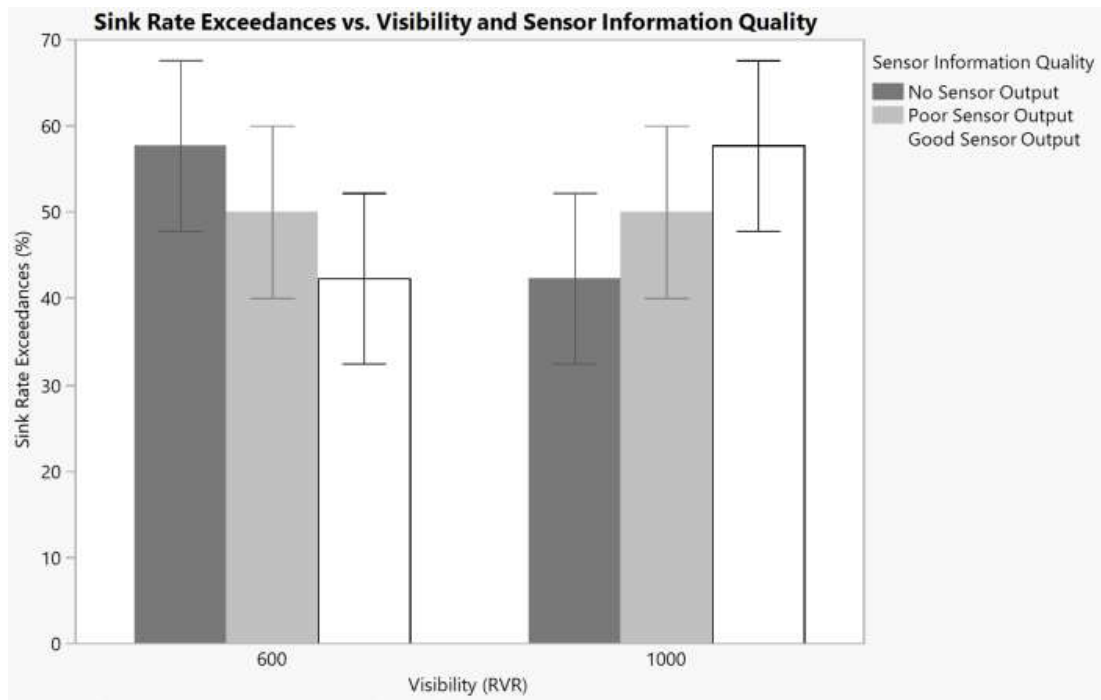


Figure 17. Sink Rate Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.1.4 Approach Airspeed

Figure 18 illustrates the results for approach airspeed for the combination of Sensor information quality and Visibility conditions. The data were normally distributed with homogenous variance. The main effect of Sensor information quality was not significant, $F(2,150) = 1.95, p = .14$. The main effect of Visibility was not significant, $F(1,150) = 0.1, p = .74$. The interaction effect was significant, $F(5,150) = 0.84, p = .43$.

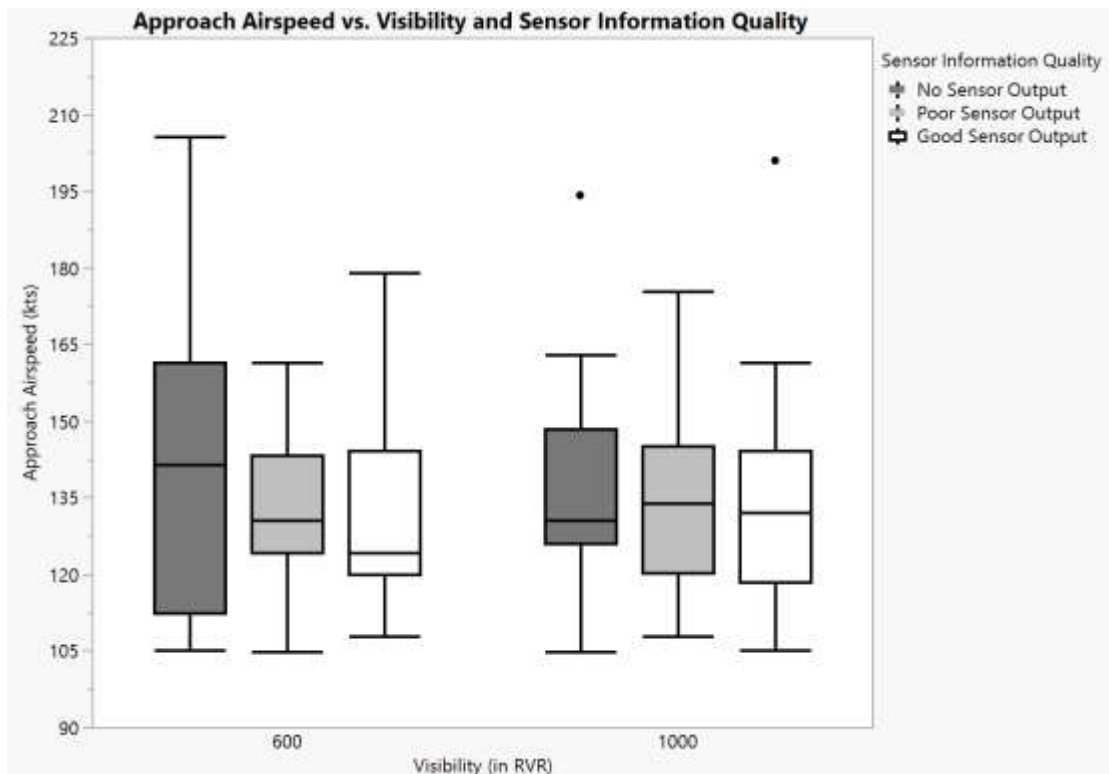


Figure 18. Approach Airspeed for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

From the trial data analyzed, the exceedance on approach airspeed was observed 61 times out of 156 trials: (i.e. 39.1%). 22 out of 52 approaches (i.e. 42.3%), conducted on good sensor output (both 600 ft and 1000 ft RVR) were observed with approach airspeed exceedances. Moreover, 20 out of 52 approaches (i.e. 38.4%), conducted on no sensor output, and 19 out of 48 approaches (i.e. 36.5%), conducted with poor sensor output has resulted in approach airspeed

exceedances. With respect to visibility, 34 out of 78 approaches (i.e. 43.6%) resulted in approach airspeed exceedances for 600ft RVR and 27 out of 78 approaches (i.e. 34.6%) resulted in approach airspeed exceedances for 1000ft RVR

Figure 19 illustrates the results on approach airspeed exceedances for the combination of Sensor Information Quality and Visibility conditions. No significant differences were observed between good sensor output ($M = 42.3\%$, $SE = 6.9$) and poor sensor output ($M = 36.5$, $SE = 6.7$, $\chi^2(1) = 2.13$, $p = .14$). No significant differences were observed between no sensor output ($M = 38.5\%$, $SE = 6.8$) and poor sensor output ($M = 36.5$, $SE = 6.7$, $\chi^2(1) = 0.05$, $p = .81$). No significant differences were observed between good sensor output ($M = 42.3\%$, $SE = 6.9$) and no sensor output ($M = 38.5\%$, $SE = 6.8$, $\chi^2(1) = 0.20$, $p = .65$). With respect to Visibility, no significant differences were observed between 600ft RVR ($M = 43.6\%$, $SE = 5.6$) and 1000ft RVR ($M = 34.6\%$, $SE = 5.4$, $\chi^2(1) = 1.48$, $p = 0.35$).

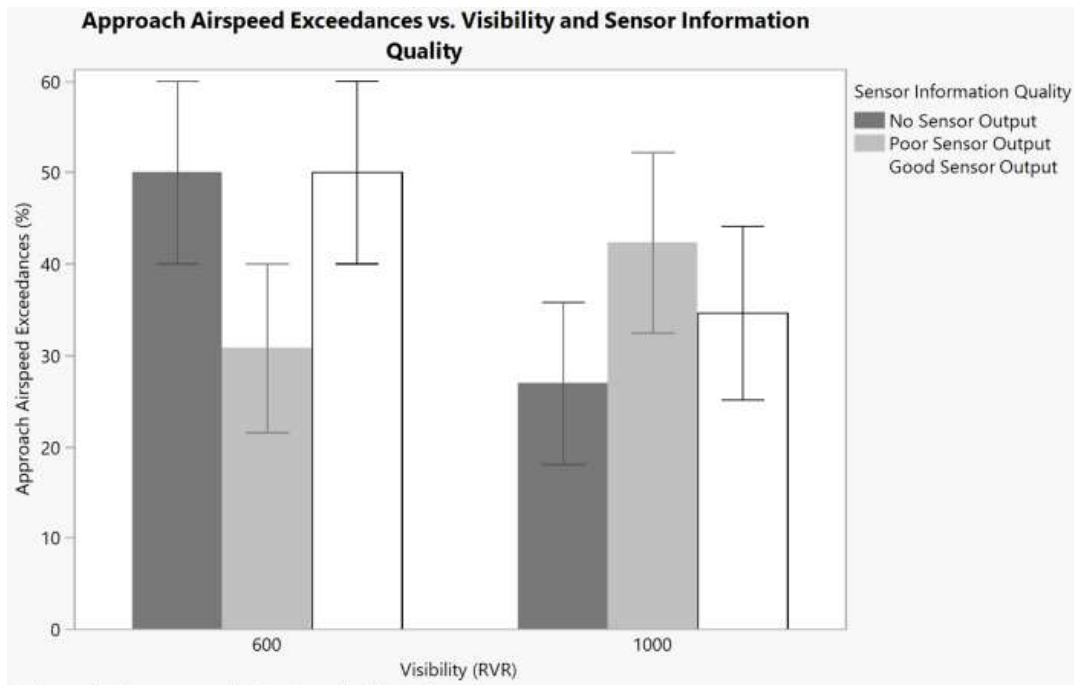


Figure 19. Approach Airspeed Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.2 Pilot Performance (Landing)

4.2.1 Distance away from Centerline

Figure 20 illustrates the results for the distance away from the centerline for the combination of Sensor Information Quality and Visibility conditions. The data were normally distributed with non-homogeneous variance. The main effect of Sensor Information Quality was significant, $F(2,150) = 12.7, p < .001$. Pairwise comparison showed that distance away from centerline in the no sensor output condition ($M = 47.0, SE = 3.03$) was significantly larger than the good sensor output condition ($M = 31.9, SE = 2.25, p < .0001, d = 0.99$) and significantly larger than poor sensor output ($M = 35.8, SE = 2.78, p = .004, d = 0.68$). No significant results were found for good-poor sensor output pairs. The main effect of Visibility was not significant, $F(1,150) = 0.03, p = .86$. The interaction effect was not significant, $F(5,150) = 0.53, p = .58$.

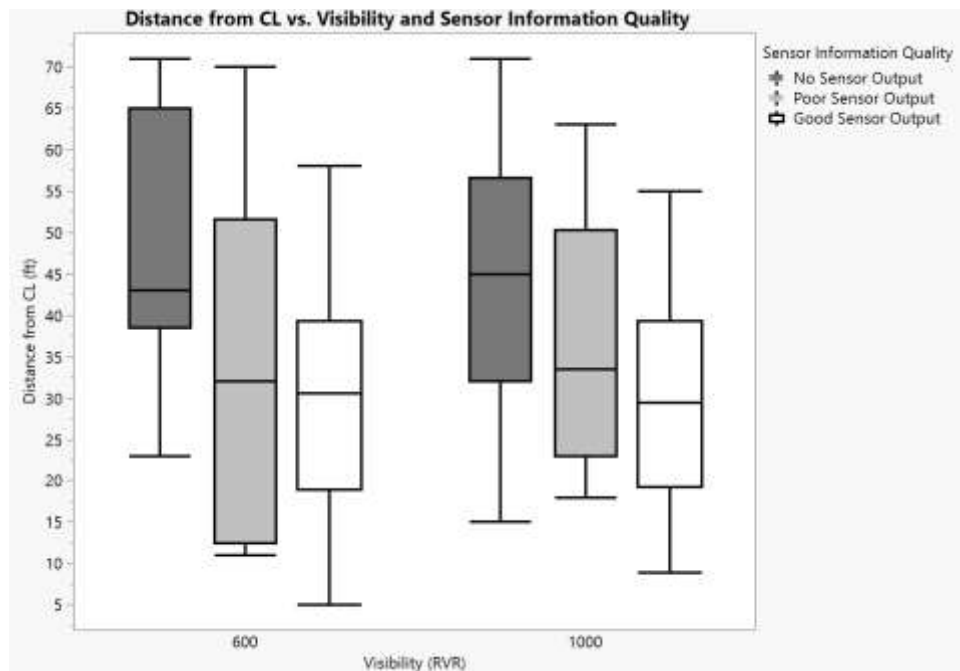


Figure 20. Distance from Centerline for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

As per FAA guidelines, an acceptable limit for runway 05 Des Moines Intl. airport is +/- 75 ft (the runway is 150 ft wide). Based on the data analyzed on 100 completed landings, no exceedance was found with respect to distance away from the centerline.

4.2.2 Distance away from Touchdown Markers

Figure 21 illustrates the results for distance away from touchdown markers for the combination of Sensor Information Quality and Visibility conditions. The data was not normally distributed with non-homogenous variance. The main effect of Sensor Information Quality was significant, $F(2,150) = 10.8, p < .001$. Pairwise comparison showed that landing distance away from touchdown markers for the no sensor output condition ($M = 25.6, SE = 126.4$) was significantly smaller than the poor sensor output condition ($M = 664.4, SE = 110.4, p = .009, d = 5.39$). Also, pairwise comparison among landing distance away from touchdown markers in the good sensor output ($M = 98.5, SE = 53.5$) was significantly larger than the poor sensor output ($M = 664.4, SE = 110.4, p < .004, d = 6.54$). The main effect of Visibility was significant, $F(1,150) = 5.5, p = .003, d = 1.27$. The landing distance from touchdown markers on 600ft RVR ($M = 324.4, SE = 91.3$) was significantly larger than the 1000ft RVR condition ($M = 201.2, SE = 89.2$). The interaction effect was marginally significant, $F(5,150) = 2.39, p = .10$.

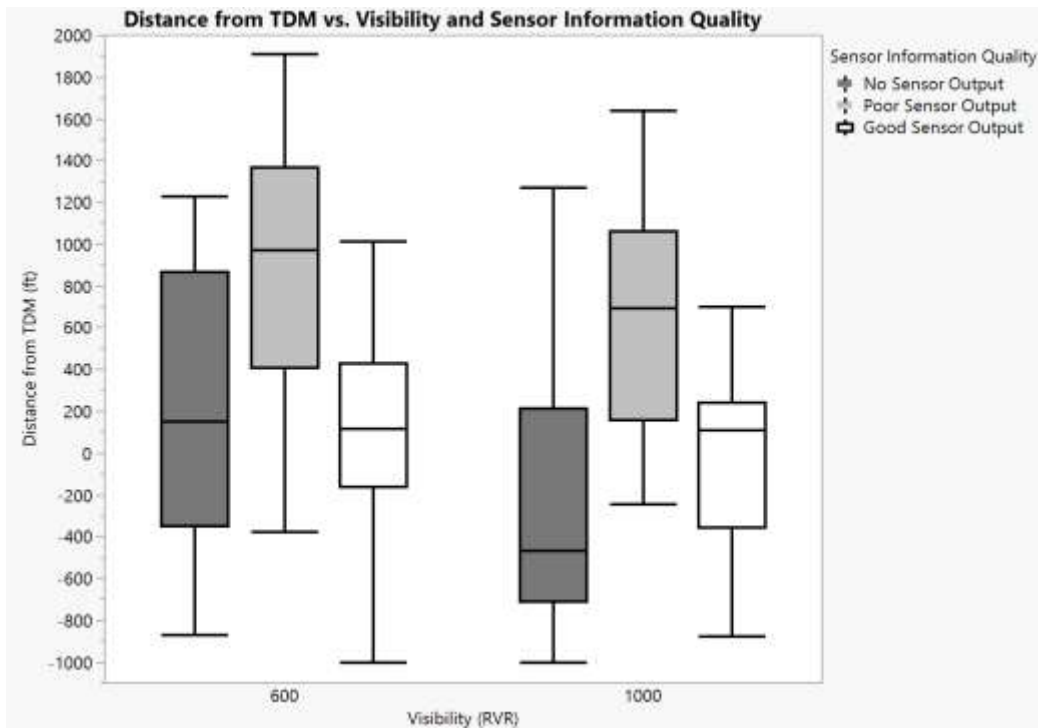


Figure 21. Distance from Touchdown Zone for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

As per FAA guidelines, pilots are authorized to achieve a landing distance of 3580 ft down the runway from the threshold line. Based on the data analyzed on 100 completed landings, no exceedance was found with respect to distance away from touchdown markers.

4.2.3 Vertical Speed at Touchdown

Figure 22 illustrates the results for vertical speed at touchdown for the combination of Sensor Information Quality and Visibility conditions. The data were normally distributed with homogenous variance. The main effect of Sensor Information Quality was not significant, $F(2,150) = 0.45, p = .63$. The main effect of Visibility was also not significant, $F(1,150) = 0.45, p = .58$. The interaction effect was not significant, $F(5,150) = 0.26, p = .76$.

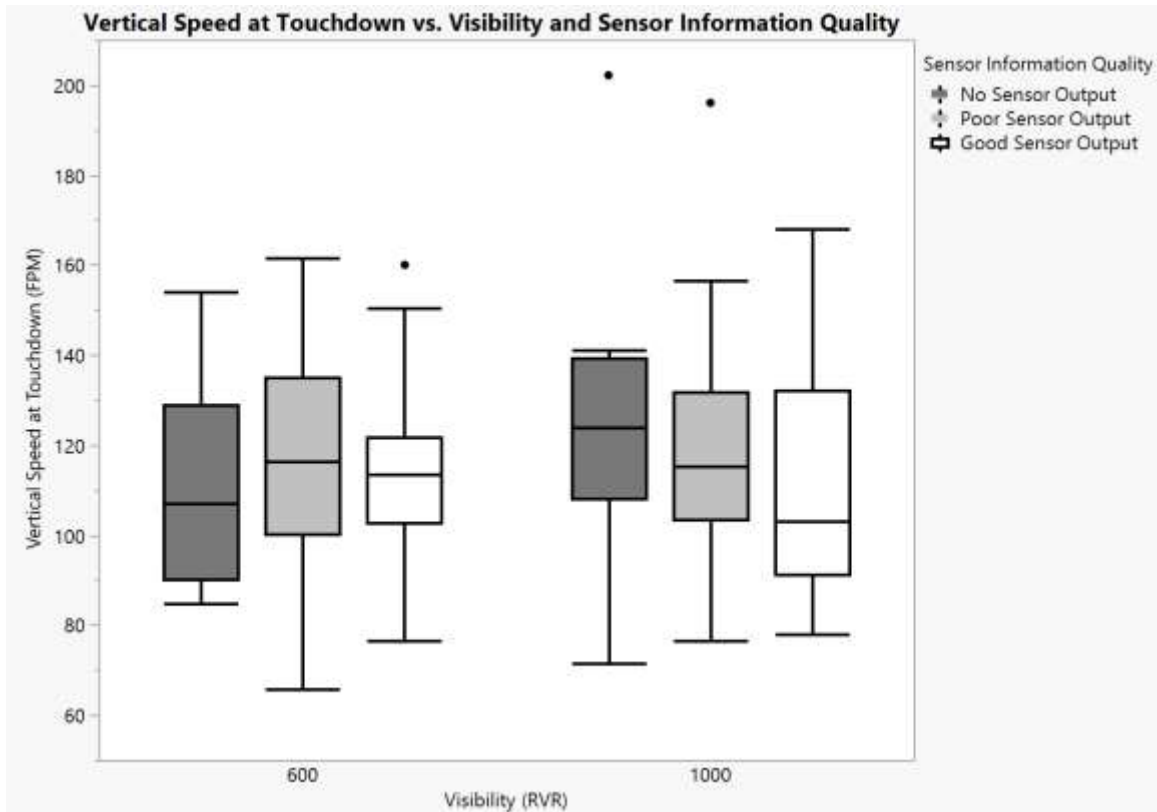


Figure 22. Vertical Speed at Touchdown for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

The desired vertical speed at touchdown should be at 1-3 fps which is 60-180 feet per minute (Siegel & Hansman, 2001). Anything higher could damage the aircraft. Based on the data analyzed, all pilots were within the FAA acceptable limits and no exceedances were found.

4.3 Overall Workload

Figure 23 illustrates the results for overall workload for the combination of Sensor Information Quality and Visibility conditions. The data was normally distributed with homogenous variance the main effect of Sensor Information Quality was significant, $F(2,150) = 10.2, p < .001$. Pairwise comparison showed that overall workload for the no sensor output condition ($M = 56.5, SE = 2.14$) was significantly larger than the good sensor output condition ($M = 48.1, SE = 2.85, p = .01, d = 0.63$). No significant results were found for good-no sensor output and good-poor sensor

output conditions. The main effect of Visibility was not significant, $F(1,138) = 0.25, p = .66$. Also, the interaction effect was significant, $F(5,138) = 5.66, p = .006$.

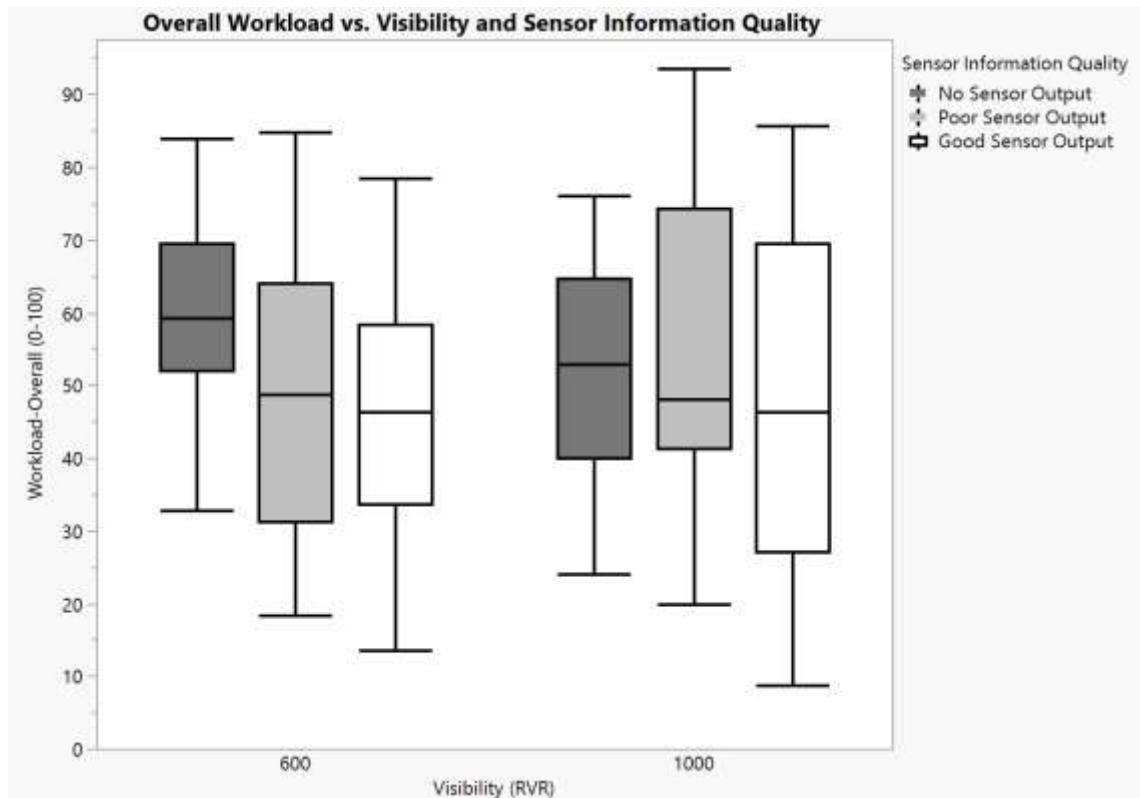


Figure 23. Overall Workload for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.4 Situation Awareness

Figure 24 illustrates the results for overall situation awareness for the combination of Sensor Information Quality and Visibility conditions. The data was not normally distributed with homogenous variance. The main effect of Sensor Information Quality was not significant, $F(2,150) = 0.09, p = .90$. The main effect of Visibility was not significant, $F(1,138) = 0.01, p = .89$. Also, the interaction effect was not significant, $F(5,138) = 0.39, p = .67$.

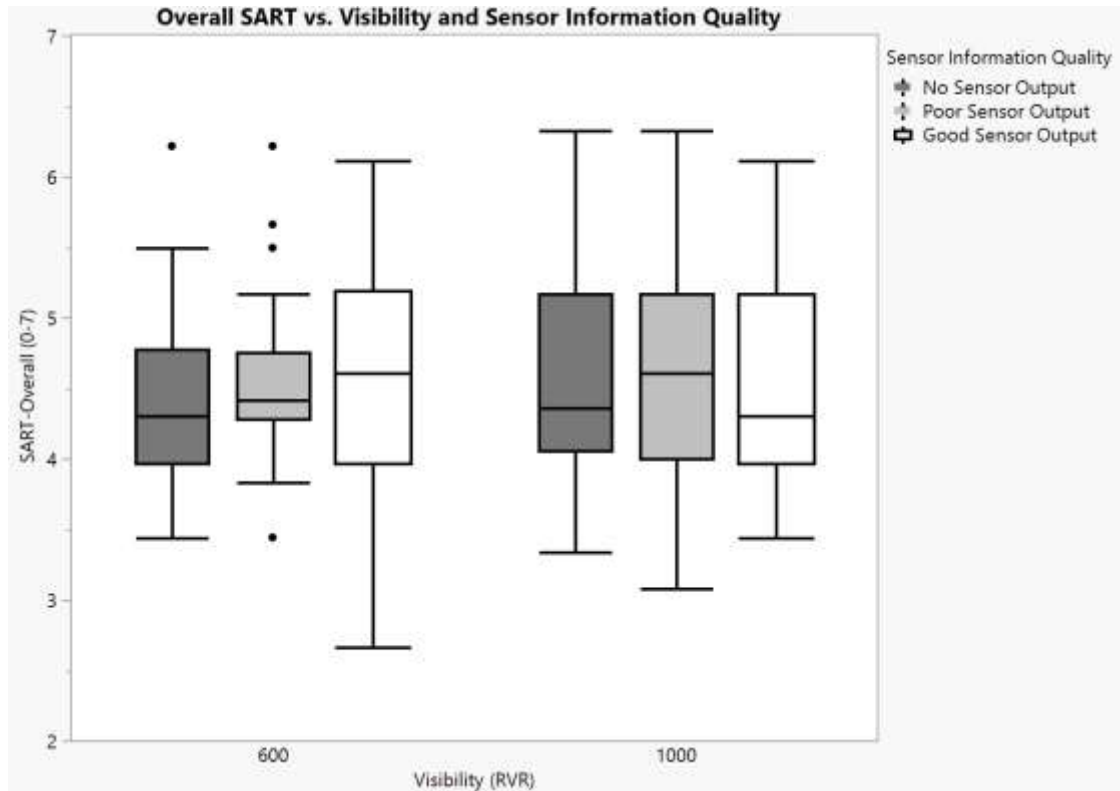


Figure 24. Overall Situation Awareness for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.5 Decision Making

4.5.1 Successful Decision to Land

Table 3 illustrates the results for a successful decision to land for each IV combination. Out of 156 flight trials conducted, 134 eye tracker recordings were assessed for the pilot's successful landing decision. Out of 22 recordings not included, 11 recordings were when pilot decide on a missed approach before they fixated on any visual cues, five recordings were incomplete which couldn't be utilized for any assessment and one pilot participant was not certain about his glass prescription which resulted in loss of six more recordings. Based on the analysis, pilots have made an inappropriate landing decision on 30 occasions out of 134 available recordings. Table 3 illustrates the pilot's landing decision exceedance for all combinations of Sensor Information Quality and Visibility.

Table 3. Landing Decision exceedances for two levels of visibility and three levels of sensor information quality

Visibility	Sensor Information Quality		
	None	Good	Poor
600 ft RVR	5.3% (n=19)	8.7% (n=23)	37.5% (n=24)
1000 ft RVR	26.1% (n=23)	13.6% (n=22)	39.1% (n=23)

Figure 25 illustrated the results of landing decision exceedances for the combination of Sensor Information Quality and Visibility conditions. The main effect on Sensor Information Quality was significant in $F(2,128) = 3.54, p = 0.038$. Pairwise comparison showed that appropriate decision making in the good sensor output condition ($M = 85.7, SE = 7.25$) was significantly larger than the poor sensor output condition ($M = 62.7, SE = 7.58, p = .05, d = 0.47$). Also, the main effect on Visibility was marginally significant $F(2,128) = 3.63, p = 0.07$. The interaction effect was not significant, $F(5,128) = 0.41, p = .67$.

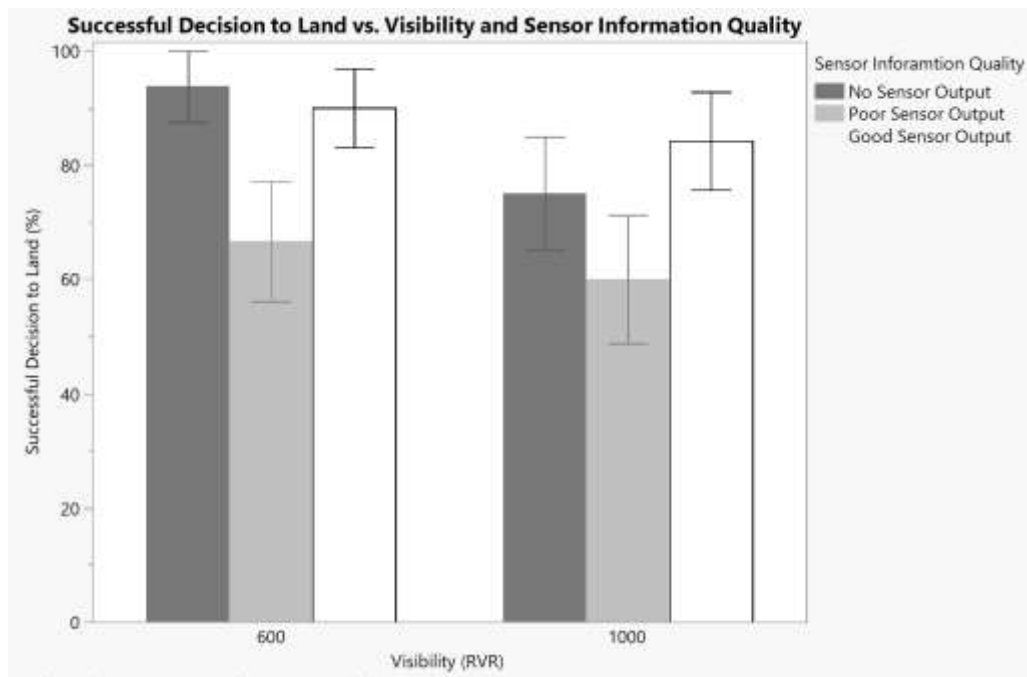


Figure 25. Successful Decision to Land for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.5.2 Decision Height

During each trial, pilots had reported the height at which they made their flight decision. This information was utilized to compare against the prescribed DH of 100ft for all approaches. Any decision made below 100ft prescribed DH is considered as an exceedance. Out of 156 flight trials conducted, 139 eye tracker recordings were available to assess this parameter. Figure 26 illustrates the results of the decision height for the combination of Sensor information quality and Visibility conditions. The data were normally distributed with non-homogeneous variance. The main effect of Sensor information quality was highly significant, $F(2,133) = 5.92$, $p = .005$. Pairwise comparison showed that decision height in the no sensor output condition ($M = 181.5\text{ft}$, $SE = 32.5\text{ft}$) was significantly smaller than the good sensor output condition ($M = 317.7\text{ft}$, $SE = 30.4\text{ft}$, $p = .010$, $d = 4.32$). Similarly, pairwise comparison among localizer RMS deviations in the poor sensor output ($M = 193.5\text{ft}$, $SE = 31.3\text{ft}$) was significantly smaller than the good sensor output ($M = 317.7\text{ft}$, $SE = 30.4\text{ft}$, $p = .013$, $d = 4.0$). Also, the main effect of Visibility was not significant $F(2,133) = 0.0073$, $p = 0.93$. The interaction effect was not significant $F(5,133) = 0.69$, $p = 0.51$.

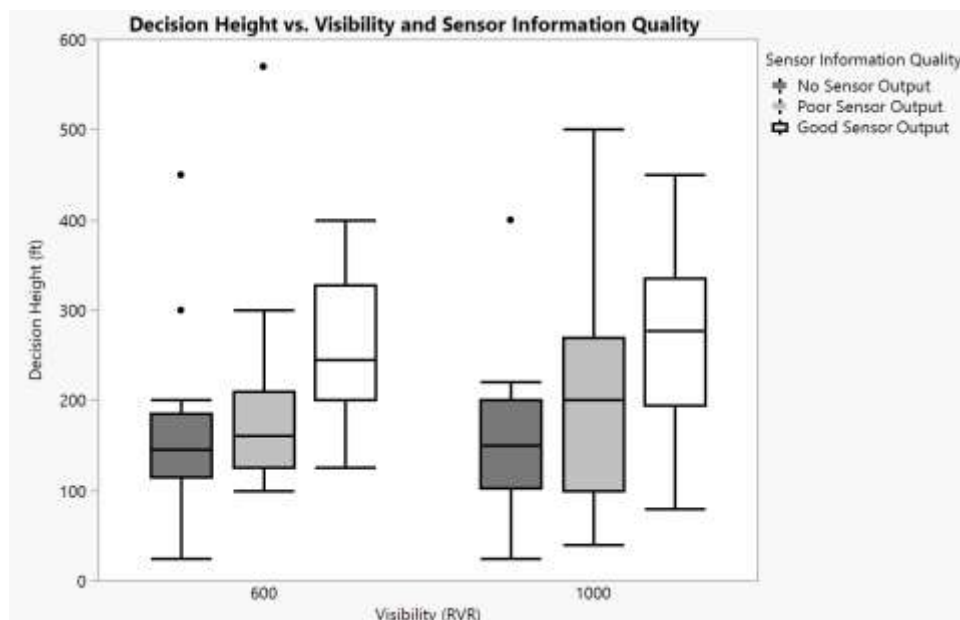


Figure 26. Decision Height for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

Based on the analyzed results, the exceedance on decision height was observed 17 times out of 139 recordings: (i.e. 12.2 %). With respect to good sensor output (both 600 ft and 1000 ft RVR), one out of 52 available recordings (i.e.1.9%), were observed with decision height exceedances. Moreover, 8 out of 46 approaches (i.e. 17.4%), conducted on no sensor output, and 4 out of 51 approaches (i.e. 7.8%), conducted with poor sensor output resulted in exceedances. With respect to visibility, 17 out of 78 approaches (i.e. 21.8%) resulted in decision height exceedances for 600ft RVR, and 10 out of 78 approaches (i.e. 12.8%) resulted in approach airspeed exceedances for 1000ft RVR.

Figure 27 illustrates the results on decision height exceedances for the combination of Sensor Information Quality and Visibility conditions. Pairwise comparison indicated that no sensor output ($M = 17.4\%$, $SE = 5.8$) has significantly more exceedances compared to good sensor output ($M = 1.9\%$, $SE = 2.0$, $\chi^2(1) = 4.5$, $p = .03$). No significant differences were observed between good sensor output ($M = 1.9\%$, $SE = 2.0$) and poor sensor output ($M = 7.8\%$, $SE = 4.2$, $\chi^2(1) = 1.0$, $p = .17$). No significant differences were observed between no sensor output ($M = 17.4\%$, $SE = 5.8$) and poor sensor output ($M = 7.8\%$, $SE = 4.2$, $\chi^2(1) = 1.0$, $p = .17$). With respect to Visibility, no significant differences were observed between 600ft RVR ($M = 21.2\%$, $SE = 2.6$), and 1000ft RVR ($M = 12.8\%$, $SE = 4.1$, $\chi^2(1) = 0.64$, $p = .29$).

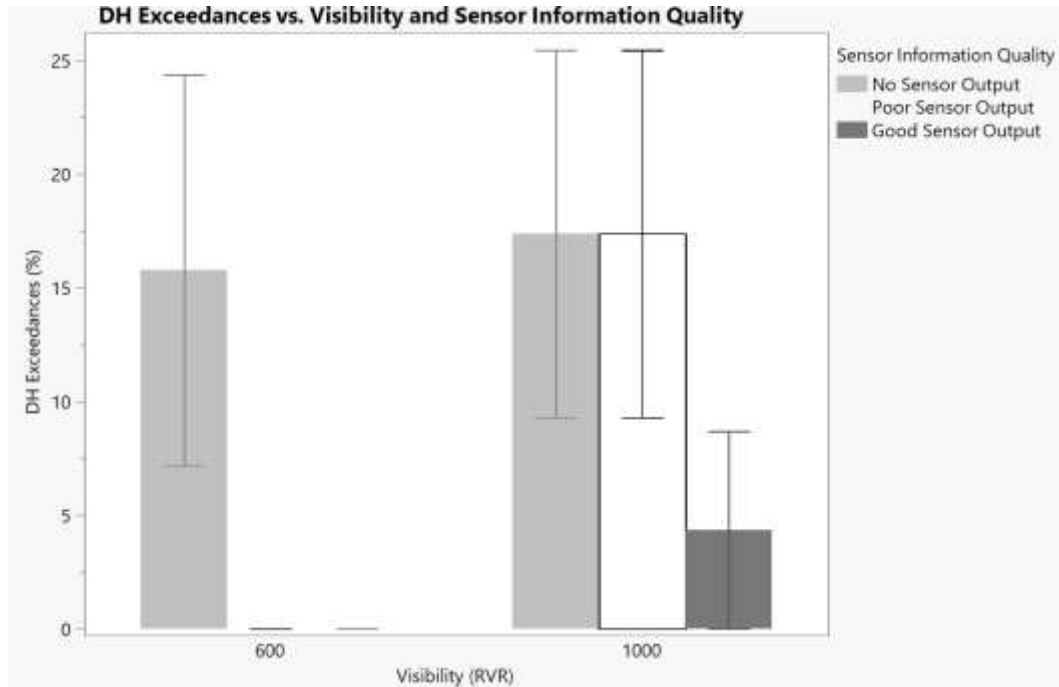


Figure 27. Decision Height Exceedances for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.5.3 Retrospective Interview on Decision Making

After the experimental trials were completed, pilots were interviewed to understand their opinions on important aspects of decision making.

1. The overall impact of the sensor-based flight vision system in pilot's decision making
2. How their decision making would be impacted by utilizing a sensor-based flight vision system displaying poor sensor output.

4.5.3.1 Pilot's Decision Making

Based on the analysis, 12 out of 26 pilots found the sensor-based flight vision system extremely helpful in obtaining the required visual information to proceed for landing operations. Their feedbacks reflected that they had an easier transition from the IFR approach to VFR landing without losing critical information such as speed and altitude. Moreover, the flight vision system

enabled pilots to gather visual cues in a low visible environment much earlier than expected and conduct a more stabilized approach as they were lined up on utilizing sensor output.

Also, 13 out of 26 pilots found the sensor technology moderately or slightly helpful. Their feedback reflected that they spent too much time on PFD (i.e. conducting the IFR approach) and utilized the HUD for a minimal time during the landing phase. One out of 26 pilots had reflected that he found the sensor-based flight vision system unhelpful in completing the landing tasks as it has caused him more problems. He also reported that he had no idea what the system was trying to inform him and seemed to be incorrect.

4.5.3.2 Identifying Degraded Sensor Output at or below DH

Pilots were also interviewed to understand the strategies they would use when poor sensor output. Nineteen out of 26 pilots indicated that they would perform a go-around or missed approach if they cannot identify the runway terrain through the HUD. Three pilots reported that they would descent below DH to gather other visual cues such as PAPI or RTL lights. If they could not visually acknowledge the lights, then they would perform a missed approach. One pilot mentioned that he would seek the aid of the tower for options. One pilot mentioned that he would categorize the issue into two types. If he identified the poor sensor output above DH, he would execute a missed approach. However, if he identified the issue below DH, he would proceed for a landing as would not have enough altitude to revert his decision. Also, two pilots described that they would disregard the sensor output and proceed for landing without relying on it.

4.6 Attention Allocation

4.6.1 First Fixation

The eye tracker analysis utilized 24 IFR pilot's data. Based on eye recording of 87 completed landings, 70% (58 out of 87) first fixations were on PAPI lights and 30 (24 out of 82) first fixations were on runway threshold line (RTL). Figure 28 illustrates the results of the first

fixation for the combination of Sensor information quality and Visibility conditions. The data were normally distributed with homogenous variance. The main effect of Sensor information quality was significant, $F(2,81) = 11.05, p < .001$. Pairwise comparison showed that first fixation in the no sensor output condition ($M = 162.8, SE = 23.6$) was significantly smaller than the good sensor output condition ($M = 278.7, SE = 17.1, p < .001, d = 1.31$). Also, pairwise comparison showed that decision height exceedances in the poor sensor output condition ($M = 190.5, SE = 20.1$) was significantly smaller than the good sensor output condition ($M = 278.7, SE = 17.1, p < .001, d = 0.89$). The main effect of Visibility was not significant, $F(1,81) = 1.06, p = 0.31$. Also, the interaction effect was not significant, $F(5,81) = 0.34, p = .71$.

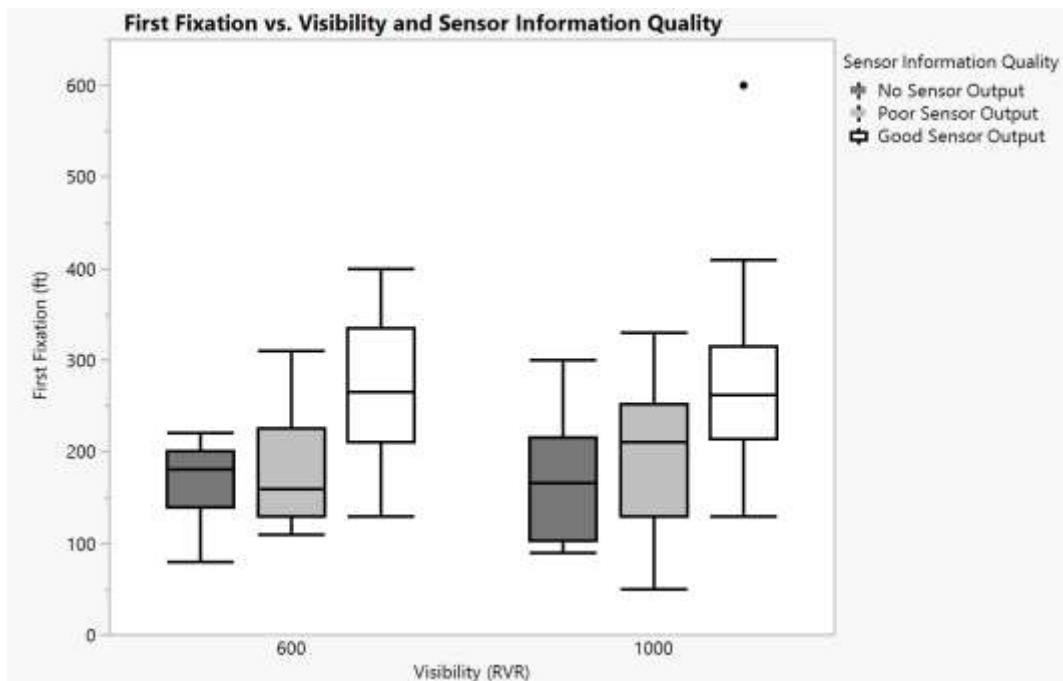


Figure 28. First Fixation on cue, measured from AGL for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.6.2 Altitude difference between First Cue Availability and First Fixation

Figure 29 illustrates the results on the difference in altitude between first availability and first fixation for the combination of Sensor information quality and Visibility conditions. The data were normally distributed with homogenous variance. The main effect of Sensor information

quality was not significant, $F(2,81) = 2.27, p = .11$. The main effect of Visibility was not significant, $F(1,81) = 0.12, p = .73$. Also, the interaction effect was not significant, $F(5,81) = 0.63, p = .53$.

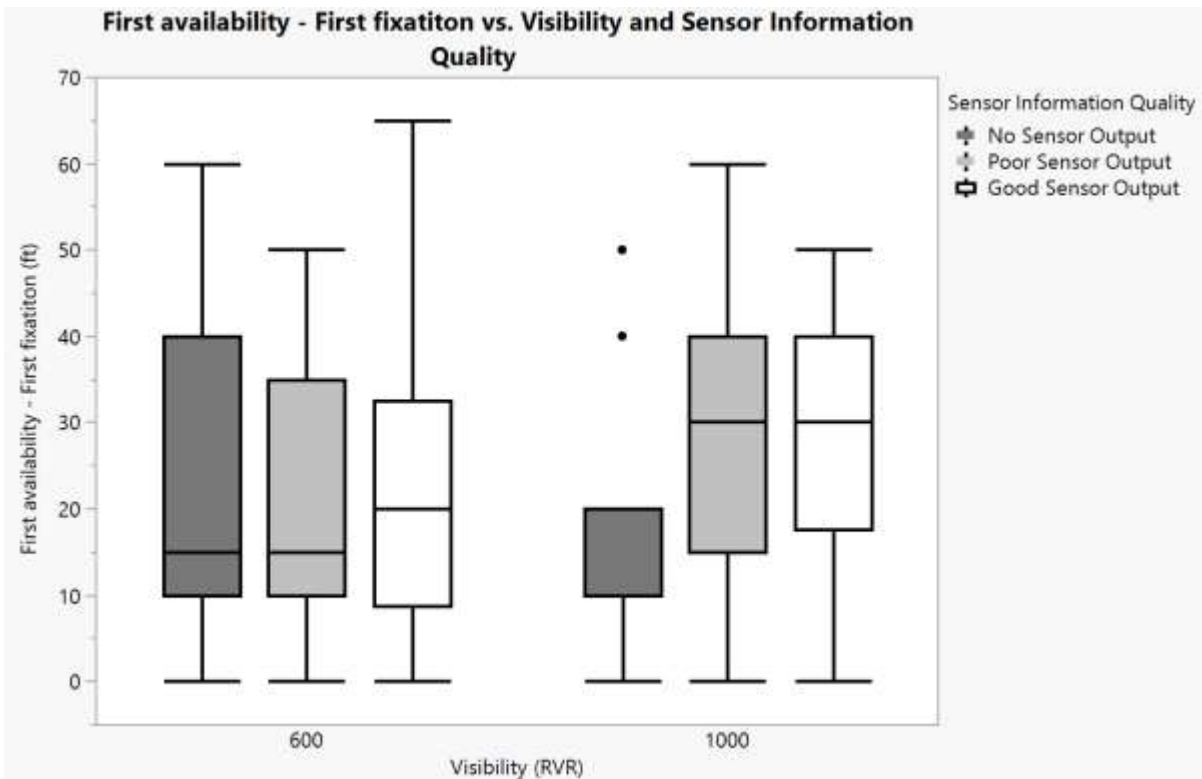


Figure 29. The difference in altitude between first availability and first fixation for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.6.3 Heat Maps

Based on 87 eye tracker data on completed performed, heat maps were generated. The color scale represents the duration of the fixation where green spots represent the participant's eye fixations of two seconds and red represents directions of six seconds. Figure 30 represents the heat map obtained for each IV combination.

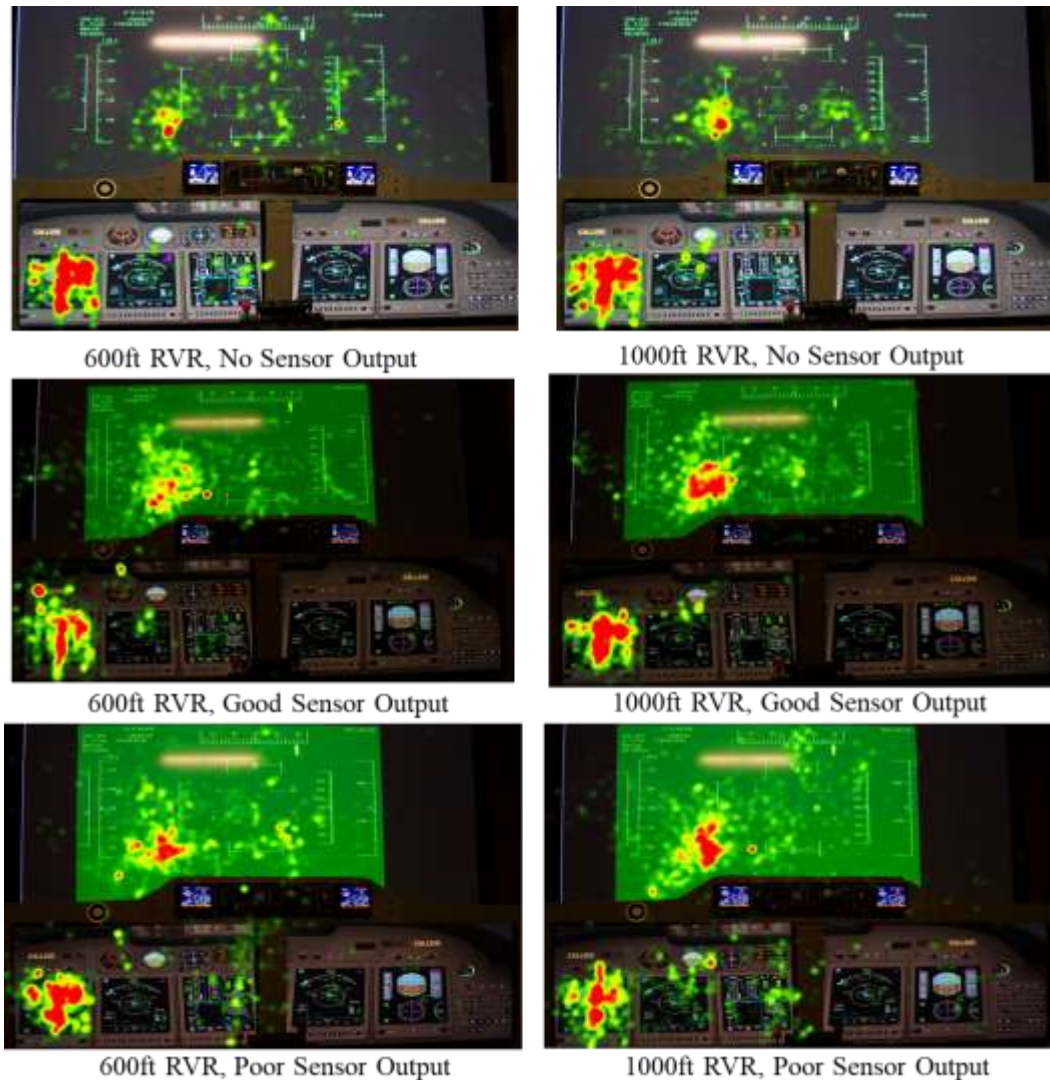


Figure 30. Heat Maps for all IV Combinations

4.6.4 Total Scan Distribution

Out of 127 eye tracker recordings, 87 completed flight recordings were utilized to determine the pilot's total scan time, which is distributed among PFD, HUD/OTW, and non-AOI region. The remaining 40 flight recordings were not considered since they were missed approaches. These data points were not reliable enough to derive the appropriate scan time during the landing phases of flight. The pilot's scan time among these areas of interest is reported for three different flight segments: IFR segment, transition segment, and VFR segment.

4.6.4.1 IFR Segment

The IFR segment begins from 1000ft AGL to 100ft prescribed DH for the flight. Figure 31 illustrates the results of total scan duration among PFD, HUD/OTW, and non-AOI for each combination of Sensor Information Quality and Visibility conditions, for the IFR segment.

For total scan duration within PFD, the main effect of Sensor Information Quality was highly significant $F(2,81) = 12.85, p < .001$. Pairwise comparison showed that PFD scan duration for the no sensor output condition ($M = 76.5, SE = 3.51$) was significantly larger than the good sensor output condition ($M = 54.6, SE = 2.56, p < .001, d = 2.1$). The main effect of Visibility was not significant, $F(1,81) = 0.07, p = .78$. and the interaction effect among them was not significant, $F(5,81) = 0.41, p = .66$.

For total scan duration within HUD/OTW, the main effect on Sensor Information Quality was highly significant, $F(2,81) = 13.01, p < .001$. Pairwise comparison showed that HUD/OTW scan duration for the good sensor output condition ($M = 37.66, SE = 2.35$) was significantly larger than the no sensor output condition ($M = 17.26, SE = 3.32, p < .001, d = 3.9$). The results for poor sensor output ($M = 31.36, SE = 2.7$) was significantly larger than no sensor output conditions ($M = 17.26, SE = 3.32, p = .0015, d = 1.9$). The main effect of Visibility was not significant, $F(1,81) = 0.06, p = .79$, and the interaction effect was not significant, $F(5,81) = 0.73, p = .48$.

The non-AOI region was excluded from the analysis as those regions did not provide any critical flight information for pilots to conduct the approach.

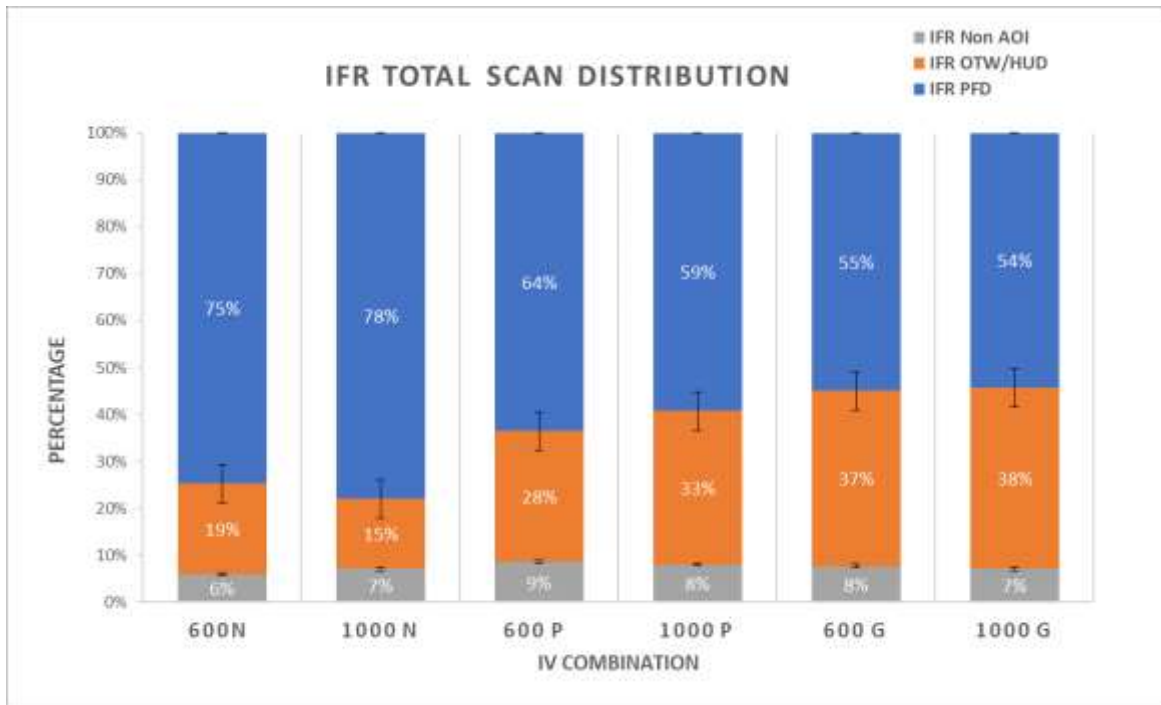


Figure 31. Distribution of Pilot's Scan for IFR Segment for the combination of six IVs
(Error bars represent the standard error)

4.6.4.2 Transition Segment

The Transition segment begins from 100ft DH to 55ft TCH of runway 05. Figure 32 illustrates the results of total scan duration among PFD, HUD/OTW, and non-AOI within the transition segment for each of the combinations of Sensor Information Quality and Visibility conditions.

For total scan duration within PFD, the main effect on Sensor Information Quality was not significant, $F(2,81) = 2.12, p = .12$. Also, the main effect on Visibility was not significant, $F(1,81) = 0.07, p = .79$. and the interaction effect was not significant, $F(5,81) = 0.08, p = .92$.

For total scan duration within HUD/OTW, the main effect on Sensor Information Quality, was not significant $F(2,81) = 2.32, p = .11$. and Visibility, $F(1,81) = 0.49, p = .48$. Also, the interaction effect was not significant, $F(5,81) = 0.37, p = .69$.

The non-AOI region was excluded from the analysis as those regions did not provide any critical flight information for pilots to conduct the approach.

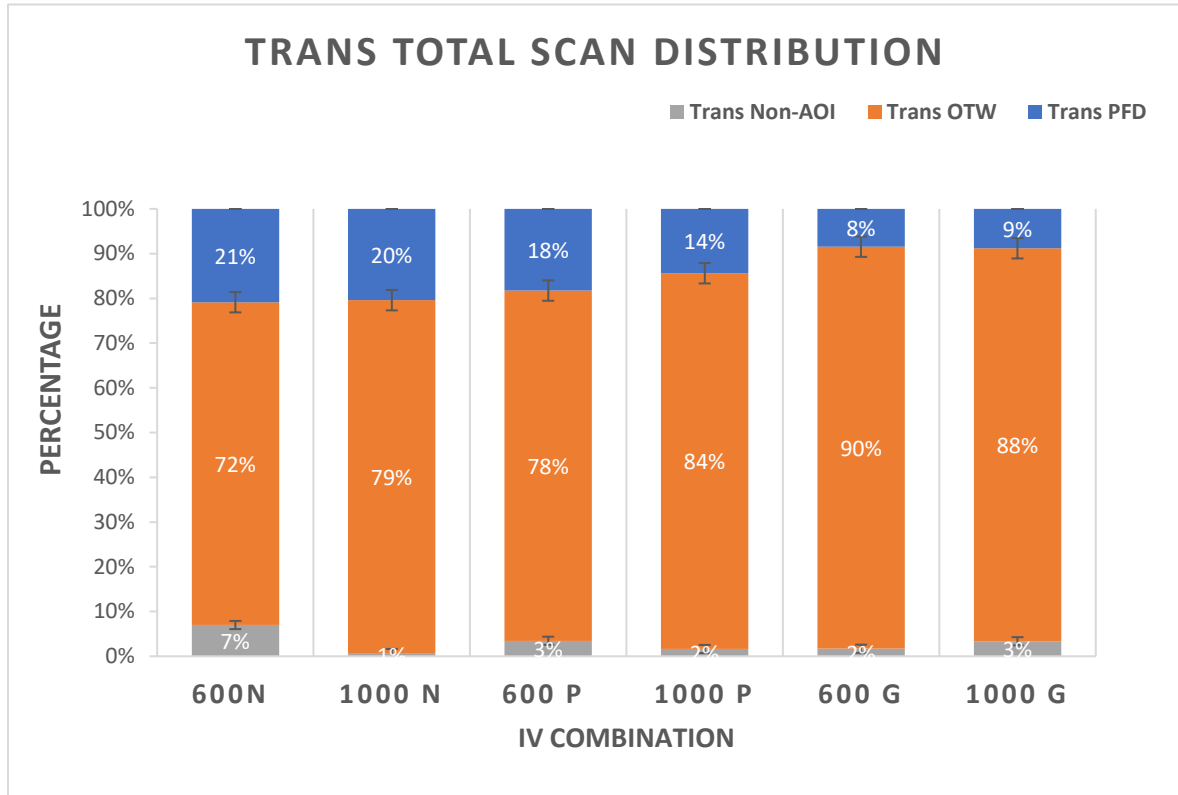


Figure 32. Distribution of Pilot's Scan for Transition Segment for the combination of six IVs
(Error bars represent the standard error)

4.6.4.3 VFR Segment

The Transition segment begins from 55ft TCH to the touchdown zone of runway 05. Figure 33 illustrates the distribution of total scan duration among PFD, HUD/OTW, and non-AOI within the VFR segment for each combination of Sensor Information Quality and Visibility conditions.

For total scan duration within PFD, the main effect on Sensor Information Quality was not significant, $F(2,81) = 2.41, p = .11$. But the main effect on Visibility was highly significant, $F(1,81) = 5.59, p = .002$. Pairwise comparison has indicated that 600ft RVR ($M = 3.2, SE = 0.95$) was

significantly larger than 1000ft RVR ($M = 0.29$, $SE = 0.86$, $d = 3.3$). The interaction effect was also highly significant, $F(5,81) = 4.72$, $p = .01$.

For total scan duration within HUD/OTW, the main effect of Sensor Information Quality was not significant, $F(2,81) = 0.88$, $p = .42$. Also, the main effect on Visibility was not significant $F(1,81) = 1.49$, $p = .22$. The interaction effect was marginally significant, $F(5,81) = 2.82$, $p = .07$.

The non-AOI region was excluded from the analysis as those regions did not provide any critical flight information for pilots to conduct the approach.

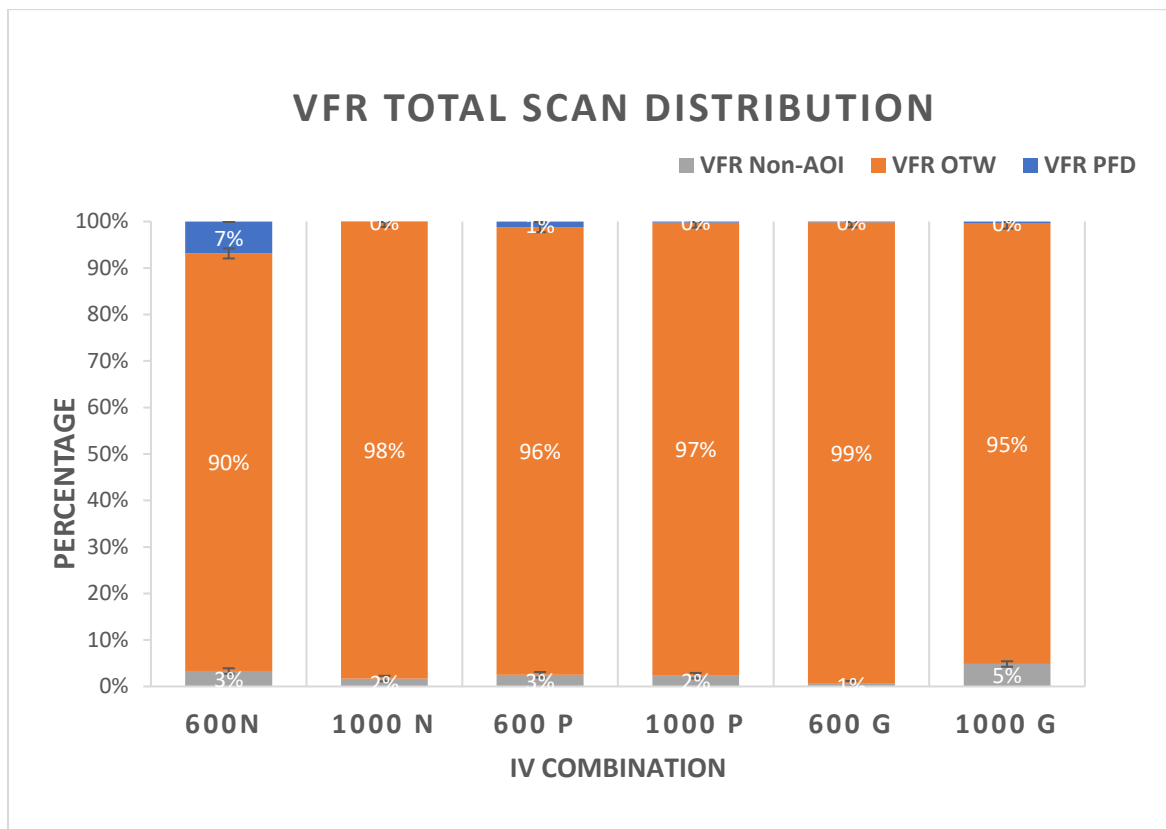


Figure 33. Distribution of Pilot's Scan for VFR Segment for the combination of six IVs
(Error bars represent the standard error)

Figure 34 illustrates the distribution of total scan duration among PFD, HUD/OTW, and non-AOI within all three segments for each combination of Sensor Information Quality and Visibility conditions.

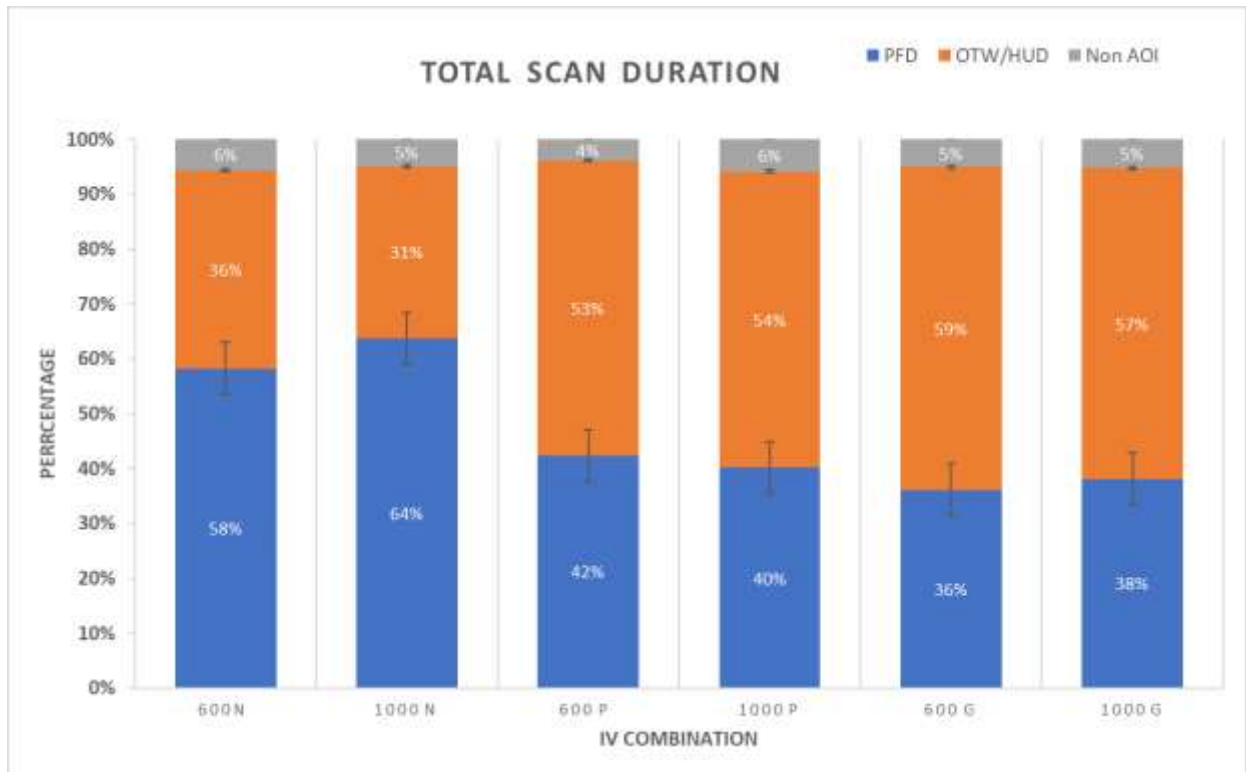


Figure 34. Distribution of Pilot's Scan for Total Scan duration for six IV combinations (Error bars represent the standard error)

4.6.5 Transitions between HUD/OTW and PFD

Out of 127 eye tracker recordings, 87 completed flight recordings were utilized to determine the pilot's transition between HUD/OTW, and PFD. Figure 35 illustrates the results of total transitions between PFD and HUD/OTW for the combination of Sensor Information Quality and Visibility conditions. The main effect of Sensor Information Quality was not significant $F(2,81) = 0.09, p = .90$. Also, the main effect on Visibility was not significant $F(1,81) = 0.92, p = .35$. The interaction effect among them was not significant $F(5,81) = 0.35, p = .72$.

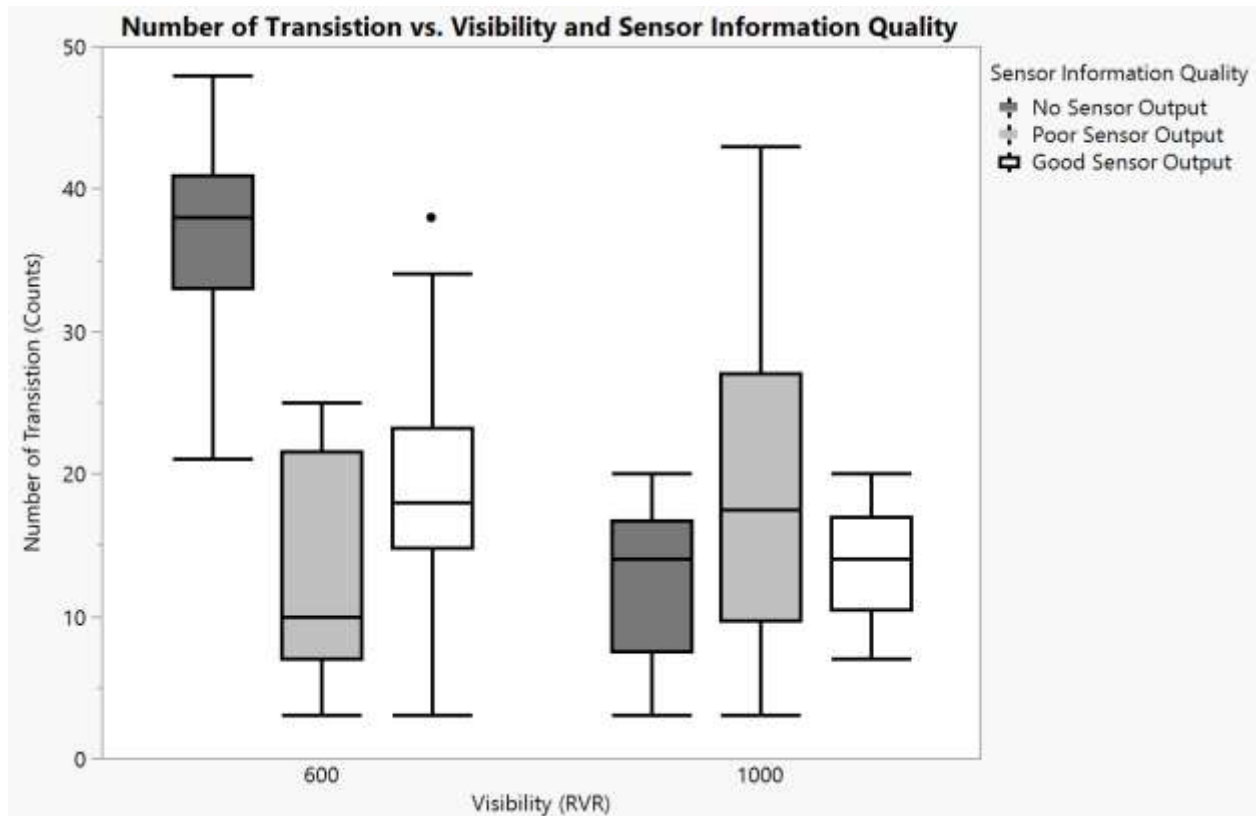


Figure 35. Total Transition among PFD and HUD/OTW for two levels of visibility and three levels of sensor information quality (Error bars represent the standard error)

4.7 IFR Experience

Figure 36 shows a histogram of the pilot's IFR experience in 50-hour bins. To determine the impact of pilot's IFR experience over independent variables, pilots were categorized into three categories: High-level experience (i.e. IFR experience greater than 200 flight hours, $n = 7$), Medium level experience (i.e. IFR experience between 100 to 200 flight hours, $n = 5$), and Low-level experience (i.e. IFR experience between 0 to 99 flight hours $n = 12$). A three-way ANOVA was performed using IFR experience, besides, the other two independent variables (i.e. Visibility and Sensor Information Quality). ANOVA results do not indicate any main effect on IFR experience nor interaction effect for any of the dependent variables with respect to IFR experience.

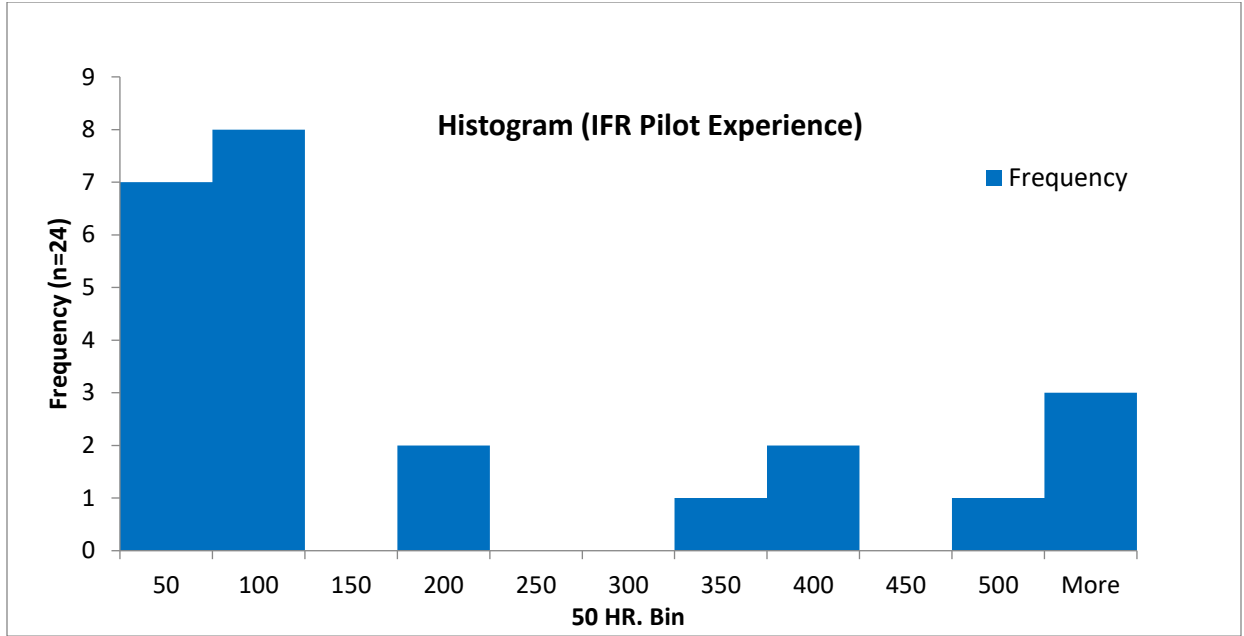


Figure 36. Pilot's IFR Experience

4.8 Summary Statistics

A summary of the statistical tests performed on each dependent variable is tabulated in.

Table 5 records the percentage of FAA exceedances occurred per flight and Table 6 records the Bowker's test summary.

Table 4. Summary Statistics for Dependent Variables

(blank cells indicate was no significant effect, ** indicate highly significant effect,

* indicates significant effect, m indicates marginal significant effect)

S.NO	Dependent Variable	Main Effect		Interaction Effect	Tukey's HSD	
		Visibility	Sensor IQ		Visibility (600ft - 1000ft)	Sensor IQ (No-Poor-Good)
1	Glideslope RMS	.71	.11	.11	-	-
	Localizer RMS	.91	.003**	.21	-	Poor > Good, No > Good
	Sink Rate	.64	.15	.004**	-	-
	Approach Airspeed	.74	.14	.43	-	-

Table 4 Continued

S.NO	Dependent Variable		Main Effect		Interaction Effect	Tukey's HSD		
			Visibility	Sensor IQ		Visibility (600ft - 1000ft)	Sensor IQ (No-Poor-Good)	
2	Landing Performance	Distance from CL	.86	<.001**	.58	-	No > Good, No > Poor	
		Distance from TDM	.003**	<.001**	.10	600 > 1000	Poor > Good, Poor > No	
		Vertical Speed at Touchdown	.58	.63	.76	-	-	
3	Overall Workload		.66	<.001**	.006**	-	No > Good	
4	Overall Situation Awareness		.89	.90	.67	-	-	
5	Decision Making	Successful Decision to Land	.07 ^m	.04*	.67	1000 > 600	Good > Poor	
		Decision Height for Flight	.93	.005**	.51	-	Good > Poor, Good > No	
6	Attention Allocation	First Fixation	.31	<.001**	.71	-	Good > Poor, Good > No	
		Difference between First Availability and First Fixation		.73	.11	.53	-	-
		Total Scan Duration in IFR Segment	PFD	.78	<.001**	.66	-	No > Poor
			HUD /OTW	.79	<.001**	.48	-	Poor > No
		Total Scan Duration in Trans. Segment	PFD	.79	.12	.92	-	-
			HUD /OTW	.48	.12	.69	-	-

Table 4 Continued

S.NO	Dependent Variable			Main Effect		Interaction Effect	Tukey's HSD	
				Visibility	Sensor IQ		Visibility (600ft - 1000ft)	Sensor IQ (No-Poor-Good)
6	Attention Allocation	Total Scan Duration in VFR Segment	PFD	.002**	.11	.01*	600 > 1000	-
			HUD /OTW	.22	.42	.07 ^m	-	-
		Number of Transitions (PFD & HUD/OTW)			.35	.90	.72	-

Table 5. Exceedance Summary (%)

S.NO	Dependent Variable	Sensor Information Quality						Visibility			
		None		Poor		Good		600ft		1000ft	
		M	SE	M	SE	M	SE	M	SE	M	SE
1	Glideslope Exceedances	65.3	8.8	44.2	13.1	34.6	12.2	51.2	6.2	44.8	4.4
2	Localizer Exceedances	25.0	8.1	17.3	8.4	9.6	6.3	20.5	4.6	14.1	3.3
3	Sink Rate Exceedances	50.0	7.0	50.0	7.0	50.0	7.0	50.0	5.7	50.0	5.7
4	Approach Airspeed Exceedances	38.4	6.8	36.5	6.7	42.3	6.9	43.6	5.6	34.6	5.4
5	Decision Height Exceedances	17.4	5.8	7.8	4.2	1.9	2.0	21.8	2.6	12.9	4.1

Table 6. Bowker's Test Summary

Pairwise IV		Glideslope Exceedances > .75 scale	Localizer Exceedances > .75 scale	Sink Rate Exceedances > 1000 fpm	Approach Airspeed Exceedances 140+/- 20 kts	DH Exceedances < 100ft
Sensor IQ	Good-Poor	.25	.20	.99	.14	.17
	Poor- No	.02	.31	.46	.81	.36
	No-Good	.002	.06	.39	.65	.03
Visibility	600 -1000	.43	.29	.99	.25	.29

CHAPTER 5. DISCUSSION

The objective of the thesis was to evaluate the effect of a sensor-based flight vision system displaying poor sensor output over pilot performance. The evaluation assessed three experimental hypotheses, each of which are discussed below based on the experimental results:

5.1 Hypothesis 1

H1: The use of sensor-based flight vision system displaying poor sensor output will decrease the pilot's approach and landing performance, situation awareness, and increase workload when compared to the flight vision system with good sensor output.

5.1.1 Approach and Landing Performance

Hypothesis H1 on the pilot's approach and landing performance was partially supported. Significant negative effects were detected in the landing performance, rather than the approach. In the approach phase, pilots were more focused on conducting the IFR approach using the PFD. This has resulted in comparatively less utilization of HUD during approach phases of flight and the sensor information quality has not affected the pilot's approach performance. In the approach side, one (i.e. localizer) out of four parameters was affected whereas the landing side was witnessed two parameters (i.e. distance from touchdown and distance from centerline) negatively affected out of three. Overall, of seven performance parameters, three of them (localizer deviation, distance from centerline and touchdown) were significantly negatively impacted due to poor sensor output. The results of the first fixation on visual cues indicated that the pilot's altitude in fixating the runway terrain in a poor sensor output is 190.5 ft. For a good sensor output, the first fixation altitude was 278.7 ft. So, pilots have less time in fixating the runway terrain which eventually led them to land much farther distances from touchdown markers than expected. These results are reflected in the mean distance away from a touchdown. For a good sensor output, the mean distance away from the

centerline was 98.4 ft, whereas the mean distance away from the touchdown for a poor sensor output was 664.5 ft.

5.1.2 Situation Awareness

Hypothesis H1 on the pilot's situation awareness was not supported. Based on previous literature (Arthur et al.,2013), an increase in the number of transitions between different displays (i.e. HUD and PFD) could lead to a decrease in situation awareness. There was not a significant change in the number of transitions between poor and good, implying the transition between PFD and HUD/OTW was not impacted by Sensor Information Quality. This observation partially supports the results of situation awareness among poor and good sensor output

5.1.3 Decision Making

Hypothesis H1 on the pilot's decision making was fully supported. The average sink rate for poor and good sensor output was -1082.3ft/min and -1019.2ft/min respectively from 1000ft AGL. The decision height for good and poor sensor output was 317.7 ft and 193.5 ft, respectively. On assuming $t = 0$ at 1000ft AGL, we could determine the time taken by pilot to reach their decision height for poor and good sensor output, by plugging sink rate and DH values into speed formula (i.e. Speed = distance covered/time taken). Replace speed with sink rates and distance covered with altitude to be covered from 1000ft to DH for respective sensor information quality. For good sensor output conditions, pilots made their decision (on average) 38 sec after crossing the 1000ft AGL. In the poor sensor output condition, pilots made their decision 48 sec after crossing 1000ft AGL. Thus, in the good sensor output condition, pilots were able to decide 10 sec earlier than pilots in the poor sensor condition.

5.1.4 Workload

Hypothesis H1 on the pilot's workload was not supported. The pairwise comparison among good and poor sensor output does not indicate any significant effect. The TLX workload measures

showed the pilots experienced significantly more workload for no sensor output case than both poor and good sensor quality, due to lack of forward visibility to complete the landing. During the poor sensor output trial briefing, pilots were informed that about the range of expected sensor outputs but were not provided details about the degraded sensor output or which part of flight they might experience it. The lack of explanation on poor sensor output was utilized to eliminate any anticipation effect within the trial (i.e. if explained at the beginning of the trial, pilots might anticipate the degraded runway terrain displayed through the HUD and prepare themselves to overcome the challenge presented by different means). During the descent and approach phases, pilots had the PAPI lights and other runway surrounding lights presented to them in both poor and good sensor output, thus leading to determine the location of the runway. So, it can be assumed that pilots have experienced less overall workload during the descent and approach phases. At the very end, during landing, there is a difference in performance. However, that did not translate into a change in the overall workload for the entire trial that includes all three phases of flight.

On comparing workload measures to previous literature (Korn, 2007), the increase in the number of transitions could lead to an increase in workload. The number of transitions in poor and good scenarios has no significant effect. This observation partially supports the non-significant results of overall workload among poor and good sensor output

5.2 Hypothesis 2

H2: The total time spent on HUD decreases with lower visibility levels

The second hypothesis evaluates the effect of visibility over the utilization of HUD. This hypothesis was not supported. The results on HUD utilization for three segments (i.e. IFR, Trans., VFR) does not reveal any significant effect with respect to Visibility. The difference in HUD utilization between 600 ft RVR and 1000ft RVR was found to be ~1% and 2.2% for good and poor

sensor output, respectively. So, it can be concluded that a margin of 400ft RVR loss of visibility does not impact the total HUD utilization.

5.3 Hypothesis 3

H3: The number of incorrect decisions to land will increase with the use of sensor-based flight vision system displaying degraded sensor output when compared to flight vision system displaying good sensor output

The third hypothesis evaluates the impact of poor sensor output over successful landing decisions. This hypothesis was fully supported as poor sensor output had a negative effect on decisions compared to the good sensor output. The good sensor output and poor sensor output resulted in 11.2% and 38.3% incorrect decisions, respectively. These results indicate that pilots might have had difficulty in identifying the runway, leading to higher incorrect landing decisions in poor sensor output as compared to the good sensor output.

5.4 Observations based on Attention Allocation

Based on the first fixation results of 87 completed flights as mentioned in Chapter 4.6.1, pilots who fixated on PAPI has committed 10 incorrect landing decision out of 62 flights (i.e. 16.2 %) and pilots who fixated on RTL has committed one incorrect landing decision out of 24 flights (4%). One incorrect decision was made of 36 flights when PAPI lights were fixated with respect to the good sensor output. Four incorrect decisions were made of 27 flights when PAPI lights were fixated with respect to the poor sensor output. The remaining five incorrect decision on fixating PAPI lights were resulted out of no sensor output. So, it can be concluded that pilots who fixated on PAPI lights were likely to commit more incorrect landing decisions compared to pilots who fixated on runway threshold line (RTL) given that they don't have enough forward visibility (i.e. no sensor output) or difficulty in distinguishing the runway from its surrounding (i.e. poor sensor output). This observation also coincides with the FAA guidelines that pilots should visually

acknowledge the ALS or the runway threshold (RTL) or the touchdown zone as mentioned in AC106-90A. Moreover, the guideline mandates that PAPI lights should not be utilized as a visual reference for HUD based landings.

5.5 Observations within Sensor Information Quality

On comparing within three levels of sensor information quality based on the pilot study findings, the no sensor output and poor sensor output were challenging for pilots. With respect to the no sensor output conditions, pilots performed a complete IFR approach using their PFD and transitioned to VFR at or around 100ft DH. Due to the lack of forwarding visibility within no sensor output, pilots performed numerous missed approaches and experienced a high overall workload compared to the other two levels of sensor information quality. Poor sensor output has resulted in no overall workload or overall situation awareness difference when compared to the good sensor output condition, however, landing performance and decision making were negatively affected. With respect to the poor sensor output condition, 70% of pilots first fixated on PAPI lights at an average of 250ft AGL, but the runway was not distinguishable. However, the PAPI lights are not an approximate cue on which to make a landing decision. This scenario has also accounted for the most incorrect landing decisions made by pilots. For the good sensor output conditions, pilots had information about the runway whereabouts at 300ft which enabled them to visually recognize the landing cues. This scenario has accounted for the least incorrect decisions.

CHAPTER 6. CONCLUSION

6.1 Summary

This thesis has identified the negative impact of utilizing a sensor-based flight vision system displaying degraded sensor output on landing performance and decision making. A within-subject simulator study was conducted to determine the impact of Sensor Information Quality and Visibility. The results of this study showed that the effect of poor sensor output has a negative impact on performance factors such as localizer deviations, distance from touchdown, decision height for flight, and successful landing decisions when compared to the good sensor output. Specifically:

- the maximum exceedances were observed on the approach side and the maximum negative impact of poor sensor output was observed on the landing side,
- the pilot's workload or situation awareness was not negatively impacted by sensor limitations,
- Pilot's decision making was found to be negatively impacted due to sensor limitation, and
- Attention allocation results indicate that out of four visual cues for decision making, pilots had utilized only two (i.e. PAPI and RTL), and fixating on RTL is critical to avoid incorrect landing decisions.

6.2 Contributions

The contributions of this thesis work are described below:

1. This thesis has identified sensor limitations which could negatively impact pilot performance.

2. Through the pilot-in-the-loop study, the negative impact of poor sensor output was identified over landing performance and decision making whereas other dependent variables such as approach performance, workload, and situation awareness were least impacted.

3. Through the pilot's eye tracker data obtained, this thesis has identified the decision cues utilized by pilots in landing operations and discussed the importance of fixating on runway threshold line (RTL) to reduce the likelihood of incorrect landing decisions.

6.3 Limitations

The pilot study had few limitations which are likely to have an impact on overall experimental results. This study has mimicked sensor limitation associated with MMWR based flight vision system (i.e. image contrast fall negative in a foggy day). There are other sensor limitations with respect to different sensor types which could be studied in the future. With respect to decision cues, this experiment has utilized runway 05, KDSM airport which lacks ALS visual cue. ALS was recommended by the FAA as one of the decision cues to be visually acknowledge by pilots for Type I EFVS operation.

6.4 Future Work

The experiment evaluates the connection between pilot performance and sensor limitations. The recommendation for further research should address the following. Designing pilot in the loop studies to evaluate sensor limitation associated with other sensor types such as Infrared or multispectral sensors would be an ideal follow up work. Given that FAA has no visibility minimums on the utilization of sensor-based flight vision system, evaluation of sensor-based flight for much lower visibility levels such as 300ft RVR or CAT III system could be performed with the use of high fidelity simulator. Also, the evaluation of the sensor-based flight vision system in airports with ALS lighting might introduce new results with respect to the pilot's attention allocation and decision making.

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APPENDIX. IRB STUDY MATERIALS FOR PILOT STUDY

1. Consent Form

ISU IRB: 18-129-00
Approved Date: 02/19/2020
Expiration Date: N/A

CONSENT FORM FOR: PILOT PERFORMANCE CONSIDERATIONS FOR SENSOR TECHNOLOGY

This form describes a research project. It has information to help you decide whether or not you wish to participate. Research studies include only people who choose to take part—your participation is completely voluntary. Please discuss any questions you have about the study or about this form with the project staff before deciding to participate.

Who is conducting this study?

This study is being conducted by Güliz Tokadli, Dr. Michael Dorneich, and Ramanathan Annamalai.

Why am I invited to participate in this study?

You are being asked to take part in this study because you are older than 18 year-old, and have at least 20 hours of instrument flight experience.

What is the purpose of this study?

The purpose of this study is to investigate how a pilot makes a flight decision with or without enhanced flight vision system.

What will I be asked to do?

You will be asked to complete the following procedure:

1. Welcoming and informed consent: You will be given a briefing of the Informed Consent form.
2. Pre-experiment Questionnaire: You will be asked to complete pre-experiment questionnaire to learn about their demographics and background.
3. The researcher will introduce the simulator, the tasks, and NASA_TLX that you will perform during the study.
4. Eye-tracker: Before the tasks start, if you are using prescription eye glasses, you will be asked to read the letters located on the wall to determine which eye-tracking glasses' lens should be attached to the eye-tracking glasses. Once the appropriate lens for the eye-tracking glasses are attached, you will be asked to wear an eye-tracking glasses and the researcher will calibrate the glasses to your prescription, should it be needed. In addition to eye-tracker device, the simulator area will be video recorded.
5. Tasks and Post-task questionnaire: You will perform flight tasks and after each task, you will complete a post-task questionnaire. In some of the tasks, you will be asked to use enhanced vision flight system display to complete the flight tasks. During the flight tasks, the flight simulator area will be video recorded, so we can review the recordings together during the post-experiment interview session.
6. Post-experiment interview: After the tasks are completed, you will participate in a post-experiment interview, where the video recordings of the flight tasks will be reviewed and

you will be asked to recount what you were thinking during the flight. Also, you will be asked to fill out and answer some questions as a part of this interview. During the interview, the researcher will record audio.

The study will take approximately 120 minutes in total.

What are the possible risks and benefits of my participation?

Risks — During the tasks, you may be asked to use eye-tracker glasses. It is unlikely that you may experience mild discomfort during the tasks. In this situation, you may take longer breaks between tasks, or remove them entirely.

Benefits — There are no direct benefits to you. By participating in this study, you can provide valuable insights into flight operations.

How will the information I provide be used?

The information you provide will be used for data analysis for this research study.

What measures will be taken to ensure the confidentiality of the data or to protect my privacy?

Records identifying you will be kept confidential to the extent allowed by applicable laws and regulations. Records will not be made publicly available. However, federal government regulatory agencies, auditing departments of Iowa State University, and the ISU Institutional Review Board (a committee that reviews and approves research studies with human subjects) may inspect and/or copy your records for quality assurance and analysis. These records may contain private information.

To ensure confidentiality to the extent allowed by law, the following measures will be taken: Your name will be replaced with an ID code, and it will also be stored separately from the data in a locked filing cabinet from the study data. All data collected will be stored in a locked cabinet at a locked office and on CyBox (digital data). Cybox, is the encrypted Box platform developed for Iowa State University, will be used to store all electronic data and information collected during the experiment. If the results are published, your identity will remain confidential. Video will be recorded while you perform the tasks. If any video recordings taken during the research study will be used publically, your face will be blurred to protect your identity.

De-identified information collected during the experiment may be shared with other researchers (who are a part of sponsored research project) or used for future research studies by the researchers or sponsor. We will not obtain additional informed consent from you before sharing the de-identified data.

The divisions of FAA (Federal Aviation Authority), Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS) and Center of Excellence (COE) for General Aviation, may inspect or copy the study records for quality assurance.

Will I incur any costs from participating or will I be compensated?

You will be compensated for \$50 for your participation.

What are my rights as a human research participant?

Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. You can skip any questions that you do not wish to answer.

Your choice of whether or not to participate will have no impact on you as a student/employee in any way.

Whom can I call if I have questions or problems?

You are encouraged to ask questions at any time during this study.

- For further information about the study contact Ramanathan Annamalai (ramanatan@iastate.edu), Guliz Tokadli (gtokadli@iastate.edu) or Dr. Michael Dorneich (dorneich@iastate.edu).
- If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, 1138 Pearson Hall, Iowa State University, Ames, Iowa 50011.

Consent and Authorization Provisions

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant's Name (printed) _____

(Participant's Signature)

(Date)

2. IRB Approval Form

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 03/19/2020
To: Michael Dorneich, Ph.D.
From: Office for Responsible Research
Title: **Pilot Performance Considerations for Sensor Technologies**
IRB ID: 18-139
Submission Type: Modification **Review Type:** Expedited
Approval Date: 03/19/2020 **Approval Expiration Date:** N/A

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.
- **Retain signed informed consent documents for 3 years after the close of the study**, when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study or study materials.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an [eligible PI](#) to remain open.
- **Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences involving risks to subjects or others; and (2) any other unanticipated problems involving risks to subjects or others.**
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of

IRB 01/2019

those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to **post-approval monitoring** by Iowa State University's Office for **Responsible Research**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.
- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the [IRB Study Closure Policy](#).

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.
- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

3. Pay Compensation Form

Account #
436-20-13

CONFIDENTIAL CONFIDENTIAL CONFIDENTIAL CONFIDENTIAL

Iowa State University
Research Participant Receipt Form (RPRF)
Use if this payment is less than \$100

Iowa State University (ISU) is required to maintain the confidentiality of information about research study participants while still complying with record keeping requirements of the State of Iowa, the Internal Revenue Service (IRS), and funding agencies. The purpose of this form is to serve as documentation of the receipt of compensation associated with participation in a research study conducted by ISU personnel.

I, _____, have received/or am requesting compensation in
(Print Research Participant Name) the form and amount indicated below:

Cash \$ _____

Check \$ 50.00

Gift Certificate/Card \$ _____

Other Property – Describe: _____

Value: \$ _____

Research Participant Signature

Date

TO ISU PERSONNEL:

Research participants may be given the opportunity to participate without receiving payment if they choose not to complete this receipt form.

This form provides documentation for gift certificates/cards or other property purchased by ISU p-card—keep original form as part of your p-card documentation.

If an ISU check needs to be issued for payment, attach the RPRF to completed Simple Disbursement Voucher (SDV) in KFS.

If a cash advance was used to pay the participants, attach the RPRF to a Distribution of Income (DI) form in KFS.

Name + Address :

Revised July 1, 2013