U.S. Department of Transportation
Federal Aviation Administration

Office of the Administrator

800 Independence Ave., S.W.
Washington, DC 20591

April 5, 2022

The Honorable Maria Cantwell
Chair, Committee on Commerce,
Science, and Transportation
United States Senate
Washington, DC 20510

Dear Chair Cantwell:

As required by the FAA Reauthorization Act of 2018 (Public Law 115-254), Section 306, the Federal Aviation Administration is pleased to provide the enclosed report on Advanced Cockpit Displays.

A similar response has been sent to the Ranking Member of the Senate Committee on Commerce, Science, and Transportation, and the Chair and Ranking Member of the House Committee on Transportation and Infrastructure.

Sincerely,

Billy Nolen
Acting Administrator

Enclosure

U.S. Department
of Transportation
Federal Aviation
Administration

Office of the Administrator

800 Independence Ave., S.W.
Washington, DC 20591

April 5, 2022

The Honorable Roger F. Wicker
Ranking Member, Committee on Commerce,
Science, and Transportation
United States Senate
Washington, DC 20510

Dear Ranking Member Wicker:

As required by the FAA Reauthorization Act of 2018 (Public Law 115-254), Section 306, the Federal Aviation Administration is pleased to provide the enclosed report on Advanced Cockpit Displays.

A similar response has been sent to the Chair of the Senate Committee on Commerce, Science, and Transportation, and the Chair and Ranking Member of the House Committee on Transportation and Infrastructure.

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U.S. Department of Transportation
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800 Independence Ave., S.W.
Washington, DC 20591

April 5, 2022

The Honorable Peter A. DeFazio
Chair, Committee on Transportation
and Infrastructure
House of Representatives
Washington, DC 20515

Dear Chair DeFazio:

As required by the FAA Reauthorization Act of 2018 (Public Law 115-254), Section 306, the Federal Aviation Administration is pleased to provide the enclosed report on Advanced Cockpit Displays.

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U.S. Department
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800 Independence Ave., S.W.
Washington, DC 20591

April 5, 2022

The Honorable Sam Graves
Ranking Member, Committee on Transportation
and Infrastructure
House of Representatives
Washington, DC 20515

Dear Ranking Member Graves:

As required by the FAA Reauthorization Act of 2018 (Public Law 115-254), Section 306, the Federal Aviation Administration is pleased to provide the enclosed report on Advanced Cockpit Displays.

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FAA
Flight Technologies and Procedures Division

REPORT TO CONGRESS:

Advanced Cockpit Displays

FAA Reauthorization Act of 2018 (Pub. L. No. 115-254) Section 306

Abstract

Advanced cockpit displays, including Head-Up Displays (HUD), Heads-Down Displays (HDD), Enhanced Vision Systems (EVS), Synthetic Vision Systems (SVS), and Combined Vision Systems (CVS), are becoming more widely available in the National Airspace System (NAS). Operators are having to make decisions about equipping their fleet with these technologies, while policymakers are evolving regulations to account for the increasing availability of advanced cockpit displays. This report characterizes the current state of advanced cockpit display technology, regulatory environment, and equipage and examines the safety and efficiency impacts of these vision systems.

Vision systems can provide better situational awareness to the flight crew, which could manifest in fewer safety events and better energy management during critical phases of flight. A review of National Transportation Safety Board (NTSB) reports revealed a number of accidents and incidents where the use of a vision system may have provided a better outcome. In addition, analysis of Flight Operations Quality Assurance (FOQA) and Aviation Safety Action Program (ASAP) data, obtained through the Aviation Safety Information and Analysis Sharing (ASIAS) program, indicated that aircraft with HUD on had lower rates of unstable approaches and terrain alerts, alerted the flight crew to safety risks, and may generally improve situational awareness.

Vision systems can also provide efficiency benefits to equipped fleets, as these technologies may enable takeoff and landing during conditions that would prevent non-equipped aircraft from doing the same, resulting in increased airport access and throughput during those weather conditions. Exploration of cancellations, ground delay, airborne delay, and diversions that occur during low visibility conditions revealed a significant potential benefits pool for vision systems that could be achieved with wider adoption of these technologies. Additionally, there are various potential applications of vision systems that could provide benefits with the continued evolution of technology, integration with flight operations, and regulations.

There are substantial costs associated with purchasing vision systems and completing required pilot training and Operations Specifications (OpSpec) processes for gaining operational credit. While costs are a big driver for investment decisions around vision systems, the other big factor is the limited space in the cockpit. When the vision system uses a HUD or HDD, it is not feasible in many cases to fit the additional display and instrumentation into an already cramped cockpit. Head Worn Displays (HWDs) may offer a path for more widespread equipage, as they can be implemented in virtually any cockpit; however, there are numerous challenges to overcome before HWDs are available for widespread use.

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1 Introduction

Advanced cockpit displays, including Head-Up Displays (HUD), Enhanced Vision Systems (EVS), Synthetic Vision Systems (SVS), and Combined Vision Systems (CVS), are becoming more widely available in the National Airspace System (NAS). Operators are having to make decisions about equipping their fleet with these technologies, while policymakers are evolving regulations to account for the increasing availability of advanced cockpit displays. This report characterizes the current state of vision systems, the regulatory environment and describes and quantifies their safety and efficiency impacts, satisfying the language in Section 306 of the Federal Aviation Administration (FAA) Reauthorization Act of 2018 [1], which reads as follows:

> *SEC. 306. ADVANCED COCKPIT DISPLAYS.*
>
> *(a) IN GENERAL.—Not later than 180 days after the date of enactment of this Act, the Administrator shall initiate a review of heads-up display systems, heads-down display systems employing synthetic vision systems, and enhanced vision systems (in this section referred to as ''HUD systems'', ''SVS'', and ''EVS'', respectively).*
>
> *(b) CONTENTS.—The review shall— (1) evaluate the impacts of single- and dual-installed HUD systems, SVS, and EVS on the safety and efficiency of aircraft operations within the national airspace system; and (2) review a sufficient quantity of commercial aviation accidents or incidents in order to evaluate if HUD systems, SVS, or EVS would have produced a better outcome in each accident or incident.*
>
> *(c) CONSULTATION.—In conducting the review, the Administrator shall consult with aviation manufacturers, representatives of pilot groups, aviation safety organizations, and any government agencies the Administrator considers appropriate.*
>
> *(d) REPORT.—Not later than 1 year after the date of enactment of this Act, the Administrator shall submit to the appropriate committees of Congress a report containing the results of the review, the actions the Administrator plans to take with respect to the systems reviewed, and the associated timeline for such actions.*

1.1 Purpose

This report covers aircraft technologies that provide pilots with electronic means to supplement their natural vision of the outside world. Although multiple technologies are discussed, this report uses the term vision systems as a generic high-level term to encompass the range of technologies that are reviewed. Specific terminology is used as appropriate when describing individual technologies.

Equipage rates of vision system technologies have been increasing across the range of Air Transport, Air Taxi, General Aviation (GA), and Helicopter operator categories, as there is a wide variety of safety and operational benefits of vision systems. The evolution of enabling technologies, changes to FAA rules and regulations, and supporting operational guidance and approvals are all contributing factors to the increase in equipage. Although vision systems continue to shrink in size and weight and market forces drive cost down, these factors still limit broader adoption by operators. Despite these current limitations, vision systems have generated significant operator interest, given rapid technology evolution and the potential for additional future benefits.

1.2 Outline of Report

Section 2 describes the current state of vision system technology. For each type of system, there is a description of benefits, guidance information, prices, and challenges associated with equipping. Additionally, the section summarizes the positions of multiple stakeholders as gathered through ongoing industry engagement.

Section 3 discusses safety analyses that were conducted to characterize the safety impact of vision systems, pursuant to language in the FAA Reauthorization Act. This section includes:

- A review of historical accident and incident reports to determine if the presence of a vision system may have resulted in a better outcome;
- A summary of a previous safety study examining how SVS can help with recovery during loss of control events;
- A study exploring the impact of HUD on unstable approaches, terrain alerts, go-arounds, and excessive float using carrier Flight Operations Quality Assurance (FOQA) data; and
- A study reviewing narratives from Aviation Safety Action Program (ASAP) data to identify how vision systems could be applied to certain safety events.

The FAA Reauthorization Act also directs an examination into the efficiency impacts of vision systems. This is presented in Section 4, which includes an analysis of several inefficiencies during low visibility periods:

- Reduced throughput
- Cancellations
- Ground delay
- Airborne delay
- Diversions

Finally, Section 5 provides a high-level summary of conclusions and offers a brief forward-looking perspective into potential applications of vision systems.

2 Current State of Vision Systems

This section provides an overview of the current state of vision systems, including benefits, prices, challenges of available technologies, and perceptions with industry stakeholders. These factors are important in framing existing and future safety and efficiency impacts of vision systems.

2.1 Definitions

2.1.1 Vision System Definitions

Vision systems encompass a range of technologies, system designs, and manufacturer offerings. For this paper, the definitions from FAA Advisory Circular (AC) 20-167A [2] are used:

> ***Enhanced Vision System (EVS)*** *- An electronic means to provide a display of the forward external scene topography (the natural or manmade features of a place or region especially in a way to show their relative positions and elevation) through the use of imaging sensors, such as a forward looking infrared, millimeter wave radiometry, millimeter wave radar low light level image intensifying.*
>
> ***Enhanced Flight Vision System (EFVS)*** *- An installed aircraft system which uses an electronic means to provide a display of the forward external scene topography (the natural or manmade features of a place or region especially in a way to show their relative positions and elevation) through the use of imaging sensors, including but not limited to forward-looking infrared, millimeter wave radiometry, millimeter wave radar, and/or low light level image intensification. An EFVS includes the display element, sensors, computers and power supplies, indications, and controls.*
>
> ***Synthetic Vision System (SVS)*** *- A computer-generated image of the external scene topography from the perspective of the flight deck that is derived from aircraft attitude, high-precision navigation solution, and database of terrain, obstacles and relevant cultural features.*
>
> ***Combined Vision System (CVS)*** *- A system which combines information from an enhanced vision system and a synthetic vision system in a single integrated display.*

In this paper, SVS will refer to systems that employ database-derived information (e.g., terrain) versus imaging sensors. Systems that use external imaging sensors will be generally referred to in this paper as EVS, while the term EFVS will be used for the specific systems that meet Title 14 of the Code of Federal Regulations (CFR) § 91.176 [3]. This is not universally agreed upon terminology, as the European Aviation Safety Agency (EASA) uses the term EVS as an equivalent term for EFVS. To help clarify the terminology usage in the United States, the FAA provided the following note in AC 20-167A [2]:

> *Note 2: Unlike an EFVS, an EVS does not necessarily provide the additional flight information/symbology required by 14 CFR § 91.176, might not use a head-up display or an equivalent display, and might not be able to present the image and flight symbology in the same scale and alignment as the outside view. This system can provide situation awareness to the pilot but does not meet the regulatory requirements of 14 CFR § 91.176. As such, an EVS cannot be used as a means to determine enhanced flight visibility or to*

identify the required visual references and descend below the minimum descent altitude (MDA) or decision height (DH).

2.1.2 Display Definitions

In understanding the application and benefits of visions systems, it is important to understand not only the type of vision system technology but also the location and nature of the display that provides information to the pilot. To define the various display options, this report uses a range of FAA sources, including FAA AC 25-11B [4].

Head-Down Display (HDD)*: A primary flight display located on the airplane's main instrument panel directly in front of the pilot in the pilot's primary field-of-view (FOV). The HDD is located below the windscreen and requires the flight crew to look below the glareshield in order to use the HDD to fly the airplane.*

Head-Up Display (HUD)*: A display system that projects primary flight information (for example, attitude, air data, and guidance) on a transparent screen (combiner) in the pilot's forward FOV, between the pilot and the windshield. This allows the pilot to simultaneously use the flight information while looking along the forward path out the windshield, without scanning an HDD. The flight information symbols should be presented as a virtual image focused at optical infinity. Attitude and flight path symbology need to be conformal (that is, aligned and scaled) with the outside view.*

HUD systems in Air Transport and Turbojet aircraft often incorporate additional Flight Guidance System Information. Flight Guidance Systems are defined in FAA AC 120-118 as *"The means available to the flight crew to maneuver the aircraft in a specific manner either manually or automatically* [5]*."* It may include a number of components such as the autopilot, flight directors, and relevant display and annunciation elements, and it typically accepts inputs from the airborne navigation system. HUDs with Flight Guidance provide additional capability and operator benefits as compared to a basic HUD installation. For this paper, the term HUD can be assumed to be a system incorporating Flight Guidance unless otherwise specified.

Head-Mounted Display (HMD): *A special case of HUD mounted on the pilot's head.* For this paper, HMD will be referred to as Head-Worn Display (HWD), which is the more widely used term in industry today.

2.2 Available Vision System Technologies

The following sections will provide additional insights on specific vision system technologies. These sections include a summary of the current state, relevant guidance information, benefits, pricing, and challenges of each technology. Pricing estimate ranges are provided to give insight into the rough order of magnitude differences between various systems and technologies. The price range estimates include both purchase and installation of the equipment; however, they do not consider certification costs or other additional costs operators may incur, such as pilot training or maintenance of the systems. It is also worth noting that pricing estimates reflect a wide range of market offerings from basic, inexpensive systems to highly complex systems, which may incorporate multiple functions that the offering manufacturer has bundled with other technologies to improve commercial opportunity. For example, these high-end (more expensive) systems may bundle navigation and surveillance systems with vision systems for one comprehensive market offering. Other manufacturers may choose to provide purchase options for runway safety and overrun protection systems provided via a HUD or HDD, thus increasing the functionality and price of the installed system. A summary of challenges that are limiting broader adoption of the specific vision system technology is also provided in the following sections.

2.2.1 HUD

2.2.1.1 Current State of HUD

Historically, HUD systems have been expensive and large in size. This limited applicability of these systems to aircraft cockpits that were large enough to accommodate the HUD, but also only acquired by operators who could justify the additional costs. Original HUD systems provided basic flight information to the pilot, allowing them to keep their eyes focused out the window while still having access to primary flight information without looking down at the primary flight instruments in the cockpit. These systems evolved into Head Up Displays with Guidance that added many features and flight guidance elements, allowing pilots to use the HUD as a substitute for certain ground infrastructure or for autoland systems. One example is using a HUD to the DH of Special Authorization (SA) Category (CAT) I approaches, with a DH as low as 150 feet and a visibility minimum as low as Runway Visual Range (RVR) 1400 feet at runways with reduced lighting. In addition, the HUD can be combined with EVS/EFVS and/or SVS, allowing even greater operator benefits. Recent developments by HUD manufacturers have resulted in smaller, lighter, and lower-priced HUD systems that can be installed on a wider range of aircraft. Figure 2-1 shows an example of the pilot's view through a HUD.

Figure 2-1. Example of information provided on a Collins Aerospace HUD [6]

Equipage is expected to continue to increase as carriers ordering new aircraft will have the option to include HUD. Worldwide HUD equipage also continues to increase, driven by factors such as the Civil Aviation Administration of China requirement that all domestic Chinese aircraft be fitted with HUD by 2025. The Chinese HUD rule has stimulated supplier offerings to a broader range of aircraft, giving United States (U.S.) aircraft operators more options for selecting HUD. As of September 2018, 27 percent of the U.S. Air Transport fleet was equipped with HUD and had operational approval for use [7].

2.2.1.2 HUD Operational Guidance

While operators can equip with HUD to provide increased situational awareness for pilots in all phases of flight, they must meet certain criteria to use HUD guidance to manually fly CAT I-III Instrument Landing System (ILS) approaches. FAA AC 120-29A and AC 120-28D lay out the requirements for an aircraft with HUD to gain approval to land in low visibility conditions [8] [9].

2.2.1.3 HUD Benefits

HUDs may provide a range of benefits, which are summarized in Table 2-1. At a high level, the benefits include operational and safety improvements from more accurate flight path management and increased situational awareness from the pilots' ability to focus their attention primarily out the window. Because they allow the pilot to look out the window during all phases of flight, especially during takeoff and landing operations, HUD systems provide operational credits not available to aircraft with only HDD systems. This could potentially manifest through a reduction in delay, cancellations, and diversions.

Table 2-1. Summary of HUD Benefits

Benefit Mechanism	Potential Ops Impact
Display of aircraft state information in pilot's primary FOV	Improved compliance with aircraft operating envelope, possibly leading to a reduction in safety events including loss of control, unstable approach, and over-rotation.
Display of contextual information including extended runway centerline, touchdown zone, and remaining runway	Improved safety by providing the flight crew with relevant contextual information of the runway environment.
Better situational awareness in the approach phase	Reduced flight technical error, which allows for HUD to be used in place of Autoland to use CAT II or CAT III approaches. HUD may provide access to airports during low visibility conditions, possibly manifesting in reduced cancellations, diversions, and delays.

2.2.1.4 HUD Prices

The price of these systems can range from $100K to over $1M, depending on how many components are already present on the aircraft and whether single or dual systems are desired. The lower end of the price range represents aircraft that have already been fitted with the appropriate sensors, and only single systems are desired. The higher end of the price range represents aircraft where dual systems are desired, and the aircraft needs to be retrofitted with the appropriate sensors.

2.2.1.5 HUD Challenges

The primary challenges of HUDs currently are the physical size of the equipment and the price. Many of the systems available on the market, particularly those that provide the greatest set of operational benefits, are of significant size and must be installed in larger, typically turbine-powered aircraft. The price of these systems is significant and lends itself to air transport or high-performance GA aircraft, where investments may be coupled with other technologies to improve return on investment.

In the case of HUD providing operational credits for landing in lower visibility, aircraft autoland systems provide the same or similar function. Thus, operators desiring operational credit have a choice between autoland and HUD. In the case of Boeing and Airbus aircraft, the autoland function is often significantly less expensive than HUD, and in some cases, has no additional cost to the operator, making the business case to equip with HUD challenging.

2.2.2 Head-Worn Display

2.2.2.1 Current State of HWD

HWDs have been in use for many years in military applications. In more recent years, there has been greater interest in applying these technologies to civil aircraft, as HWDs provide many of the same capabilities that can be found in HUD systems but without the space challenges of a classic HUD system. HWDs can be combined with other vision system technologies such as EVS, SVS, and CVS if determined to be an “equivalent display” as envisioned in the applicable regulations.

Although no U.S. Air Transport Fleet operators are currently using HWD systems, Elbit Systems is in the process of certifying their HWD system on an ATR 42/72 Turboprop Aircraft and the Airbus A320 series aircraft. With additional technology advances, such displays may be able to qualify under 14 CFR § 91.176 as an “equivalent display” and thereby achieve full EFVS status.

2.2.2.2 HWD Operational Guidance

The term “head-worn display” is a more recent evolution of the terminology associated with this type of display. Previously, AC 25-11B defined head-mounted displays, which is the historical reference to systems worn on a pilot’s head [4]. Although these systems are only now being offered on commercial Air Transport aircraft, it is anticipated that these systems will gain operators operational credit for CAT I-III approaches, similar to existing HUD implementations.

2.2.2.3 HWD Benefits

As a result of their smaller size and lower price as compared to HUD, these systems can be implemented in nearly any aircraft, regardless of the aircraft size. This is a significant benefit over HUD systems that are challenging to retrofit in aircraft not originally designed for HUD capability. Although HWDs may still not be affordable for most lower-performance GA aircraft, size and weight would no longer be a factor in equipping even the smallest piston aircraft. The HWD, with its many benefits and application to a wide range of aircraft, has the potential to significantly enable vision system equipage across a wide range of aircraft and operator types.

Although this technology is only now emerging for use on air transport aircraft, the anticipated benefits are expected to match those found in Table 2-1 for the HUD section.

2.2.2.4 HWD Prices

The price of these systems can range from $100K to over $250K depending on how much of the equipage is already present on the aircraft and whether single or dual systems are desired. The lower end of the price range represents aircraft where single systems are desired, and the aircraft has already been fitted with the required sensor. The higher end of the price range represents aircraft where dual systems are desired, and the aircraft does not have the required sensors.

2.2.2.5 HWD Challenges

Human factors and pilot acceptance are the biggest challenges for HWD systems. Operators that use aircraft multiple times per day or fly for long periods of time may find their pilots having comfort issues wearing the system all day. Simple daily wear and tear may also present durability challenges, as pilots might take the units on and off multiple times throughout a flight, limiting widespread operator acceptance.

Some HWDs use a monocular eyepiece versus binocular; this can present human factors and performance issues for pilots. A pilot might experience problems focusing on or even seeing the desired information or with depth perception. Operators desire the widest FOV available for vision system technologies, and some HWD systems may have smaller usable FOVs than an installed HUD.

2.2.3 Synthetic Vision Systems

2.2.3.1 Current State of SVS

An SVS is a broad category of advanced display which can depict a view of the external environment derived from databases of terrain, obstacles, and other cultural features. The view is drawn egocentrically from the pilot’s assumed eyepoint and thus closely represents what the pilot would see looking forward through the cockpit windscreen. The display can be implemented on both head up and head down displays. Many avionics manufacturers have brought SVS products to the market, from small single-engine airplanes to transport category airplanes. An SVS can have several possible intended functions depending on the design standards used in its implementation. The broadest function is pilot situation awareness regarding airplane attitude (provided by the synthetic image) and basic flight control parameters such as airspeed, altitude, and vertical rate, provided by an integrated display of those values. An SVS may have additional design features to enhance the situational awareness function, known as Aircraft State Awareness (ASA), or be implemented as a fully integrated guidance system, known as Synthetic Vision Guidance System (SVGS).

Per RTCA DO-371, the ASA SVS is a situational awareness system integrated with the primary flight reference, either on an HDD or HUD, with the intent of reducing the potential for spatial disorientation, controlled flight into terrain, and Loss-of-Control In-flight (LOC-I) accidents [10]. ASA SVS is not intended to be granted operational credit resulting in improved access to airports during low visibility conditions.

SVGS is a combination of synthetic vision and flight guidance displayed on an HDD or HUD. RTCA DO-359 was written for use with several approach types: ILS, Localizer Performance with Vertical Guidance (LPV), or Ground Based Augmentation System (GBAS) Landing System (GLS) with a DH as low as 150 feet [11]. After that point, the pilot(s) must use visual cues utilizing natural vision to complete the landing. However, the initial FAA certification guidance, as documented in AC 20-185, limits the expected usage of SVGS to SA CAT I Instrument Landing System (ILS) approaches [12]. As SVGS is a fully integrated system, it is required to have system performance and aircraft position monitors with alerts and additional flight symbology, as outlined in RTCA DO-359. Since the synthetic image is generated entirely from onboard databases, the image can include symbols to represent potential obstruction hazards (e.g., windmills, radio towers, or power lines) which are drawn from the obstructions database. In addition, SVGS will highlight nearby terrain and the landing airport, as shown by the green dome in the image of the Collins Aerospace SVGS in Figure 2-2.

Figure 2-2. Collins Aerospace SVGS HUD [13]

When installed on a HUD as opposed to an HDD, SVGS could potentially be integrated with the sensor-based imagery provided by EFVS, which is the basic configuration for a Combined Vision System (CVS), which will be discussed later in this report.

ASA SVS and SVGS are currently available systems. ASA SVS is more common in the piston GA fixed-wing fleets as compared to other aircraft types, although it can be found on a wide range of aircraft and operator types. SVGS is available on HUD, but not yet on HDD, and as such, has not been broadly adopted beyond larger HUD-equipped aircraft found in High-Performance GA, Air Taxi, and Air Transport. The reduced cost of installation as an HDD may facilitate increased equipage in the future.

2.2.3.2 SVS Operational Guidance

Table 2-2 shows the main RTCA Minimum Aviation System Performance Standards (MASPS) documents for SVS.

Table 2-2. Summary of RTCA documents for SVS

RTCA Document (equivalent EUROCAE document)	Pub Date	Key Takeaways
DO-315B MASPS for Enhanced Vision Systems, Synthetic Vision Systems, Combined Vision Systems and Enhanced Flight Vision Systems [14] (EUROCAE ED-179B)	June 21, 2011	• Adds system design criteria for the use of SVGS for lower-than-standard Category I ILS minima, including specific features for system performance, database, alerts, pilot controls, display, and symbology requirements.
DO-359 MASPS for Synthetic Vision Guidance Systems [11]	May 14, 2015	• Defines performance standards to enable operations to a DH as low as 150 feet.
DO-371 MASPS for Aircraft State Awareness Synthetic Vision Systems [10] (EUROCAE ED-249)	December 19, 2017	• Expands on the previously defined function of an SVS to include enhanced aircraft attitude and energy state awareness cues with the purpose of reducing LOC accidents.

At this time, the use of SVGS has not been approved for additional operational credit, an example of which could be the use of a SVGS with HDD during a Special Authorization Category I (SA CAT I) ILS approach, as opposed to the currently required HUD. However, such approval has been anticipated in FAA guidance documents related to the certification and operation of SVGS. RTCA DO-359, described above, provides the system performance requirements for SVGS, and any such system approved for operational credit will be expected to meet those requirements [11]. FAA AC 20-185 provides a means to achieve certification of such systems, which will demonstrate compliance with the performance standard [12]. Guidance for operational approval for the use of vision systems, including SVGS, is published in FAA AC 120-118, where a New Technology Demonstration (NTD) described in the document may provide a path for the approval of SVGS for operational credit [5].

2.2.3.3 SVS Benefits

The key potential benefit for ASA SVS are improved situational awareness for pilots by utilizing the current aircraft position with a database to show a graphic representation of a moving external scene around the aircraft. These functions can be supplemented with key terrain features for both navigation awareness and obstacle avoidance purposes. Additionally, ASA SVS can provide pilots with airport and runway information, improving visual search for the landing runway and reducing the potential for landing at the wrong runway.

When properly integrated with the navigation system to correctly locate the aircraft in relation to the navigation database maps, the overlay of symbolic representations over potential obstruction threats or to mark key points may reduce the potential for landing at the wrong runway and provide critical obstruction avoidance information during aircraft emergencies. Another benefit of some SVS systems is a lower price since they can be incorporated into an HDD, saving the additional cost necessary with a HUD or HWD.

In addition to the benefits of ASA SVS, SVGS may provide operational credit for aircraft to take off or land during low visibility conditions that prevent non-equipped aircraft from doing so. This may provide an efficiency benefit for equipped flights through a reduction in delays, cancellations, and diversions and corresponding system-wide benefits. SVS benefits are summarized in Table 2-3.

Table 2-3. Summary of SVS Benefits

Benefit Mechanism	Potential Ops Impact
Display of aircraft state information	Improved conformance with aircraft operating envelope (fewer LOC-I, unstable approach, over-rotation, etc.).
Better identification and awareness of terrain and obstacles	Reduction in Terrain Awareness and Warning System (TAWS) alerts or close proximity events with terrain or obstacles.
Better identification of navigational cues in the runway environment	Potential for OpSpec approval to takeoff or land during low visibility conditions when non-equipped aircraft cannot (SVGS only).

2.2.3.4 SVS Prices

Basic prices for SVS systems installed in GA aircraft are estimated to range from $15K to $50K. The higher end of the price range includes offerings where SVS is part of a more comprehensive system, while the lower range systems have minimal capability. It is typical for avionics companies that sell high-end systems to group multiple components and capabilities beyond just SVS into their market offerings. These systems often include additional NextGen navigation and surveillance capabilities, along with highly desired technologies such as cockpit Wi-Fi and personal tablet interfaces.

2.2.3.5 SVS Challenges

The key challenges for ASA SVS are that price points are still high for some piston aircraft operators, and alternatives exist to provide similar flight deck capability – for example, software applications running on portable devices can offer a cheaper option for some operators. SVS and SVGS rely on electronic databases to render their image; therefore, it is critical to ensure a high degree of accuracy and integrity of the database, which can be a challenge. As SVS and SVGS do not have a visual input, the synthetically created image will always have a delta from the current flying environment, which creates additional challenges for these systems to replace natural vision and thus limiting potential operational benefits. This may decrease the likelihood that SVGS alone could be approved for landing operations.

2.2.4 Enhanced Flight Vision System

2.2.4.1 Current State of EFVS

An EFVS is a combination of forward-facing sensors that can identify and present to the pilot/co-pilot the ground and objects ahead of the aircraft during periods where natural vision may be difficult, such as nighttime, low visibility, and ground obscuring weather like clouds or fog. An EFVS requires a transparent HUD or equivalent display to combine flight information, flight symbology, navigation guidance, and a real-time image of the external scene to the pilot on one display. Figure 2-3 shows an EFVS display, with the combination of sensor imagery of the runway environment, flight control information such as airspeed, heading, altitude, and navigation guidance.

Figure 2-3. EFVS example from Collins Aerospace [15]

It is estimated that 4 percent of the U.S. Air Transport Fleet is equipped and operationally approved to use EFVS. However, operators of turbojet airplanes in Corporate/GA equip at higher rates, as they seek all-weather operations and redundancy offered by vision systems, especially when operating at smaller and more challenging airports with less infrastructure.

2.2.4.2 EFVS Operational Guidance

Table 2-4 summarizes the relevant RTCA standards documents relating to EFVS.

Table 2-4. Summary of RTCA documents relating to EFVS

RTCA Document (equivalent EUROCAE document)	Pub Date	Key Takeaways
DO-315B MASPS for Enhanced Vision Systems, Synthetic Vision Systems, Combined Vision Systems and Enhanced Flight Vision Systems [14] (EUROCAE ED-179B)	June 21, 2011	• Provides high-level system requirements for EFVSs when installed in aircraft, with the express purpose of gaining additional operational credit under FAA Order 8400.13.
DO-341 MASPS for an Enhanced Flight Vision System to Enable All-Weather Approach, Landing and Roll-Out to a Safe Taxi Speed [16]	Sep 26, 2012	• Establishes the high-level system requirements for EFVS, which can be used on a straight-in instrument approach with published vertical guidance to touchdown, landing, and roll-out to a safe taxi speed in visibility as low as 300 ft RVR (100 m), without reliance on natural vision. • Incorporates fail-operational design including use of a repeater display for the monitoring pilot.
DO-374 Safety, Performance and Interoperability Requirements (SPR) Document Defining Takeoff Minima by Use of Enhanced Flight Vision Systems [17] (EUROCAE ED-257)	Oct 5, 2018	• Provides the minimum operational, safety, and performance requirements and interoperability requirements to support takeoff operations using EFVS in natural visibilities lower than currently authorized. • Includes recommendations for EFVS takeoff minima defined through various associated aircraft equipage, operational and interoperability requirements, and airport infrastructure.

The first regulations authorizing the use of an advanced vision system were published in 2004 as amendments to 14 CFR § 91.175 Takeoff and Landing under Instrument Flight Rules (IFR). Subparagraphs (l) and (m) were added, which defined the operations authorized by the use of an EFVS and required system components and display features of the EFVS. In 2017, the EFVS related sections were consolidated and relocated to the new 14 CFR § 91.176. This enabled more direct access to the operating rules governing EFVS operations, including the original authorization to 100 ft. above touchdown and a newly authorized operation to touchdown and rollout. For the touchdown authorization, when the minimum flight crew requirement calls for more than one pilot, the monitoring pilot must be provided with a display of the EFVS sensor imagery [3].

When the part 91 regulations were revised in 2017, the FAA made related modifications for air carriers under 14 CFR Part 121. These changes incorporate the part 91 EFVS requirements by reference, specifically in 14 CFR § 121.651 (e) [18]. The new rule also requires that operators under part 121 (air carrier), part 129 (foreign air carrier), or part 135 (commuter and on-demand operations) do so in accordance with OpSpec issued for that purpose. Operational approvals for approach to touchdown and rollout are available through OpSpec C048 to visibilities as low as RVR 1000 feet. The 2017 changes also included the addition of flight crew training requirements in 14 CFR § 61.66 to ensure that crews were properly qualified for EFVS operations in reduced visibilities [19].

Operational credit for reduced ground infrastructure when using EFVS for takeoff is not yet defined; however, RTCA DO-374 provides the safety, performance, and interoperability requirements for equipment that would support such operations. Approvals for using EFVS during takeoff in lieu of ground infrastructure may be possible via an NTD, as described in FAA AC 120-118 [5].

2.2.4.3 EFVS Benefits

An EFVS provides a real-time image of the external scene, which allows the pilot to use enhanced vision imagery provided by an EFVS to operate in the visual segment of an instrument approach procedure when the flight visibility is not sufficient to conduct the approach with natural vision. As this system is not an augmented guidance system, there are no requirements for additional position monitors, and the additional HUD symbology is integrated into the HUD image as opposed to overlaid onto the visible surface. This results in a less complex integration than SVGS. EFVS Landing has lower RVR requirements than CAT II ILS and does not require an autoland or auto-throttle system. EFVS Benefits are summarized below in Table 2-5.

Table 2-5. Summary of EFVS Benefits

Benefit Mechanism	Potential Ops Impact
Display of aircraft state information in pilot's primary field of vision	HUD element of EFVS provides improved compliance with aircraft operating envelope (fewer LOC-I, unstable approach, over-rotation, etc.).
Provides flight crew with a visual advantage compared to natural vision only	Can be used for operational credit to land during conditions that would be prohibited with natural vision only. Flight crews may use a wider array of approaches during low visibility conditions, as opposed to simply CAT II or III ILS. Better situational awareness when flying through clouds, fog, or precipitation.

2.2.4.4 EFVS Prices

EFVS systems that provide operational credit are installed with HUD systems. The price of these systems is estimated to range from $100K to over $1M depending on how much of the equipage is already present on the aircraft and whether single or dual systems are desired. The lower end of the price range represents aircraft where single systems are desired, and the aircraft has already been fitted with a HUD system. For this type of system, the aircraft would only need appropriate sensors and hardware added. The higher end of the price range represents aircraft where dual systems are desired, the aircraft does not already have the required HUD systems, and the aircraft would also need various sensors and hardware added.

2.2.4.5 EFVS Challenges

Other than the cost, a key challenge for EFVS is that the sensor input is presented as an overlay onto the pilot's forward visual field, necessitating a HUD installation. EFVS also requires the installation of a compatible sensor, which may be infeasible for certain aircraft types (such as propeller aircraft), and the HUD must have the full required symbology set.

Although not currently available, integration with an HWD may accelerate equipage moving forward if that becomes a viable option.

2.2.5 Combined Vision Systems

2.2.5.1 Current State of CVS

The CVS combines the features of the SVS and EFVS to present an integrated image during descent in IFR conditions. Integration of the real-time EFVS sensor would compensate for potential database accuracy/currency errors that may be associated with the SVS imagery. The integration of EFVS and SVS provides a continuous, weather-independent display of the airport environment early in the approach and a real-time, enhanced view of the runway environment during the final phase of landing. The obstacle database element of an SVS would enable the display of man-made obstacles which the EFVS sensor may not be able to image. Figure 2-4 shows an example of a CVS installation on a HUD.

Figure 2-4. Example of CVS: Dassault FalconEye [20]

2.2.5.2 CVS Operational Guidance

RTCA DO-315B provides the MASPS for SVS, EVS, CVS, and EFVS; however, CVS is not currently approved for use for approach and descent [14]. The capability exists as an option on some business aircraft.

2.2.5.3 CVS Benefits

As shown in Table 2-6, the positive aspects of CVS are that it supports the augmented vision approach as well as database display images, and it also provides synthetic symbols overlaid on the enhanced visuals. As obstruction identification is a part of normal helicopter operations in all visibility conditions, helicopter operators would likely have significant benefits from a CVS installation.

Table 2-6. Summary of CVS Benefits

Benefit Mechanism	Potential Ops Impact
Display of aircraft state information in pilot's primary field of vision	Improved compliance with aircraft operating envelope (fewer LOC-I, unstable approach, over-rotation).
Better identification and awareness of terrain and obstacles	Reduction in TAWS alerts or close proximity events with terrain or obstacles.
Better identification of navigational and visual cues in the runway environment	Potential for OpSpec approval to take off or land during low visibility conditions when non-equipped aircraft cannot.

2.2.5.4 CVS Prices

CVS systems that provide operational credit are installed with HUD. The price of these systems is estimated to be from $200K to over $1M depending on how much of the equipage is already present on the aircraft and whether single or dual systems are desired. The lower end of the price range represents aircraft where single systems are desired, and the aircraft has already been fitted with a HUD system. For an aircraft with a HUD system, the aircraft would need the EFVS and SVS components and sensors added to result in a CVS. The higher end of the price range represents aircraft where dual systems are desired, and the aircraft requires the installation of HUD and the additional CVS sensors and components.

2.2.5.5 CVS Challenges

CVS requires a highly complex integration of technologies, especially combining visual sensor data with databases; therefore, there is increased potential for conflicting information sources, which require resolution during flight (e.g., a discrepancy between sensors and airport maps). Integration with the EVFS requires the SVGS to be a HUD system, meaning an HDD system would not currently be an option.

2.2.6 Dual HUD

2.2.6.1 Current State of Dual HUD

The dominant configuration of HUD installations is Single HUD, meaning the HUD is installed only in the Captain's position. The more expensive and less-common dual HUD installation provides each pilot position with a HUD in their FOV, as shown in Figure 2-5, meaning each pilot has access to the same information and situational awareness cues. As either position may command the aircraft for extended periods of time, dual HUD provides the capability for either position to use HUD for operational credit.

Figure 2-5. Example of a cockpit with a Thales Dual HUD installation [21]

2.2.6.2 Dual HUD Operational Guidance

The FAA has published guidance for dual HUD installations in AC 25-11B Electronic Flight Displays, which provides a broad range of recommendations regarding the operational use of dual HUD installations. [4].

As with single HUD, FAA AC 120-29A and AC 120-28D lay out the requirements for an aircraft with HUD to gain approval to land in low visibility conditions [8] [9].

2.2.6.3 Dual HUD Benefits

Dual HUD installations are anticipated to provide operational and safety improvements. Operational benefits may include redundancy for operations in cases where one system experiences failure. In single HUD installations, if a failure occurs in the system, all the benefits of HUD are no longer available to the pilots for that flight. If repairs cannot be made quickly, it is likely an airline would take appropriate maintenance actions to disable the use of the faulty equipment and continue to fly normally as a non-HUD-equipped aircraft would. However, if the aircraft was fitted with dual HUDs, depending on the nature of the failure, it is quite possible the aircraft may be able to continue flight using the remaining HUD while maintaining the associated operational benefits.

Safety benefits of dual HUD are likely to accrue in both normal and emergency operations, similar to dual primary instrumentation already existing in cockpits today. In normal operations, dual instrumentation allows both pilots to have access to the same flight information, thus improving monitoring and cross-checking functions. Providing both pilots with access to all available flight information can improve emergency operations through decision-making and overall situational awareness.

2.2.6.4 Dual HUD Prices

For a single HUD, the range of price estimates is $100k to over $1 million. Dual HUD does not automatically double the pricing but can add significant costs beyond a single HUD installation.

2.2.6.5 Dual HUD Challenges

The biggest barrier to increased dual HUD equipage is the significant added price for installing a second HUD without an equivalent associated efficiency benefit to recuperate the costs. In other words, it can be costly to add a second HUD, and the efficiency benefits would only be realized in anomalous situations where the primary HUD has failed.

An additional challenge is that HUDs are extremely difficult to install after an aircraft has been built because they require very precise mounting in the aircraft, which can be nearly impossible after the aircraft is fully assembled. Some newer aircraft being delivered have available options for dual HUD installation, or, at a minimum, operators can order provisions that include the mounting points allowing for future retrofit. The result is a trend toward new delivery aircraft having dual HUD or the potential to have a second HUD added in the future. It is important to consider that HWD systems do not have many of the space, price, and installation requirements of HUD systems, and the potential pool of dual-equipped aircraft greatly increases where HWD systems are economically viable.

2.2.7 Comparison of Technologies

As operators make investment decisions, they evaluate substantial amounts of data on vision system benefits, costs, usability, and future scenarios. Table 2-7 depicts the relationship between these various technologies and highlights differences between them.

2.3 Industry Feedback and Perspective

In preparation for this report, multiple industry communities were engaged to provide insight into vision systems. Feedback from industry included discussions on benefits, technology options, prices, system availability and applicability, future opportunities, and challenges to wider adoption rates. The range of industry stakeholders engaged included: Airline Operators, High-Performance GA (Turbine powered 14 CFR parts 135 and 91), Lower Performance GA (Piston powered 14 CFR parts 135 and 91), Airline Pilot Unions, Airframe Manufacturers, and Avionics Manufacturers. This section describes the summary highlights of these engagements in the following paragraphs.

2.3.1 Airline Operator Feedback

Many operators recognize that HUD helps aircraft fly more precisely and ultimately enhances safety and airline operations. It is the expense of the systems that limits greater HUD equipage rates. Enhanced, Synthetic, and Combined Vision Systems are viewed as additional improvements and expected evolution of these technologies.

Table 2-7. Comparison of vision system technology

Technology	Differentiator	Pros	Cons	Status
HUD (single and dual installations)	Provides a direct, visual method to improve situational awareness and reduce flight technical error	• Improved situational awareness • Can be used to manually fly CAT I-III approaches in place of Autoland	• Only certain aircraft types will have the space in the cockpit to install • Does not provide for descent below published minima	Fielded technology that now comes standard or as an option on most new aircraft
HWD	Provides a direct, visual method to improve situational awareness by having the pilot wearing the display	• Improved situational awareness • Potentially can be used to manually fly CAT I-III approaches in place of Autoland • Can be installed on more aircraft types than HUD	• Human factors issues include possible pilot disorientation and hygiene issues • Wear and tear may lead to durability issues	Used in military applications for many years but not yet available commercially
SVGS	Provides a computer-generated image of the runway environment	• Integrates navigation system with map databases • Potential for descent below published minima • Minimal hardware addition (does not require the installation of an external sensor); primarily software or data • Installation on HDD may reduce costs and expand equipage	• Reliance on high-quality position data; a loss of position integrity makes it potentially unusable • Requirement for maintaining accurate databases for terrain, obstacles, and infrastructure • If installed on an HDD, it still requires head-down to head-up transition at minimums	Currently available on HUD, but not yet on HDD; future HDD availability may enable more aircraft to equip
EFVS	Combines HUD with an imaging sensor to provide the pilot with a visual advantage relative to natural vision	• Augmented vision is the primary tool • Inherits HUD benefits • Certification (CFR 91.176 (b)) exists for use down to 100 feet above the runway • Certification (CFR 91.176 (a) exists for operations to landing and roll-out	• Currently limited to HUD installations for landing below minimums • Requires the installation of an imaging sensor on the outside of the aircraft	Mature technology option and currently implemented in multiple non-military aircraft
CVS	Combines the features of the SVS and EFVS to present an integrated image to the pilot	• Multiple navigation sources are used to provide the pilot with the most relevant information • Supports vision approach as well as display • Would inherit benefits of HUD, EFVS, and SVGS	• High complexity for integration (e.g., determining which information gets priority on the display) • Increased potential for conflict between information sources • Likely to be most costly as it requires installation of external sensors, HUD, and database maintenance	Multiple systems are being tested now

Airline Operator HUD Equipage continues to increase slowly due to a challenging business case. Operators value lower takeoff and landing minimums and are hopeful that low visibility taxi benefits may be possible in the future. An additional benefit noted by some airlines were that vision systems can help identify the proper landing surface and thus increase safety during day, night, and lower visibility operations.

2.3.2 High Performance GA Feedback

This group of turbine-powered aircraft operators greatly value airport access. These aircraft are operated at the busiest airports but also at smaller, more remote airports both in the U.S. and in foreign countries. Vision systems can provide operational benefits through improved access to airports with reduced ground infrastructure, such as airport lighting systems and instrument approach systems. These important operational benefits can justify investment decisions, as noted by some operators. In addition, unlike airlines that run predictable schedules, these operators may not have familiarity with their destination airport, possibly never landing there before. Vision systems can provide additional situational awareness to help locate the proper airport landing surface and important terrain features, thus greatly improving safety for crews that may not have experience at a particular airport. Some systems available can provide runway remaining information to the pilots, which is also considered a significant safety advantage, particularly at smaller airports with shorter runways. With an operational need for flexibility and access, it is common for newer large turbine-powered aircraft to be equipped with HUD and often outfitted with combinations of EFVS, SVGS, and CVS.

2.3.3 Lower Performance GA

The operators in this category consist of Air Taxi and GA operators with piston-powered aircraft. These operators tend to be more price-sensitive for avionics upgrades, and their aircraft tend to have lower monetary value compared to High-Performance GA and Air Transport aircraft. The operators in this category range from those who fly during Instrument Meteorological Conditions (IMC) to those who only fly in Visual Meteorological Conditions (VMC). For this aircraft space, weight and price present significant challenges, and therefore, HUD and even existing HWD are usually not viable solutions. Therefore, this group reports that their interest is mostly in HDD with synthetic systems. Lower Performance GA operators see the benefits of ASA SVS to improve safety. The operators who fly in IMC indicate that they see the potential for SVGS to provide improved airport access during reduced visibility and nighttime operations.

2.3.4 Airline Pilot Unions

We engaged with Air Line Pilots Association (ALPA) on vision system technologies, which they generally support as a technical aid to pilots. ALPA recognizes that EFVS-type systems that rely on imaging sensors are different from synthetic systems reliant on databases, and thus the benefits and potential constraints of the systems will be different. ALPA reported that safety is likely increased in all phases of flight using HUD-based systems.

Although sensitive to the significant cost hurdles for dual HUD, ALPA believes dual HUD would be particularly helpful in improving safety during an emergency and non-routine operations. Typical airline policy is that during an emergency, and if appropriate, the Captain should transfer the duties of flying the aircraft to the First Officer while the Captain manages the emergency and required checklists. Considering that the benefits of HUD include optimized flight path and control, during emergencies, the HUD might be even more valuable to the crew than in normal operations in terms of providing improved ability to fly the aircraft in challenging circumstances. With today's single HUD implementations, transfer of control to the First Officer during an emergency eliminates the HUD benefits in controlling the aircraft. In a dual HUD aircraft, the First Officer would still have HUD information available, and thus there is no reduction in available flight information during the transfer of control. The lack of dual HUDs should not be interpreted as less safe, but rather safety may be improved further through the implementation of dual HUDs.

2.3.5 Avionics Manufacturers

Avionics manufacturers and suppliers continue to be a significant source of the research and development of vision system technologies. For smaller piston and jet aircraft, manufacturers see significant operator interest in SVS and smaller, lighter-weight HUD and HWD displays. According to some manufacturers, situational awareness and safety are primary reasons for operator interest in vision systems.

Avionics suppliers who produce equipment for large jet-powered aircraft cite operational benefits as a significant reason for interest. It was also mentioned by some suppliers that the majority of GA and Air Taxi jet aircraft do not have Autoland capability or available options for purchase. Operators of these aircraft highly value all-weather operations and airport access. Combining high operator interest and fewer technology options can result in improved business cases for equipping with vision system technologies. One of these suppliers to the GA and Air Taxi jet community mentioned that these operators often operate at unfamiliar airports during the night or IFR conditions and that vision systems are seen as significantly improving situational awareness and pilot performance in these scenarios. Avionics suppliers noted that these types of operational benefits are perceived to be applicable to the range of head-up and head-down displays and also encompass synthetic vision and enhanced vision systems. It is worth noting that multiple avionics suppliers believe combined vision is of significant interest and expect these systems to provide the maximum operational value by combining the best features of enhanced and synthetic vision technologies on either a HUD or HDD.

Avionics suppliers of HUD and HWD systems indicated that another significant benefit of vision systems is the potential for these systems to improve pilot performance. The pilot performance improvements cited were across a range of operator types, operational use scenarios, and aircraft. One HUD supplier explained that their research suggests that newer pilots with less experience can often learn the flight characteristics of an aircraft quicker and perform better as compared with pilots who learn without the HUD. The supplier said this is also applicable to experienced pilots who may be simply transitioning to a new aircraft where the HUD can help the pilot learn appropriate landing and takeoff pitch rates, contributing to better tail strike avoidance while also demonstrating improved performance on day visual approaches and nighttime approaches.

2.3.6 Aircraft Manufacturers

Aircraft Manufacturers continue to expand their offerings of vision systems, offered as both standard and optional equipment. Manufacturers recognize continued interest from operators in vision systems for both operational and safety enhancements. However, some manufacturers indicate that equipage like Autoland, runway safety technologies, and other available display enhancements present alternatives to vision systems that can be more widely available and less expensive. These alternatives make business cases challenging for the operators and the manufacturers. Aircraft manufacturers acknowledge they continue to assess vision systems and take advantage of opportunities to provide increased opportunities to add these systems. An example of one such opportunity is that some manufacturers are making HUD mounting points and other provisioning standard on new aircraft and, in some cases, are also making dual HUD provisioning available at the time of purchase of the aircraft. This allows the operator to retrofit the aircraft with HUD in the future, which can be particularly important considering that many aircraft operate for twenty-five or more years and may change owners.

Further, manufacturers point out that global requirements, like the aforementioned HUD rule in China, can impact equipage offerings. Manufacturers have also stated that ownership and leasing agreements over the life of an aircraft result in changes to the operational profile of a particular aircraft. With changes to operational profiles, there are corresponding changes in interest and needs for equipage. As a result, new aircraft and the evolving opportunity that vision systems technology enable will likely further the expansion of vision systems. Some manufacturers noted that although vision systems are likely to expand in use, the rate of change and specific technology trends are not clear when comparing the range of display and sensor combinations and the potential for new technologies and future aircraft systems.

3 Safety Impacts

Vision systems provide a variety of information about external conditions and aircraft state, this has the potential of improving situational awareness and, accordingly, safety in flight. The benefits realized will depend upon the equipment used, the tasks being performed, the operational conditions under which it is used, and the training provided to the pilot. This section examines the safety impact of vision systems, including a review of historical accident and incident reports, a study of unstable approach risk using FOQA data, and a review of narrative ASAP safety reports.

3.1 Review of Accidents and Incidents

3.1.1 Previous Accident Reviews

The Flight Safety Foundation (FSF) produced a detailed report in 2009, evaluating 983 domestic and international accident reports from 1995 through 2007 to determine if a head-up guidance system might have prevented the accident. It was concluded that a HUD-like system would have positively influenced or potentially prevented 38 percent of the accidents. Furthermore, they conclude that HUD may have had a positive impact on 69 percent of accidents occurring during the critical phases of takeoff and landing [22]. Although the report is now ten years old, these findings are still generally applicable in today's environment.

3.1.2 NTSB Accident Review

We conducted a review of National Transportation Safety Board (NTSB) accident and incident reports to identify those where vision systems might have provided appropriate mitigation, specifically evaluating the potential impact of HUD, EFVS, and SVGS. For this review, HUD was examined in all conditions, but the focus for EFVS and SVGS was on accidents occurring during low visibility or nighttime conditions, where typical visual cues around the runway environment could be obscured. In these situations, EFVS and SVGS (or CVS) may provide substantial improvement in situational awareness.

For each of the technologies (HUD, EFVS, and SVGS), a subject-matter expert manually reviewed reports to determine whether the technology would have prevented the accident. With the context of each technology, each report was graded as follows:

- "Likely Provides Mitigation" – denotes an accident where there likely would have been a benefit in using the vision system. These reports often indicated visual disorientation, unstable approaches, or limitations of the navigation system in use.
- "Possibly Provides Mitigation" – denotes an accident where there may have been a benefit to the vision systems, but there were a number of extenuating circumstances in the accident that may have overridden the benefit of the vision systems.
- "Not Likely to Provide Mitigation" – denotes an accident where the vision system will probably not provide a benefit that would have prevented the accident.
- "Not Enough Information" – the report did not contain enough information to judge whether the vision system would have prevented the accident.

In evaluating whether the vision system would have prevented the accident, there was the consideration of the feasibility that a given aircraft type could be outfitted with the associated vision system. For example, it is unlikely that single-engine propeller aircraft would be outfitted with EFVS, which requires a sensor on the nose of the aircraft.

3.1.2.1 HUD Mitigation

For the period from 2008 onward, the reviewer examined parts 121 and 135 accident and incident reports from NTSB to examine whether HUD would have provided mitigation given the context in the reports. All part 121 accidents were assessed. For the part 135 occurrences, single-engine airplanes and helicopters were excluded as they are unlikely to equip with HUD. All part 135 multiengine events were reviewed since advances in HUD technology may make it possible for smaller airplanes to equip with HUD in the future. In addition, large numbers of reports indicating turbulence or factors beyond the pilot's control were excluded. This filtering reduced the set of reports from 971 to 365. Table 3-1 summarizes the impact that HUD may have had on accidents and incidents.

Table 3-1. Possible HUD Mitigation on accidents and incidents

Technology	Time Frame	Total NTSB Reports (part 121 and 135)	Relevant Reports	Likely Provides Mitigation	Possibly Provides Mitigation	Not Likely to Provide Mitigation	Not Enough Information
HUD	2008-2018	971	365	3	35	321	6

The reports where HUD may have provided a positive impact were often related to unstable approaches and tail strikes during landing, takeoff, or go-around. In these cases, HUD may have provided the flight crew with the appropriate situational awareness (e.g., display of speed and attitude cues) to prevent the incident.

MITRE's review of incidents and accidents resulted in a lower proportion of reports where HUD may have provided a positive impact than the FSF report. There are three potential reasons for this result:

- Different time range (FSF – 1995 through 2007, MITRE – 2008 onward); other mitigations, such as continued emphasis by operators on the importance of stable approaches, may have reduced the occurrence of events where HUD may have been judged helpful;
- Different sources; FSF used a much larger dataset, including international reports as well as NTSB reports; and
- Subjective nature of judging the impact of HUD.

3.1.2.2 SVGS and EFVS Mitigation

While EFVS and SVGS may also provide similar situational awareness cues to those provided by HUD, the safety impact of these technologies is expected mostly during conditions where typical visual cues around the runway environment may be obscured. Under these conditions, the sensor-based imagery of the runway environment with EFVS or the database-derived depiction with SVGS may provide powerful situation awareness cues that pilots would find easier to interpret. Therefore, this analysis focused on accidents and incidents during low visibility conditions or nighttime. Table 3-2 summarizes the potential impact that SVGS and EFVS may have had on accidents and incidents for the time period from January 2000 through April 2018, across a total of 2,164 reports involving part 121 and part 135 aircraft. Reports were evaluated for feasibility of equipping based on aircraft type before they were manually reviewed. SVGS can realistically be installed on more aircraft types (e.g., single-engine and light twin-engine) than EFVS, as the technology does not necessitate a HUD installation.

Table 3-2. Possible SVGS and EFVS mitigation of accidents and incidents

Technology	Condition	Number of Reports Examined	Likely Provides Mitigation	Possibly Provides Mitigation	Not Likely to Provide Mitigation	Not Enough Information
SVGS	Low Visibility	43	7	18	18	0
SVGS	Nighttime	177	21	31	113	12
EFVS	Low Visibility	38	5	1	32	0
EFVS	Nighttime	177	18	19	129	11

SVGS may have provided a positive impact for more accidents and incidents than EFVS in both low visibility and nighttime conditions.

3.2 Study on Loss-of-Control In-Flight

A Commercial Aviation Safety Team (CAST) study of worldwide LOC-I accidents found that a lack of external visual references (e.g., darkness and/or instrument meteorological conditions) was associated with flight crew's loss of attitude or energy state awareness in 17 of the 18 accidents studied. Under these conditions, flight crews cannot determine a visible horizon outside the flight deck windows and lack the natural visual cues that are available during VMC. Instead, pilots rely on current flight deck instruments. To mitigate this problem, CAST recommended in Safety Enhancement (SE) 200 that manufacturers should develop and implement virtual day-VMC display systems, such as synthetic vision or equivalent systems, which support flight crew attitude awareness similar to a VMC and daytime environment [23].

The intended function of virtual day-VMC is to improve "attitude, altitude, and terrain awareness, reducing the likelihood of unstable approach, inadvertent entry into unusual attitude, spatial disorientation, and or collision with terrain" [24]. To support CAST and manufacturers, the National Aeronautics and Space Administration (NASA) project called "Technologies for Airplane State Awareness" (TASA) has conducted research to support the definition of MASPS for virtual day-VMC displays that improve flight crew airplane state awareness.

The TASA project conducted a series of human-in-the-loop flight simulator experiments that placed flight crews into unusual attitude recovery scenarios, and compared outcome measurements across different display types, such as the traditional "blue-over-brown" baseline display against SVS. Objective measurements determined how quickly flight crews recovered from the unusual attitude the simulation placed them in. In addition, the experiments used subjective measures, including questionnaires and survey instruments administered to the flight crews between and after experiment scenarios to measure the pilot's perception of workload.

In the objective measures, the studies typically did not find statistically significant differences between display types. However, this may be due in part to the fact that the research pilots for the earlier experiments were highly experienced U.S. commercial pilots. One later experiment did use less-experienced foreign commercial pilots, but the quantitative analysis from that study is not yet available [25].

In the subjective measures, however, synthetic vision often outperformed the traditional blue-over-brown according to the pilots. For instance, during the unusual attitude recoveries, the mental workload was lower, situational awareness was higher, display efficacy was rated as higher, and crew coordination efficacy ratings were higher for SVS [24].

In another set of experiments, in addition to comparing non-SVS displays to SVS displays, the researchers compared HWDs to HUDs. With one exception, "the quantitative data showed no statistically significant" differences between the two. In pilot ratings of the equivalence between HWD and HUD, there was nearly even agreement and disagreement. Discomfort and latency effects caused many pilots to rate the HWD lower than the HUD. Although the HWD might provide similar benefits to the HUD for upset recovery, "the HWD used in this test would require ergonomic improvements for a typical commercial operation" [26].

3.3 ASIAS Safety Studies

The Aviation Safety Information and Analysis Sharing (ASIAS) program is a partnership between industry, the FAA, and MITRE that aims to improve overall safety across the NAS. As part of this partnership, participating airlines are willing to share proprietary data to facilitate relevant safety analysis. The ASIAS program has access to both airline-provided FOQA data and ASAP reports [27] [28]. Due to the sensitive nature of this safety data, the ASIAS Issues Analysis Team (IAT) must approve every analysis that requires the use of airline-proprietary data. For this report, the IAT has approved analysis into potential HUD impacts on system safety, specifically via evaluation of the metrics in Table 3-3.

This section splits the ASIAS analysis into the FOQA metrics in Section 3.3.1, and the ASAP reports in Section 3.3.2.

3.3.1 FOQA Analysis

Vision systems deliver important aircraft state information to the flight crew; it is expected that this information may help pilots fly stabilized approaches. As a modest-sized portion of the traffic in the NAS is equipped with HUD, the impact of HUD on unstable approach rates and the other FOQA approach metrics can be measured through the ASIAS program.

3.3.1.1 Methodology

The ASIAS team developed FOQA-based unstable approach criteria to provide insight into approach safety and to support the monitoring of the effectiveness of CAST SEs. There are 13 criteria that contribute to the unstable approach metric, shown in Table 3-4, and the metric is computed in two segments:

- From 1000 feet Height Above Threshold (HAT) to 500 feet HAT (labeled as 1000 feet)
- Below 500 feet HAT (labeled as 500 feet)

Table 3-3. ASIAS safety metrics approved for analysis

Safety Metric	Data Source	Description
Unstable Approach	FOQA	Flags approaches that trigger 3 of the 13 criteria involving ILS deviation, speed, descent rates, terrain alerts, aircraft configuration, thrust, and attitude
Ground Proximity Warning System (GPWS) Alerts	FOQA	Any alerting to a flight crew related to potentially unsafe proximity to terrain or obstacles
Go-Arounds	FOQA	Includes aircraft that execute a go-around
Excessive Float	FOQA	Identifies approaches that hover just above the runway for a long period prior to touching down
Tail Strikes (on approach)	ASAP	The tail of the aircraft strikes the runway during approach, as reported by the flight crew
Hard Landings	ASAP	Aircraft lands on the runway with excessive force, as interpreted and reported by the flight crew
Wrong Runway	ASAP	Aircraft lands on a different runway than the cleared runway, as reported by the flight crew
Occupied Runway	ASAP	Approaching aircraft must go-around due to another aircraft or ground vehicle on the runway, as reported by the flight crew

Table 3-4. Standard ASIAS unstable approach criteria

Category	Criteria	Standard Threshold
ILS	Above Glideslope	> 1 dot high for 5 seconds
	Below Glideslope	< 1 dot low for 5 seconds
	Localizer Deviation	> 1 dot left/right for 5 seconds
Airspeed	High Speed	> (Vref + 20 knots) for 3 seconds
	Low Speed	< Vref for 3 seconds
Rate of Descent	High Descent Rate	> 1000 feet/minute for 3 seconds
GPWS	GPWS Alert	Any GPWS Alert
Configuration	Late Flap Extension	Any flap movement > 2 degrees
	Late Gear Extension	Any gear movement
	Speed Brakes Deployed	Any deployment of speed brakes
Attitude	Unstable Yaw	Std Dev (Yaw Rate) > 1.25
	Unstable Pitch	Pitch > 15 degrees for 3 seconds OR Std Dev (Pitch Rate) > 1.25
	Unstable Roll	Roll > 40 degrees for 3 seconds OR Std Dev (Roll Rate) > 3.5

If three of the 13 criteria are triggered on the approach segment when the aircraft is less than 1000 feet HAT, it is flagged as unstable.

The digital flight data that powers the FOQA system has airline, fleet type, and recorder configuration variations that impact what parameters are recorded and from what data source on the aircraft. Typically, aircraft that have a HUD system installed and available in the data recording will record a discrete 'on' or 'off' parameter to indicate the status of the HUD throughout the flight. This parameter was used to compute where along the approach path the HUD was on. It is important to note that while this parameter indicates whether the HUD system was on or off, it does not record the details of how the guidance is being used by the flight crew or who is the 'pilot flying' for that segment (e.g., if the First Officer is flying a single HUD aircraft, the guidance may not be leveraged at all). After merging this data with MITRE's equipage database [7], it is possible to determine if an aircraft is equipped with HUD and, if equipped, whether the HUD is on.

The ASIAS program collects digital flight data from 37 commercial operators and dozens of corporate operators to populate the FOQA system. This dataset represents a significant but not complete portion of commercial flights in the NAS. In order to ensure large flight samples in each of these categories within each analyzed aircraft type and arrival airport, only aircraft in the Boeing 737 family (including -300, -400, -700, -800, -900, MAX8, and MAX9 variants) were considered. While certain aircraft and recording mediums are less capable of routinely providing flight data to the program, the Boeing 737 family is one of the better equipped and data-rich fleet groups for the ASIAS FOQA system and should provide representative results.

Furthermore, the analysis focused on arrivals at ten airports (BOS, DEN, EWR, IAD, IAH, MSP, LAS, LAX, ORD, and SFO). These airports were chosen as they were the largest airports with sizable populations of both HUD-equipped and non-equipped 737 arrivals. The examined date range encompasses 2016 to 2018 arrivals at these airports, except for one carrier with data available only for 2017-2018.

After scoping the analysis to the 737 family at ten airports from 2016 to 2018, a set of 1.15 million FOQA approaches was developed. For the HUD analysis, these flights were separated into two categories for comparison:

- *Not HUD Equipped* or *HUD Off* (~608k flights)
- *HUD Equipped, On* (~541k flights)

3.3.1.2 Results

Figure 3-1 shows the rate of the examined FOQA metrics by HUD status, aggregated across the ten airports. The *HUD Equipped, On* arrival sample, has a lower rate of unstable approach and GPWS alerts at both the 1000 to 500 feet HAT segment and the less than 500 feet HAT segment. Excessive float rates, however, are slightly higher in the *HUD Equipped, On* flight sample.

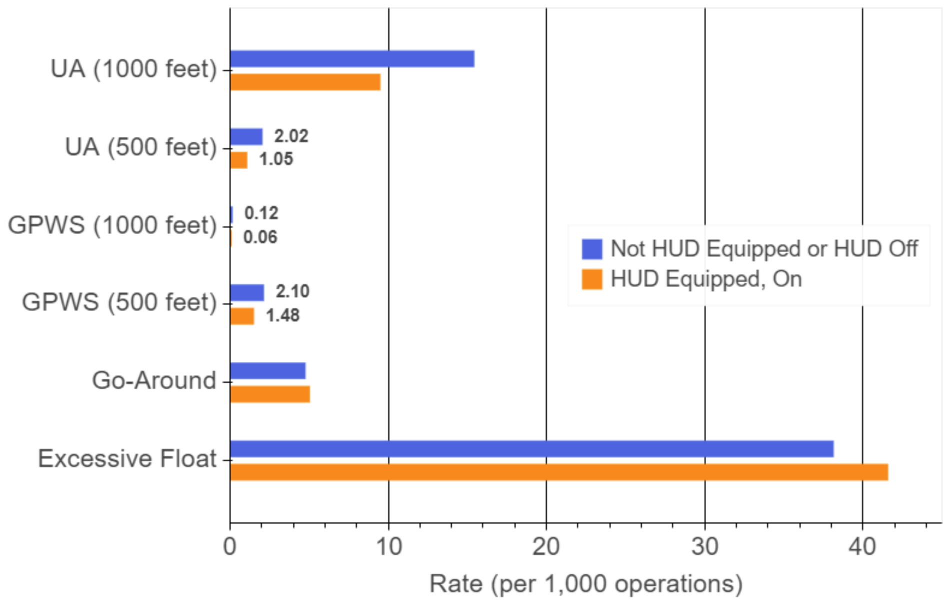

Figure 3-1. Summary of relevant FOQA metrics by HUD status

Figure 3-2 shows the rates that the flight samples in each HUD category exceed the component criteria used to compute an unstable approach (a flight must have three exceedances in a given altitude band to be considered an unstable approach). *HUD Equipped, On* arrivals, have lower rates of High Speed and High Descent Rate, indicating that using HUD may help the pilot maintain appropriate speed and descent rates.

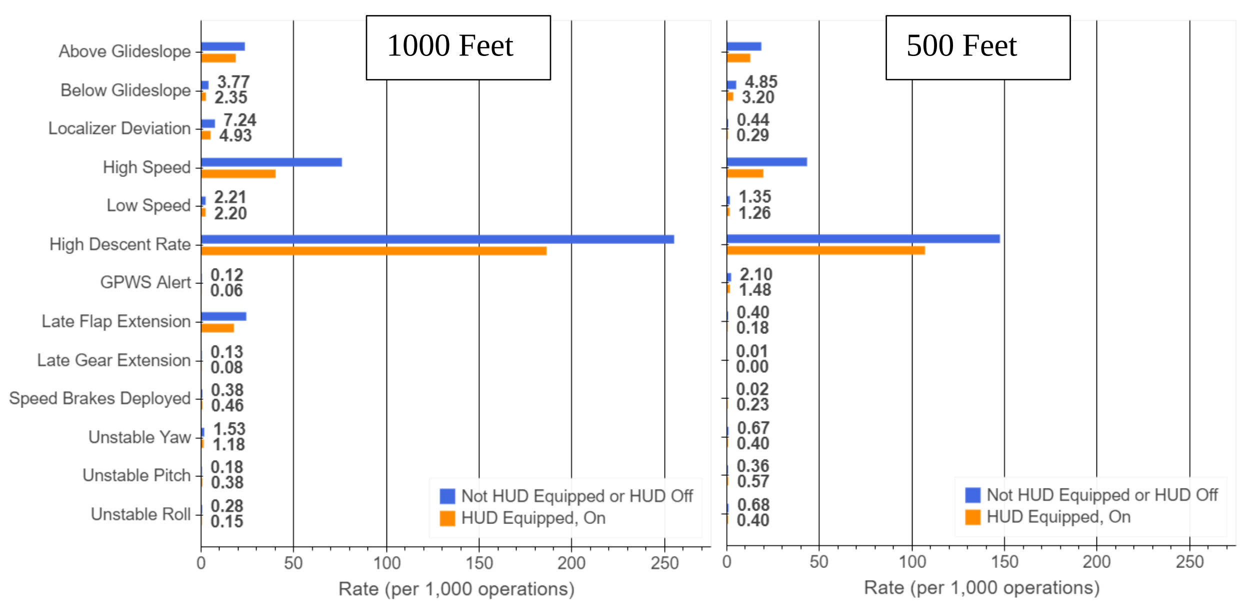

Figure 3-2. Summary of criteria used for unstable approach by HUD status

While the rates varied airport-to-airport, the trend of the *HUD Equipped, On* group having lower rates of unstable approach and GPWS alerts was consistent across all examined airports.

While these results are consistent with expectations given that HUD provides various aircraft state indicators on final approach, there are likely many confounding factors such as carrier impacts, flown approach type, and weather conditions that were not considered. Therefore, while the rates for unstable approach and terrain alerts are lower when HUD is on, more analysis would be needed to control for these confounding factors and quantify the impact directly attributable to HUD.

3.3.2 ASAP Analysis

The ASIAS ASAP system contains a collection of voluntarily submitted pilot reports describing safety events using categorization fields and free-text narratives. Due to differences in operator's reporting cultures, reporting tools, and event reporting requirements, ASAP data likely only captures a portion of relevant events and is not suitable for the computation of comprehensive event rates. However, the reports can provide insight into certain safety events where HUD may have had an effect. In the period from 2016 to 2018, ASAP was queried using a relevant keyword search to identify narratives that may shed light on the possible impact of HUD related to the following safety events:

- Tail strikes
- Hard landing
- Wrong runway
- Occupied runway

3.3.2.1 Tail Strikes

An option on the HUD includes a tail strike warning, notifying the pilot when the aircraft is in a state that may result in a tail strike. Table 3-5 shows some pertinent narrative excerpts relating to HUD and tail strikes.

Table 3-5. Relevant ASAP excerpts about tail strikes

Context	Relevant Excerpt	Takeaway
Pilot notices the tail strike warning and appears to not take any action	"[after receiving a HUD Tail strike warning]… The crew taxied to the gate where a post flight walk around inspection was accomplished. There was no evidence of a tail strike observed […]. The combination of higher then [sic] normal pitch, airspeed decreasing and sink rate meet the criteria for a Tail Strike warning."	HUD communicates the risk of a tail strike, but in this instance, there was no actual strike.
Pilot noticed the tail strike warning and adjusted the angle of attack	"… the "TAILSTRIKE" warning flashed twice very briefly in the HUD. I decreased back pressure and, I think, increased power slightly to allow the aircraft to touchdown with a slightly lower attitude. Touchdown did not feel abnormal on flight deck, however, one F/A mentioned that it was a bit hard. No damage to aircraft and no indication of tail strike. I do not fully understand why this event occurred…"	HUD warned the pilot of a tail strike, allowing corrective action to potentially mitigate the risk of a tail strike.
These two excerpts show that the flight crew noticed the tail strike warning but was not able to mitigate	"It was not until I looked back into the HUD that I noticed the Tail Strike annunciation." "During the last 10 or 20 feet before landing, CA noticed flashing 'tail strike' [on the HUD]."	Either the aircraft entered a state that would trigger a tail strike warning too late for corrective action, the flight crew did not notice the alert until it was too late, or the flight crew simply did not take corrective action.

3.3.2.2 Hard Landings

Hard landings are included in ASAP reports based on the judgment of the flight crew. HUD may help the pilot maintain appropriate speed and descent rates, potentially helping mitigate the risk of hard landings. Table 3-6 presents two narratives relevant to hard landings.

Table 3-6. Relevant ASAP excerpts about hard landings

Context	Relevant Excerpt	Takeaway
Pilot lands hard (without HUD) before going around and landing successfully using HUD.	First Attempt: "This was his first -900 landing without the HUD…. I realized it was going to be a hard landing and pulled the yoke back with both hands as far as I could. … The aircraft did not seem to respond at all and hit pretty hard and then bounced probably 5-6 feet. The Capt called for the Go Around…." Second Attempt: "This time [as opposed to the first time] the Capt had the HUD down for the approach and we discussed landing techniques for the -900. He did a very good landing and we made the second high speed turn off."	HUD may have contributed to the pilot executing a successful approach on the second attempt.
Pilot sees an indication of high descent rate on the HUD; notes that landing was firm and filed the report due to the HUD warning.	"I did see on the HUD in vivid, green letters 'DES RATE'. This was at 50."	HUD indicates high descent rate, but it was either too late for the pilot to adjust the approach, or the pilot simply did not take corrective action, resulting in a hard landing.

3.3.2.3 Wrong Runway

Wrong Runway reports indicate that the aircraft landed on a different runway than what the pilot was cleared to. HUD guidance may help the pilot identify the correct landing runway, or at a minimum, identify situations where they are lined up with the wrong runway. Table 3-7 shows a sample of three relevant Wrong Runway ASAP narratives.

Table 3-7. Relevant ASAP excerpts about wrong runway

Context	Relevant Excerpt	Takeaway
Arrival airport had parallel runways, and the aircraft aligned with the left runway instead of the right one.	"I noticed via the HUD that the aircraft guidance cue was not capturing the Localizer/glideslope."	HUD provided indication that the aircraft was lined up with the wrong runway.
Aircraft cleared for visual approach on Runway 33, and HUD is displaying vertical guidance to that runway. During base turn, the crew sees Runway 03, thinking it is 33, and that they are too high.	"I got focused on getting down for stabilized approach. Was dividing time between HUD (in IMC mode to utilize "3.0 degree line") and observing outside. I omitted the "heads down" displays from my 'scan'….. fixation on stabilized approach and HUD while omitting from my usual scan cues from Flight Displays and FMC led to hampered situational awareness."	Reliance on HUD may have caused the pilot to neglect other indicators.
Snow on the ground may have impacted the ability to identify the correct airport.	"The ground was covered with snow and the airports have almost identical runways and are located just 6 miles from one another. … This was the only airport I saw and it all added up until I crossed checked instruments. I even had the airports option selected on the MFD. I guess I was looking outside the cockpit a little to [sic] much and not reading the instruments."	If HUD were used, it may have provided appropriate cues to identify the correct runway without having to look down.

3.3.2.4 Occupied Runway

Occupied runway reports in the ASAP analysis include flights where a pilot executed a go-around either due to another aircraft occupying the runway or risk of an occupied runway. While the go-arounds could be initiated by the flight crew or the controller, HUD would likely only impact pilot-initiated go-arounds. Since HUD may help the flight crew identify the correct runway, it could also help them identify occupying aircraft sooner. Furthermore, EFVS may help the flight crew see aircraft on the runway in low-visibility conditions, as shown in the excerpt in Table 3-8.

Table 3-8. Relevant ASAP excerpt about occupied runway

Context	Relevant Excerpt	Takeaway
Pilot-initiated go around inside of 500 feet due to occupied runway.	"Tower still put the [Cherokee] aircraft in front of us as we slowed to our Vref speed. However once we were inside the 500 ft call we were stable however the aircraft in front of us had not gotten off the runway yet. So as a precaution we executed a Go Around."	HUD could permit continuous attention to the landing environment and awareness that the previous arrival had not cleared the runway. If this was in low visibility, the pilot may have needed EFVS to identify the occupying aircraft.

3.3.2.5 Additional ASAP Takeaways

In reading through the narratives highlighted in this section and many others, there were several key takeaways that emerged, including the following:

- HUD can provide valuable aircraft state information to pilots in their forward FOV
- Information displayed on HUD is indicative of risk at that instant; due to the dynamic nature of aircraft state, like other alerting systems, alerts displayed on the HUD can occur late in descent with limited pilot response time
- Like other displays and instrumentation in the cockpit, there is a learning curve and adjustment period associated with the HUD before the pilot becomes fully comfortable with it
- While HUD may enhance the pilot's situational awareness, it is important for the pilot to also consider other indicators of aircraft state and the runway environment

4 Efficiency Impacts

In addition to the safety benefits described in Section 3, vision systems can have substantial efficiency impacts, as equipped aircraft may be able to takeoff or land during conditions that would prevent non-equipped aircraft from doing the same. Specifically, vision systems are expected to provide efficiency benefits during periods of low visibility at the airport. For purposes of examining efficiency impacts, low visibility periods where vision systems could potentially provide efficiency impacts were defined as follows:

- Minimum of reported visibility or RVR is at or below 1 Statute Mile (SM) at the departure or arrival airport (depending on the efficiency metric), further broken down to at or below ½ SM and at or below ¼ SM
- Absence of high wind conditions (defined here as reported wind greater than 20 knots and reported wind gusts greater than 25 knots)
- Absence of thunderstorms in the area

The data sources used for each of the weather conditions are Automated Surface Observing System (ASOS) and Meteorological Aerodrome Report (METAR).

While current regulation states that vision systems can provide takeoff and landing credit during specific weather conditions and operation type, this section provides a general look into low visibility conditions to understand the general pool of benefits that could be realized through various technologies.

This section quantifies the efficiency impacts of vision systems in various ways. Table 4-1 shows how each technology may provide efficiency impacts.

Table 4-1. Efficiency impact mechanism

Technology	Possible Efficiency Impact Mechanism
HUD	• Can be used to manually fly CAT II and CAT III approaches without the need for autoland systems. • May provide pilots with improved situational awareness, possibly reducing the need for go-arounds.
EFVS	• Provides operational credit to land during conditions below published minima. • Provides operational credit to dispatch during conditions below published minima at the arrival airport.
SVGS	• May allow aircraft to fly SA CAT I approaches. • If the aircraft is approved to fly SA CAT I approaches, it would also be authorized to dispatch during SA CAT I minima at the arrival airport.

The following inefficiencies due to low visibility weather, along with the potential impact of vision systems, are quantified in this section across three years of data (2016 to 2018), ultimately considering about 37 million operations:

- Reduced throughput
- Cancellations

- Diversions
- Ground delay
- Airborne delay

Cancellations, ground delay, airborne delay, and diversions inefficiencies were ultimately monetized using available FAA data, and Table 4-2 shows the total potential range of efficiency impact by minimum visibility. It is expected that vision systems will impact a portion of these total inefficiency values.

Table 4-2. Total potential efficiency impact of vision systems (2016 through 2018)

Minimum Visibility	Range of Potential Efficiency Impact ($)
<= 1 SM	$1.6 to $3.1 billion
<= 0.5 SM	$1.0 to $1.9 billion
<= 0.25 SM	$640 million to $1.1 billion

4.1 Reduced Throughput

Low visibility conditions (visibilities less than one statute mile) typically result in lower departure and arrival throughput compared to typical IMC operations. This lower throughput could be a result of cancellations, diversions, ground delay, or airborne delay.

MITRE used available ASOS and METAR data to identify how often low visibility conditions occur. Low visibility periods were defined by the minimum of reported visibility or RVR, if applicable. Note that reported visibilities are often binned to the nearest quarter of a mile, which limits the analysis of some specific scenarios (e.g., visibility requiring a CAT II approach). Also, while the rest of the analysis in Section 4 removes convective weather events, this analysis does not. Low visibility conditions occur rarely; Table 4-3 shows the percentage of time across 2016 through 2018 where the weather is at or below the given visibility.

Table 4-3. Time in low visibility across the NAS

Visibility	Percentage of Time
<= 1 SM	2.3%
<=0.75 SM	1.7%
<= 0.5 SM	0.8%
<= 0.25 SM	0.5%

To determine the impact of low visibility conditions on throughput, MITRE computed baseline IMC throughput for each available airport. For time periods in these baseline IMC conditions, <=3 SM reported visibility for this study, throughput was computed across the period from 2016 through 2018. To examine the relative throughput during low visibility conditions, MITRE compared throughput during periods with <=1.0 SM, <=0.5 SM, and <=0.25 SM minimum visibility to the nominal IMC throughput for both arrivals and departures on an airport-by-airport basis.

The airport throughput comparisons were then aggregated by Navigation Service Group (NSG) level, with NSG levels 1 and 2 representing large commercial airports that typically have CAT II or CAT III ILS approaches and a better-equipped commercial fleet. NSG 3 airports are typically smaller airports with less commercial traffic, and NSG 4 and 5 airports are mostly GA airports, as defined in the PBN NAS Navigation Strategy [29].

Figure 4-1 shows the relative throughput for each grouping of weather conditions and NSG level for arrivals. The larger airports included in NSG levels 1 and 2 will typically have the appropriate infrastructure (e.g., CAT II ILS approaches) to land during these low visibility conditions, resulting in throughput that is close to the nominal IMC throughput. At the NSG 1 level, throughput is around 90 percent of the nominal IMC throughput, even for <= 0.25 SM visibility. At the NSG 2 level, throughput drops to about 80 percent of the nominal IMC throughput when visibility is <= 0.25 SM. However, the smaller airports (NSG 3 and higher) may not have the infrastructure or the fleet equipage to continue IMC-like operations in low visibility conditions, and throughput is reduced substantially, especially during visibility at or below 0.25 SM.

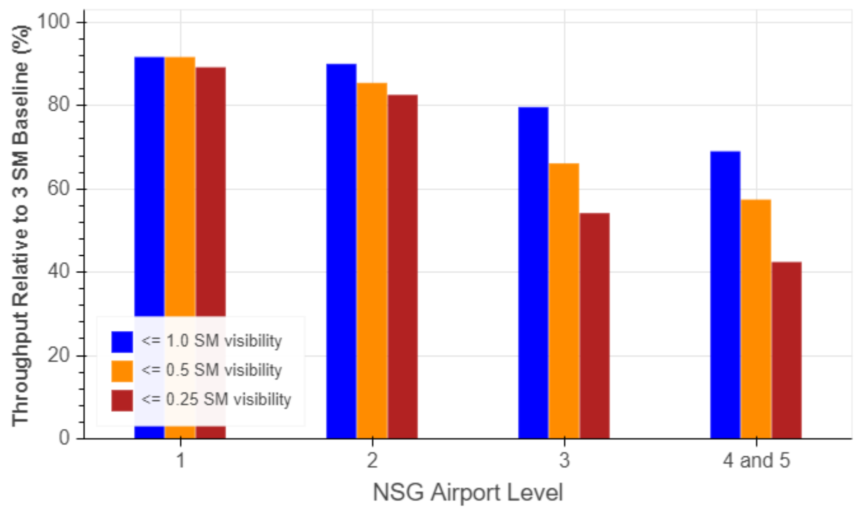

Figure 4-1. Impact of visibility on arrival throughput relative to nominal IMC throughput

Figure 4-2 shows a depiction of relative throughput for departures, similarly highlighting reductions in throughput during the lowest visibility at the NSG 3 and higher airports. However, departure throughput is a bit higher than the arrival throughput at the NSG 3-5 airports, indicating that low visibility impacts arrivals more than departures at these airports.

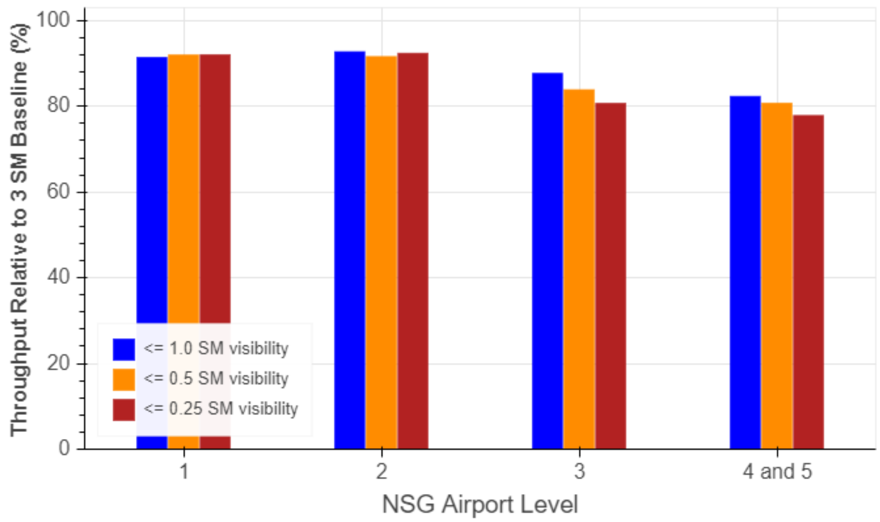

Figure 4-2. Impact of visibility on departure throughput relative to nominal IMC throughput

4.2 Cancellations

Cancellations may occur if low visibility conditions exist at either the departure or arrival airport, and the operators do not expect the weather to improve in a reasonable timeframe. This is one mechanism that could reduce throughput during low visibility conditions.

4.2.1 Methodology

OAG maintains a historical database of flight statuses[1], which tracks cancellations of participating carriers. This data, which should include all major part 121 operators and many part 135 operators, was used to identify cancellations during low visibility periods from 2016 through 2018. This data does not include GA or military flights.

METAR and ASOS data were examined for low visibility conditions at either the scheduled departure or arrival airports during the following time periods, as these should account for the relevant time periods where the operator decides whether to depart or cancel:

- Scheduled Departure Airport - from the scheduled departure time until two hours after the scheduled departure time
- Scheduled Arrival Airport - from the scheduled departure time until the scheduled arrival time

One notable limitation regarding this methodology should be noted. Cancellations are often issued in advance as a result of predicted weather. It is possible that there are situations where the flight was canceled due to predicted low visibility conditions, but the predicted weather does not materialize during the examined time periods; this cancellation would not be included in this analysis.

Due to lack of high-fidelity weather data at international airports, this set of cancellations only includes flights that were scheduled to depart and arrive at U.S. airports.

[1] https://www.oag.com/flightview-flight-status

Cancellations were monetized using values from FAA's Economic Information for Investment Analysis, specifically the sum of Airline Direct Operating Cost (ADOC) and Passenger Value of Time (PVT). For commercial aircraft, ADOC is $203 per cancellation as there is little cost to the operator when the aircraft does not actually take off, and PVT is $19,022 per cancellation, indicating that passengers bear the brunt of the cost when a cancellation occurs. Cancellations are much more costly for cargo operators; however, no cargo cancellations were found across the three years of examined data, as cargo operators rely on other methods to handle low visibility conditions such as delay and diversions. The values provided here are only an estimate for the generic cost of a cancellation; each individual event is undoubtedly unique in terms of total cost and dependent on many factors [30].

4.2.2 Results

From 2016 to 2018, there were a total of 424,681 cancellations (about 1.2 percent of examined operations), totaling more than $8.1 billion in cost using the FAA Economic Information for Investment Analysis values [30]. Flights can be canceled for many reasons, including equipment concerns, lack of demand, and various weather phenomena. Vision systems are expected to provide the most efficiency benefits during low visibility conditions, which impacts a portion of the total cancellations, as shown in Table 4-4. The data consists of low visibility conditions (eliminating periods with thunderstorms or high-wind conditions) at either the departure and arrival airport around the scheduled departure time, and the last column in the table shows the distribution of where the low visibility weather occurs. The low visibility conditions leading to cancellations appear to be split relatively evenly between the departure and arrival airport.

Table 4-4. Summary of cancellations resulting from low visibility

Visibility	Number of Cancellations	Portion of Total Cancellations (%)	Total Monetization ($M)	Proportion of Low Visibility at Origin/Destination/Both (%)
<=1 SM	49,838	11.7%	$958	46/43/11%
<=0.5 SM	29,796	7.0%	$573	48/45/7%
<=0.25 SM	16,169	3.8%	$311	48/47/5%

Although the results are split out by where the low visibility conditions occur, it is important to note that EFVS operational credit for dispatch only exists when weather is below published approach minima at the arrival airport. As there may be an additional credit to dispatch below departure minima forthcoming at runways without centerline lights, the cancellations occurring when there is low visibility at the origin airport represent a potential pool of benefit that vision systems may address in the future.

Figure 4-3 provides a look into the cancellations over the three years of analysis. The large peaks in the cancellation data typically correspond to a high-impact weather event, like a hurricane in the southern U.S., or a snowstorm in the northeastern U.S. The portion of cancellations potentially impacted by vision systems is represented by the blue, orange, and red colors on the bottom of the plot, which exclude low visibility periods that include thunderstorms or high-wind conditions.

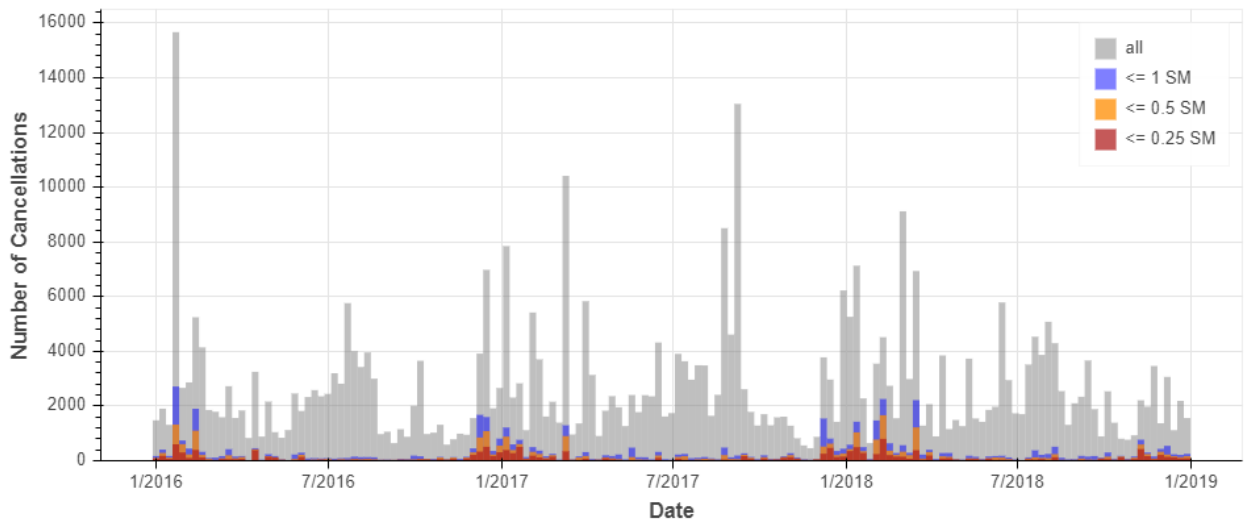

Figure 4-3. Cancellations over three years of analysis

4.3 Ground Delay

When weather conditions at either the departure airport or arrival airport are below minima for a commercial flight, the flight cannot takeoff, leading to ground delay. This is another mechanism that reduces throughput at an airport during low visibility conditions.

4.3.1 Methodology

Ground delay is defined as the positive difference between push-back time and the scheduled departure time. The push-back time for a given flight is often available in the OAG data, but if it is not available, the pushback time is estimated as fifteen minutes prior to the wheels-off time, as derived from MITRE's Threaded Track dataset [31].

We attributed pushback delay to low visibility if those conditions were present at the departure or arrival airport at the scheduled departure time, excluding periods with thunderstorms or high wind at the airport.

Ground delay was monetized as follows from the Economic Factors document [30]:

- Carrier ADOC: $1,169 per gate hour
- Cargo ADOC: $3,153 per gate hour
- Carrier PVT (not applicable to cargo operators): $3,803 per hour ($49.2 per passenger times 77.3 average enplanements across air carriers and air taxi)

4.3.2 Results

Ground delay is the cheapest method to delay a flight for an airline, as it costs an operator about one-third of the cost of taking the same amount of delay in the air. Still, ground delay happens frequently in the NAS and therefore adds up to a substantial cost.

Airlines will often pad scheduled times to allow for a certain amount of delay while still meeting their scheduled arrival time. Therefore, two values are used to represent the impact of low visibility on ground delay:

- Total realized delay – only counts ground delay if the delayed departure leads to actual arrival delay
- Total ground delay – total ground delay without considering if the aircraft arrived late or not; this includes the delay that is built into flight schedules

Table 4-5 shows the total ground delay during low visibility conditions, with delay apportioned to either the departure or arrival airport. Figure 4-4 presents the data for realized ground delay in a visual format.

Table 4-5. Summary of ground delay occurring during periods of low visibility

Visibility	Low Visibility at Dep. or Arr. Airport	Total Dep.	Dep. with Realized Ground Delay (% of total)	Realized Ground Delay (thousands of minutes)	Realized Ground Delay ($ M)	Dep. with Total Ground Delay (% of total)	Total Ground Delay (thousands of minutes)	Total Ground Delay ($M)
<=1 SM	Departure	523,111	88,679 (17%)	920	$76	206,952 (40%)	10,402	$851
<=1 SM	Arrival	503,747	88,334 (18%)	1,067	$88	192,488 (38%)	10,096	$828
<=0.5 SM	Departure	279,199	46,369 (17%)	492	$41	104,960 (38%)	5,614	$460
<=0.5 SM	Arrival	267,973	46,451 (17%)	609	$50	101,007 (38%)	5,713	$468
<=0.25 SM	Departure	153,769	26,340 (17%)	279	$23	56,340 (37%)	3,148	$258
<=0.25 SM	Arrival	148,009	26,109 (18%)	358	$30	56,120 (38%)	3,357	$275

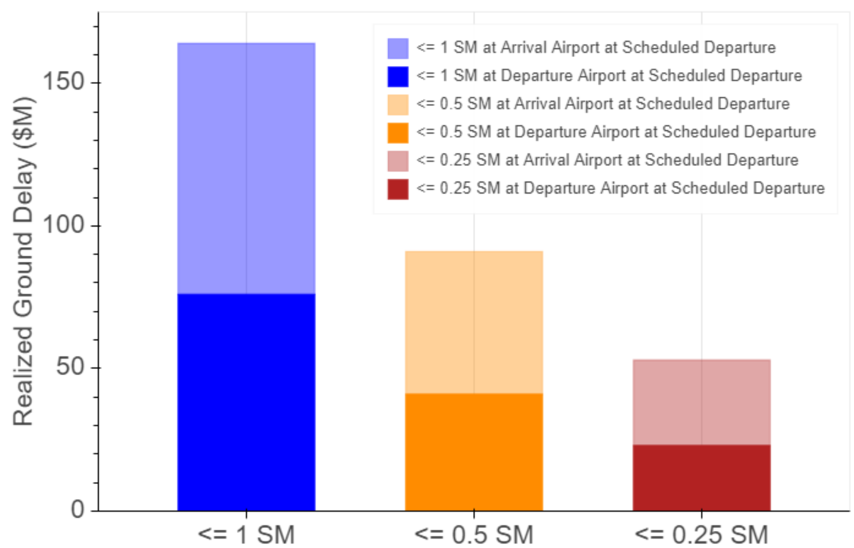

Figure 4-4. Realized ground delay during low visibility (2016 through 2018)

Ultimately, when visibility drops to 1 SM or less at either the departure or arrival airport, the ground delay ends up costing operators between about $160 million and $1.7 billion. When that visibility is further reduced to 0.25 SM or less, the ground delay ends up costing operators between $53 million and $533 million. It is expected that vision systems would mitigate a portion of these ground delay costs.

4.4 Airborne Delay

Airborne delay is another contributing factor to reduced throughput during low visibility conditions. Flights may experience airborne delay when conditions at both the departure and arrival are suitable for takeoff, but conditions at the arrival airport deteriorate while the flight is airborne, causing the flight to delay until conditions improve enough to land at the intended airport. Vision systems may provide access to allow aircraft to land during low visibility conditions; therefore, some of this airborne delay could potentially be avoided with additional equipage of vision system technologies.

4.4.1 Methodology

We computed airborne delay against flight schedule data from OAG, but specific conditions had to be met to attribute the delay for a given flight to low visibility conditions at the arrival airport. Similar to the computation of ground delay, two values will be provided here for the impact of airborne delay: realized delay (based on scheduled arrival time) and total potential delay (airborne delay regardless of scheduled arrival time).

Flights potentially impacted by low visibility conditions were defined as those that landed within half an hour of a weather report with visibility or RVR below 1 SM, as determined from Threaded Track data. If the flight was delaying until the conditions improved, the half an hour period should provide enough time to capture that arrival as part of the impacted flights.

The realized arrival delay was computed using OAG data as the difference between in-gate time (if available) and scheduled arrival time. If in-gate time was not available, a derived landing time from Threaded Track data was used in lieu of the in-gate time. Separately, departure delay was computed using the difference between out-gate time (or derived wheels-off time from Threaded Track if out-gate time is not available) and the scheduled departure time. Arrival delay relative to the schedule was then computed as the difference between arrival delay and departure delay. As an example, if the total arrival delay was 30 minutes, but the same flight had 20 minutes of departure delay, the realized arrival delay would be 10 minutes.

In addition, it is expected that flights with arrival delays as a result of the low visibility conditions take longer-than-normal paths to the airport, specifically in the last 250 Nautical Miles (NM) of the arrival airport, as they might hold or vector to wait until the weather improves. Therefore, a baseline distance flown was computed, representative of nominal IMC operations, as 110 percent of the median distance flown in the last 250 NM for a given city-pair where the visibility at the airport was 3.0 SM or less within half an hour of landing. For city-pairs less than 250 NM apart, 110 percent of the median distance flown for the entire flight was used for the baseline. To be considered for airborne delay, the aircraft had to fly a distance that was longer than the baseline distance flown for a given city-pair under nominal IMC. If there was no extra distance flown, then the flight would not have been tagged as having a delay, even if there was a delay relative to the scheduled arrival time.

To summarize, in order for a flight to have realized airborne delay in this analysis, the following conditions had to be met:

- In-gate time after the scheduled arrival time
- Arrival delay greater than the departure delay
- Flown distance greater than baseline distance (110 percent of the median) for the relevant city-pair during IMC conditions

For the total potential delay, the excess time flown inside of 250 NM of the arrival airport (or total flight time if city-pair distance is less than 250 NM) was computed in a similar fashion to how the excess distance was computed. This value represents the potential time saved in the air, regardless of whether the flight arrived late relative to its scheduled arrival time.

For flights with airborne delay that can be attributed to low visibility at the arrival airport, the delay was monetized using the following data from the FAA's Economic Factors document [30]:

- Carrier ADOC: $3,337 per airborne hour
- Cargo ADOC: $9,481 per airborne hour
- Carrier PVT (not applicable to cargo operators): $3,803 per hour ($49.2 per passenger times 77.3 average enplanements across air carriers and air taxis)

4.4.2 Results

Figure 4-5 shows a few examples of aircraft that were forced to delay until conditions improved at the airport to land. In both cases, the aircraft enter holding patterns for more than half an hour as it waits for conditions to improve. In the case of the arrival to Allentown (left), the FedEx flight enters a holding pattern west of the airport. In the case of the arrival to Buffalo (right), the Endeavor Air flight attempts an approach before going around and landing.

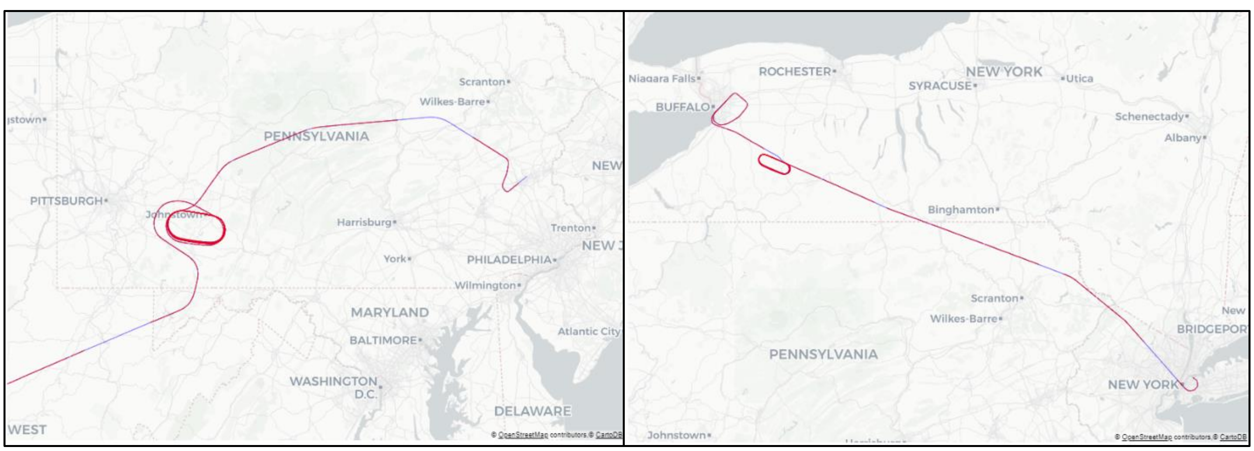

Figure 4-5. Examples of flights accumulating airborne delay while waiting for improved visibility at arrival airport

Table 4-6 shows the summary of airborne delay occurring during low visibility conditions from 2016 to 2018, separating out the realized delay (schedule-based) and the total potential delay (track-based). Ultimately, less than 0.5 percent of the total examined operations experienced airborne delay as a result of low visibility conditions of 1.0 SM or less.

Table 4-6. Summary of airborne delay occurring during periods of low visibility

Minimum Visibility	Total Flights Arriving during or within 30 Minutes of Low Visibility	Arrivals with Realized Airborne Delay (% of total)	Realized Delay (thousands of minutes)	Realized Delay Monetization ($ millions)	Arrivals with Flown Airborne Delay (% of total)	Total Flown Delay (thousands of minutes)	Total Flown Delay Monetization ($ millions)
<=1.0 SM	278,916	22,475 (8.1%)	266.9	$32	60,910 (21.8%)	460.9	$56
<= 0.5 SM	131,669	12,050 (9.2%)	159.6	$19	29,623 (22.5%)	258.6	$31
<= 0.25 SM	65,252	6,747 (10.3%)	95.9	$12	15,411 (23.6%)	149.5	$18

Airborne delay during low visibility, although more costly when it occurs, is of smaller total cost than ground delay. This is somewhat expected, as operators would prefer to take delay on the ground, as it is roughly three times more expensive to take the same delay in the air.

Figure 4-6 shows how the percentage of arrival flights with realized airborne delay in low visibility conditions varies by NSG airport level. At the busier NSG 1 and 2 airports, typically, less than 10 percent of arrivals during or within 30 minutes of low visibility will experience airborne delay relative to their scheduled arrival time. This number goes up to above 20 percent at NSG 4 and 5 airports during <=0.25 SM visibility.

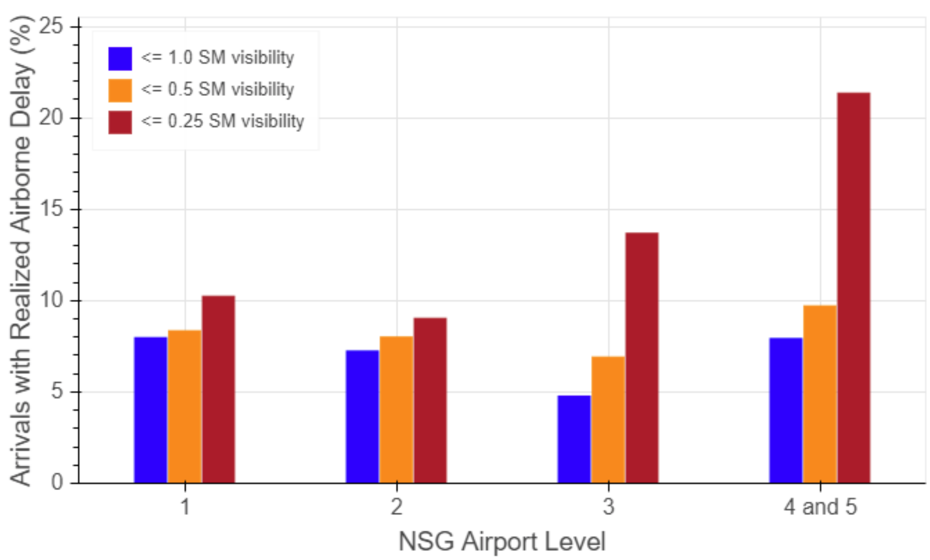

Figure 4-6. Portion of arrivals with realized delay by NSG airport level

4.5 Diversions

Another mechanism that contributes to lost throughput during low visibility conditions is diversions. These aircraft make the decision to take off but ultimately arrive at an airport that is different from what is filed as its destination. Diversions can be a result of mechanical issues, onboard emergencies, bad weather, or a number of other reasons. This analysis examines those diversions potentially resulting from low visibility conditions.

4.5.1 Methodology

The analysis relied on Traffic Flow Management System (TFMS) flight plan information to identify diversions from 2016 through 2018. The arrival airport contained in the last flight plan message prior to takeoff was considered as the intended destination. Diversions were identified as those flights with an amendment that indicated a change in arrival airport that occurred at least 5 minutes after wheels-up time, as identified using MITRE's Threaded Track data source.

ASOS and METAR data were leveraged to identify those diversions that may have resulted from low visibility weather at the intended arrival airport. If low visibility occurred at the intended arrival airport any time during the period from one hour prior to the amendment until the time of the amendment, that flight was labeled as a low visibility diversion. In addition, flights diverting during time periods with convective weather or high wind conditions (winds greater than 20 knots or gusts greater than 25 knots) were removed, as it is likely they diverted due to those conditions instead of low visibility.

Furthermore, since the total aircraft arriving during these low visibility conditions was computed in the Airborne Delay section, it was also possible to compute the likelihood of experiencing a diversion. For each weather condition, the likelihood of experiencing a diversion is calculated using the number of diversions divided by the sum of diversions and arriving aircraft. This value only considers aircraft that are in the vicinity of the airport during the low visibility conditions; aircraft on the ground and cancellations are not considered in this calculation.

Diversions are expensive for airlines, as well as passengers, as they often require a recovery flight to ensure the aircraft returns to where it needs to be for schedule purposes and to accommodate stranded passengers. Using the FAA's Economic Information for Investment Analysis, each diversion was monetized the following values [30]:

- Carrier ADOC: $17,887 per diversion
- Cargo ADOC: $9,481 per diversion
- Carrier PVT (not applicable to cargo operators): $19,108

Each diversion is unique, but these monetized values will provide an estimate of how much a typical event costs. Diversions are counted independently from airborne delay, so a flight that held for a period of time before choosing to divert would only show up in this data and not in the airborne delay metrics in Section 4.4.2.

4.5.2 Results

Across the three years of data, MITRE identified a total of 86,728 diversions (about 0.2 percent of total operations) totaling around $3 billion. Table 4-7 summarizes the diversions occurring during low visibility conditions.

Table 4-7. Summary of diversions resulting from low visibility

Minimum Visibility	Number of Diversions	Portion of Total Diversions (%)	Likelihood of a Diversion (%)	Total Monetization ($M)
<= 1.0 SM	12,201	14.1%	4.2%	$420
<= 0.5 SM	9,696	11.2%	6.9%	$334
<= 0.25 SM	7,756	8.9%	10.6%	$267

In addition to the inefficiency of diversions, diverting aircraft are also likely to experience abnormal operations that may cause pilot and controller workload issues. For example, of the 12,201 diversions during <=1 SM minimum visibility, 41 percent experience holding, and almost 20 percent attempt a landing before diverting to another airport.

Figure 4-7 provides a few examples of diversion flights. They are clearly anomalous flights that can be very disruptive to airlines. In the example on the left, the aircraft intends to land at Miami International Airport (MIA) but ends up holding before attempting to land, executing a missed approach, and diverting to Tampa International Airport (TPA). In the example on the right, the flight intends to land at Sioux Falls Regional Airport (FSD) and attempts multiple approaches before diverting to Minneapolis-Saint Paul International Airport (MSP).

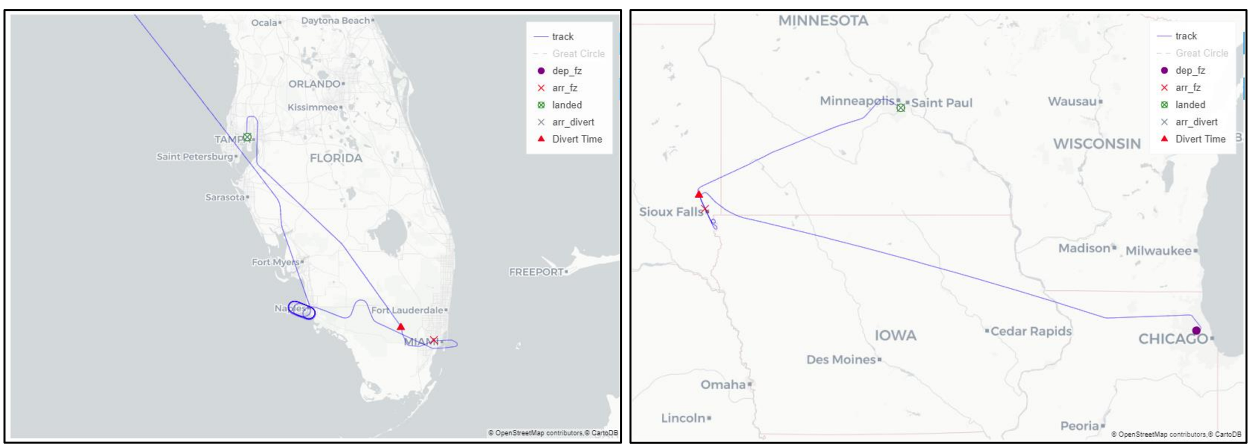

Figure 4-7. Examples of identified diversions

Figure 4-8 shows the likelihood of diversion by weather category and NSG airport level. At the larger NSG 1 and 2 airports where aircraft are more likely to be able to use available CAT II and III ILS approaches, the likelihood of diversion is less than 10 percent, even during <=0.25 SM visibility. At the smaller NSG 4 and 5 airports where CAT II or III ILS approaches might not be available, or the aircraft are not equipped to use them, the likelihood of diversion jumps up to nearly 70 percent in <=0.25 SM visibility.

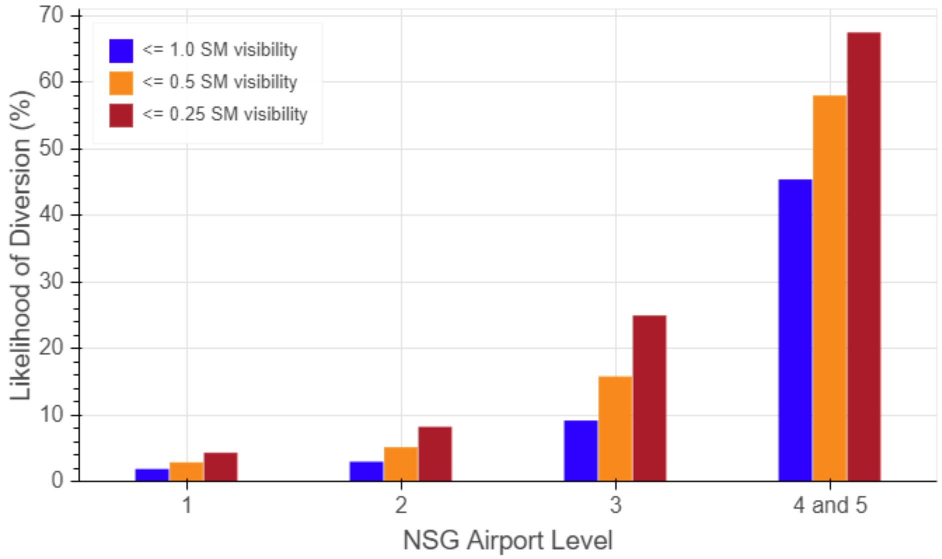

Figure 4-8. Likelihood of diversion by NSG airport level

5 Conclusions and Future Applications

Vision systems including HUD, HWD, SVS, and EFVS can have a substantial safety and efficiency impacts. These technologies can provide better situational awareness to the flight crew, which could manifest in fewer safety events and better energy management during critical phases of flight. The FAA has identified a number of accidents and incidents from NTSB reports where the use of a vision system may have provided a better outcome. In addition, analysis of ASIAS data indicates that HUD may reduce the rate of unstable approaches and terrain alerts.

On the efficiency side, these technologies may enable takeoff and landing during conditions that would prevent non-equipped aircraft from doing the same, potentially resulting in increased airport throughput. In this report, the FAA explored cancellations, ground delay, airborne delay, and diversions that occur during low visibility conditions to evaluate the potential pool of benefits where vision systems may provide an efficiency impact. Ultimately, across the time period from 2016 through 2018, the FAA estimates that low visibility conditions caused between $640 million and $3.1 billion of NAS-wide efficiency losses.

As discussed in Section 2.2, vision systems can vary in cost from tens of thousands of dollars to upwards of a million dollars per aircraft installation. Furthermore, there are substantial costs associated with pilot training and going through the OpSpec process to gain operational credit for these systems.

While costs are a big driver for investment decisions around vision systems, the other big factor is the limited space in the cockpit. In the case of HUD, it is not feasible in many cases to fit the additional display and instrumentation into the already cramped cockpit. HWDs may offer a path for additional equipage as they can be implemented in virtually any cockpit; however, there are numerous challenges to overcome before HWDs are available for widespread use.

This report has shown the impact of vision systems as they are being implemented in the current operating and regulatory environment. However, with the continued evolution of technology, integration with flight operations, and regulations, there is potential for future applications of vision systems that could provide substantial benefits. Table 5-1 summarizes some of these possibilities.

Table 5-1. Potential future applications of vision systems

Application Description	Potential Benefit Mechanism
Vision system could provide necessary guidance to flight crew in the takeoff phases	Reduction in ground-based infrastructure, such as runway lighting systems.
Vision systems could fully mimic the view out the cockpit window	Elimination of windows in the cockpit, getting rid of some aircraft design challenges associated with the windshield. Possible enabler for ultra-high-speed aircraft.
Display of RNAV/RNP procedures	May allow for tighter procedure conformance and innovative procedure design.
Display of nearby aircraft	Provide situational awareness of surrounding traffic during conditions where the pilot's vision is obscured.
Create a virtual VMC environment	Enable an environment that mimics VMC, possibly reducing the capacity constraints associated with IMC, and reducing the likelihood of LoC-I accidents.

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Appendix A Abbreviations and Acronyms

Acronym	**Definition**
AC	Advisory Circular
ADOC	Airline-Direct Operating Cost
AFS-410	FAA Flight Technologies and Procedures Division, Flight Operations Branch
ALPA	Air Line Pilots Association
ASA	Aircraft State Awareness
ASAP	Aviation Safety Action Program
ASIAS	Aviation Safety Information and Analysis Sharing
ASOS	Automated Surface Observing Systems
CAST	Commercial Aviation Safety Team
CAT	Category
CFR	Code of Federal Regulations
CVS	Combined Vision System
DH	Decision Height
EASA	European Aviation Safety Agency
EFVS	Enhanced Flight Vision System
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FOQA	Flight Operations Quality Assurance
FOV	Field-of-View
FSD	Sioux Falls Regional Airport
FSF	Flight Safety Foundation
GA	General Aviation
GBAS	Ground Based Augmentation System
GLS	GBAS Landing System
GPWS	Ground Proximity Warning System
HAT	Height Above Threshold
HDD	Head-Down Display
HMD	Head-Mounted Display
HUD	Head-Up Display

Acronym	Definition
HWD	Head-Worn Display
IAT	Issues Analysis Team
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
LOC-I	Loss of Control In-Flight
LPV	Localizer Performance with Vertical Guidance
MASPS	Minimum Aviation System Performance Standards
MDA	Minimum Descent Altitude
METAR	Meteorological Aerodrome Report
MIA	Miami International Airport
MSP	Minneapolis-Saint Paul International Airport
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NM	Nautical Miles
NSG	Navigation Service Group
NTSB	National Transportation Safety Board
OpSpec	Operations Specifications
PVT	Passenger Value of Time
RVR	Runway Visual Range
SA	Special Authorization
SE	Safety Enhancement
SM	Statute Mile
SVGS	Synthetic Vision Guidance System
SVS	Synthetic Vision System
TASA	Technologies for Airplane State Awareness
TAWS	Terrain Awareness and Warning System
TFMS	Traffic Flow Management System
TPA	Tampa International Airport
U.S.	United States
VMC	Visual Meteorological Conditions