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Awareness and Detection of Traffic and Obstacles Using Synthetic and Enhanced Vision Systems

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January 2012

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Space Administration

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Nomenclature

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance-Broadcast
ANSP	Air Navigation Service Provider
CDTI	Cockpit Display of Traffic Information
CFR	Code of Federal Regulations
CRT	Cathode Ray Tube
DA	Decision Altitude
DH	Decision Height
DOT	Department of Transportation
EP	Evaluation Pilot
EFVS	Enhanced Flight Vision System
EV	Enhanced Vision
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FLIR	Forward Looking Infra-Red
FOV	Field-of-View
HAT	Height Above TDZE
HDD	Head-Down Display
HUD	Head-Up Display
ILS	Instrument Landing System
GA	General Aviation
LaRC	Langley Research Center
MASPS	Minimum Aviation System Performance Standard
MDA	Minimum Descent Altitude
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NextGen	Next Generation Air Transportation System
OTW	Out-the-Window
PF	Pilot-Flying
PFD	Primary Flight Display
PNF	Pilot-Not-Flying
PM	Pilot-Monitoring
PMA	Pilot-Monitored Approach
RIPS	Runway Incursion Prevention System
RVR	Runway Visibility Range
SEVS	Synthetic and Enhanced Vision Systems
SOP	Standard Operating Procedure
SURF-IA	Surface Indications and Alerts
SV	Synthetic Vision
SVS	Synthetic Vision System
TDZE	Touchdown Zone Elevation
T-NASA	Taxiway Navigation And Situation Awareness
VFR	Visual Flight Rules

1. Introduction

The NASA Langley Research Center (LaRC) and the Department of Transportation/Federal Aviation Administration (DOT/FAA) are conducting collaborative research activities to ensure effective technology development and implementation of regulatory and design guidance to support the use of Synthetic Vision Systems (SVS) and Enhanced Flight Vision Systems (EFVS) advanced cockpit vision technologies in Next Generation Air Transportation System (NextGen) operations.

SVS/EFVS technologies have the potential to provide an additional margin of safety and performance to enable the implementation of operational improvements for low visibility surface, arrival, and departure operations with equivalent efficiency as visual operations.

SVS uses a terrain and obstacle database to present a computer-generated view of the outside world, often on a Head-Down Display (HDD). While HDDs are cheaper and more widely available than Head-Up Displays (HUDs), presentation of SVS information on a HDD display has the potential to significantly increase pilot head down time which may detract from ground-referenced navigation and hazard detection/avoidance.

EFVS uses active or passive sensors to present a visual image of the outside view on a HUD. Previous research on HUD use in airborne applications suggests that clutter and masking can lead to decreased conflict detection. Safe and effective use of EFVS information presented on a HUD will require assessment of the impact of EFVS presentation on ground conflict detection and avoidance.

In this report, the research literature is reviewed to assess awareness and detection of traffic and obstacles when using SVS and EFVS systems, as follows:

- Qualify the critical issues influencing the time required, accuracy, and pilot workload associated with recognizing and reacting to potential collisions or conflicts with other aircraft, vehicles and obstructions related to the use of SVS and EFVS (SEVS) technologies during approach, landing, and surface operations.
    - This work includes the effect of HDD and HUD implementations of SVS and EFVS, respectively, as well as the influence of single and dual pilot operations.
- Identify methods and strategies of adding Cockpit Display of Traffic Information (CDTI) with head-down SVS and head-up EFVS in low-visibility landing and surface operations and their effect on time required, accuracy, and pilot workload for recognizing and reacting to potential ground collisions or conflicts. This work includes the impact of emerging requirements for CDTI and alerting for NextGen.

Based on this review, a knowledge gap assessment is conducted to create recommendations for subsequent ground and flight testing which promote the safe and effective implementation of SEVS technologies for NextGen.

2. Background

Synthetic vision (SV) is a computer-generated image of the external scene topography that is generated from aircraft attitude, high-precision navigation, and data of the terrain, obstacles, cultural features, and other required flight information (Figure 1). The term, SVS, as opposed to SV, is often used to indicate that this database information is enhanced with integrity monitoring to ensure the validity of the databases and/or independent navigation accuracy verification. Part of this integrity monitoring function may also include real-time traffic surveillance and obstacle/object detection (Parrish et al, 2008).

Under NASA's Aviation Safety Program/Synthetic Vision Project, NASA and its partners in industry and the FAA, developed and deployed SVS technologies for commercial, business, and general aviation (GA) aircraft. SVS concepts were shown to provide significant improvements in terrain awareness and reductions for the potential of Controlled-Flight-Into-Terrain incidents/accidents compared to current generation cockpit technologies (Kramer, 2004; Kramer, 2005; Arthur 2003; Parrish et al, 2008).

Enhanced Vision (EV) is an electronic means to provide a display of the external scene by use of an imaging sensor, such as a Forward-Looking InfraRed (FLIR) or millimeter wave radar. EV has been used for decades by the military for night missions, especially for low-level navigation and targeting. Various development activities and demonstrations have been conducted. The FAA conducted its own EV technology demonstration program – then called a Synthetic Vision System – to assess the state-of-the-art and the operational implications of the technology (Burgess, 1993). As HUD technology has migrated into commercial and business aircraft, EV technology and its potential for all-weather operations and improved safety naturally followed (e.g., see Looking Ahead, 1993). EV has been shown to be complementary to SV due to their inherently different technological bases (Bailey, 2008).

The applications of EV technology for commercial, business, and GA aircraft were energized in January 2004 (FAA, 2004a) when Title 14 of the US Code of Federal Regulations (CFR) §91.175 was amended such that operators conducting straight-in instrument approach procedures (in other than Category II or Category III operations) may now operate below the published Decision Altitude (DA)/Decision Height (DH) or Minimum Descent Altitude (MDA) when using an approved EFVS. An EFVS, in this application, is an integrated conformal display of EV and symbology shown on the pilot's HUD (see Figure 2). The required conformal symbology includes the flight path vector, flight path angle reference, and flight guidance with other non-conformal flight information shown as necessary and appropriate. The EFVS is approved for use in lieu of natural vision. This rule change provides "operational credit" for EV equipage. No such credit exists for SV.

Minimum Aviation System Performance Standards (MASPS) have been published as DO-315 (RTCA, 2008), which provides the system performance standards for EFVS ("operational credit") and SV ("no operational credit").

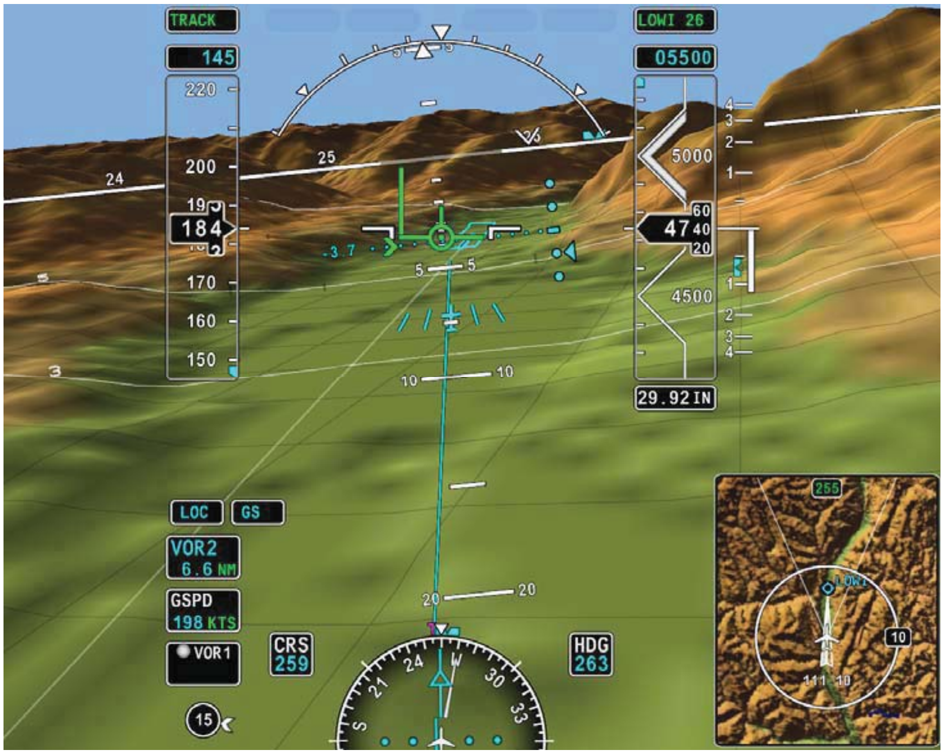

Figure 1: **Honeywell Synthetic Vision Concept**

2.1. SV and EFVS Operations

Even though SV and EFVS are certified and operational, research issues still abound, especially as the applications for these technologies are broadened and expanded.

SEVS technologies have been identified as fundamental building blocks to NextGen (FAA, 2004b); integral to the concept of "equivalent visual operations." Equivalent visual operations imply the ability to achieve or even improve on the safety of current-day Visual Flight Rules (VFR) operations, maintain the operational tempos of VFR, and even, perhaps, retain VFR-derived procedures independent of the actual weather and visibility conditions. These vision technologies (SEVS) serve as enabling technologies to meet that challenge following the precedent that SEVS may be used in lieu of a pilot's natural vision. This is currently only the case for EFVS under §91.175 (l) and (m).

Figure 2: **Enhanced Flight Vision System Concept**

In this report, a truly "equivalent visual operation" is *not* assumed. While this is the ultimate objective of using this technology, this initial work examines SEVS technologies only to enable or assist in low visibility approach and landing, surface, and take-off/departure operations where there is *no change* in the present-day roles and responsibilities of Air Navigation Service Providers (ANSPs) for spacing and separation. Future growth and usage of SV and EV "vision systems" technology may eventually enable the flight crew to perform VFR-like operational capability (i.e., "see-to-follow," "see-and-avoid," and "own navigation" including the pilot's ability and responsibility to self-separate from other traffic, terrain, and obstacles) but in this report, the implications of creating these capabilities are *not* considered. *Future work should investigate the vision system technology (SEVS) requirements for an equivalent visual operational capability (R-1).*

In this work, the current and incremental improvements in operational capabilities using SVS and EFVS are considered as follows:

- SEVS technologies are used under VFR and Instrument Flight Rules operations, day and night.

- In addition to the current "no operational credit" use of SV, the use of SV is examined to enable descent below the published DA or DH to 100 ft height above the touchdown zone elevation (TDZE) from a straight-in instrument approach procedures with published vertical guidance.

- In addition to the current "operational credit" use of EFVS identified under 14 CFR §91.175 (l) and (m), the use of EFVS is examined to enable descent below the published DA or DH, landing and roll-out in visibility as low as 1000 ft Runway Visual Range (RVR) flying a straight-in instrument approach procedure with published vertical guidance.

- Further, the use of EFVS is assumed to enable take-off and surface operations in visibility conditions down to 700 ft RVR.

2.2. SEVS Research Issues and Report Organization

Two overarching research issues are addressed in this report arising from present and future operational concerns associated with SEVS technology:

1) SV operations are presently focused on HDD implementations since they are less expensive and have a broader user base (i.e., it is not practical to install a HUD in many aircraft). Presentation of SV information on a HDD during low altitude and surface operations has the potential to significantly increase pilot head-down time which may detract from ground-referenced navigation and hazard detection/avoidance.

2) In EFVS operations, the HUD display must present all EFVS-required imagery and symbology *and* for compliance with 14 CFR §25.1301 and §25.1303, data elements of primary flight displays which are essential or critical to the phase of flight. Conversely, for compliance with 14 CFR §25.773, HUD symbology must not excessively interfere with a pilots' forward view and their ability to visually maneuver the airplane, acquire opposing traffic, and see the runway environment. These conflicting requirements necessitate an examination of how EFVS information presented on a HUD impacts its safe and effective use and especially, the potential for HUD clutter and obscuration to negatively impact traffic and obstacle collision detection and avoidance.

In both cases, a critical issue is the ability of a human observer to perform "target detection." In Section 3, a review of traffic and obstacle detection by a human observer is presented. This work points to the wealth of data pertaining to this activity, and more importantly, highlights that the speed and accuracy of traffic and obstacle detection is a function of awareness (i.e., is the observer alerted to the conflict?), workload (i.e., is the observer engaged in a divided attention or full attention task?), localization (i.e., does the user have other information directing them where to look?), and the characteristics of the object to be seen, the device being used to image and display the object, and the atmospheric properties, lighting, and background in which the object/traffic is being viewed.

Research is then reviewed, in Section 4, regarding pilot/flight crew tasking for awareness and detection of targets/obstacles. Head-down to head-up transitions and pilot/crew roles and responsibilities are presented. This work discusses the issues of transitioning from head-down to head-up operations and emphasizes how this impacts target (i.e., traffic or obstacle/object) detection, recognition, and resolution while attending to required flight deck and piloting tasks.

To address the specific nuances of the second issue, the state-of-the-art regarding clutter, obscuration (masking), and attention capture using HUDs is reviewed in Section 5. These issues have garnered a wealth of study and merit special consideration as to its direct applicability in this research. This work is also related to target (i.e., traffic or obstacle/object) detection, recognition, and resolution while attending to required flight deck and piloting tasks.

In Section 6, these two topics are considered as they might be influenced and affected by the design and use of CDTI for approach and landing, surface, and take-off/departure operations. This work includes the impact of emerging technology for traffic indication, warning, and alerting during approach, landing, and surface operations.

Finally, in Section 7, concluding remarks and recommendations are presented. This section summarizes the critical research areas that need to be explored further to advance the state-of-the-art and to effectively implement and possibly expand the operational capabilities of SEVS technologies for NextGen.

2.3. Assumptions and Limitations

Several assumptions and limitations have been invoked for this work.

First, the limitations:

1. This work is not intended to be stand-alone; instead, numerous references are used to point the reader where additional, important information is contained. The intent of this work is to integrate numerous disparate pieces of information from which to form a unifying picture as well as to identify knowledge gaps which highlight future research requirements for SEVS technologies.

2. This work focuses on the use of CDTI and the pilot’s awareness and detection of traffic and obstacles almost exclusively on the runway and airport surface. This emphasis examines traffic detection issues in those operations (i.e., during final approach and landing, taxi, and departure/take-off) where SEVS technologies provide notable operational benefits. Significant work has been conducted in other flight phases (e.g., en-route merging and spacing) and this work may be referenced as relevant, but it is not extensively reviewed.

3. The work considers only fixed-wing aircraft operations. The analyses may be applicable to vertical take-off and landing or rotary wing vehicles, but this work has not been validated for the unique operational aspects of these vehicles. No warranty as to the applicability of this review should be assumed or implied.

4. This work assumes that the imaging sensor for the EFVS is a FLIR. This limitation may not be a serious limitation since only FLIR sensors have been

approved to date as an EFVS, but it does merit note as a slight loss in generality is created.

The primary assumption imposed in this review is that the pilots (and crew) are sufficiently trained in the use and operation of the equipment. Also, that during crewed operations, both pilots are effectively functioning as a crew and a break-down in crew coordination or crew resource management has not occurred.

At present, the roles and responsibilities of the ANSPs for spacing and separation from other traffic are assumed to be unchanged by the presence or use of these flight deck technologies. These technologies are not intended to change the roles and responsibilities of the airport services providers for foreign object damage control, wildlife control, or other airport infrastructure and service functions. *Future work should explore the impact, if any, of SEVS in changing the roles and responsibilities of the ANSP (R-2)*.

SEVS technologies also offer unique capabilities which might be used in lieu of certain airport and aircraft infrastructure or equipment for low visibility approach, landing, surface, and take-off/departure operations. *Future work should explore the potential for SEVS to replace the need for or functional elements currently required for Surface Movement Guidance and Control Systems and for approach lighting systems (R-3)*.

SEVS technologies may eventually enable the pilot/crew to perform “see-to-follow,” “see-and-avoid,” and “self-navigation” including the ability and responsibility of the pilot/crew to self-separate from other traffic, terrain, and obstacles. As previously mentioned, this work does not focus on these new capabilities but the work is fundamentally applicable to it.

3. Traffic and Obstacle Detection

The visual traffic and obstacle detection task is, in essence, a human observer performing "target acquisition" of which a wealth of data and research are available, mostly in the military domain. These works are too numerous to detail; instead, key findings are extracted from this work and briefly summarized to establish "first-principles." From this basis, later sections extend these principles into research specific to SEVS operations and display design issues to qualify the time required, pilot workload, and accuracy of traffic and obstacle detection and the attendant critical issues.

Two perceptual mechanisms are considered in this research:

- Target detection by a human observer looking through cockpit windows;
- Target detection by a human observer looking at cockpit displays, using a HUD or HDD.

3.1. Target Detection by a Human Observer

While a wealth of research and data are available, the target detection task by a human observer is complicated by many complex and incompletely understood processes and interactions, especially when applied to the flight environment.

Target detection research (Boff and Lincoln, 1988) shows that the probability that a target will be recognized by a human observer is a function of:

- the probability that the observer is searching an area that is known to contain a target, looks with his/her foveal vision for a specified glimpse time (⅓ s) in the direction of the target; and,
- the probability that the displayed target image is viewed foveally for one glimpse period with sufficient contrast and size to be detected;

The later element – the saliency of the object in terms of whether the target is of sufficient contrast and size – can be considered as a necessary but perhaps not sufficient prerequisite for successful target detection by a human observer.

3.2. Target Perception By A Pilot With and Without EV

The concept of target saliency and the use of SEVS technologies for target detection by a pilot is schematically diagramed in Figure 3. The diagram does not attempt to map out a cognitive process, but rather, tries to capture the physical effects and perceptual mechanisms involved in determining if the necessary but not necessarily sufficient condition for visual target acquisition exists (i.e., whether the human's perception of the target has sufficient contrast and size).

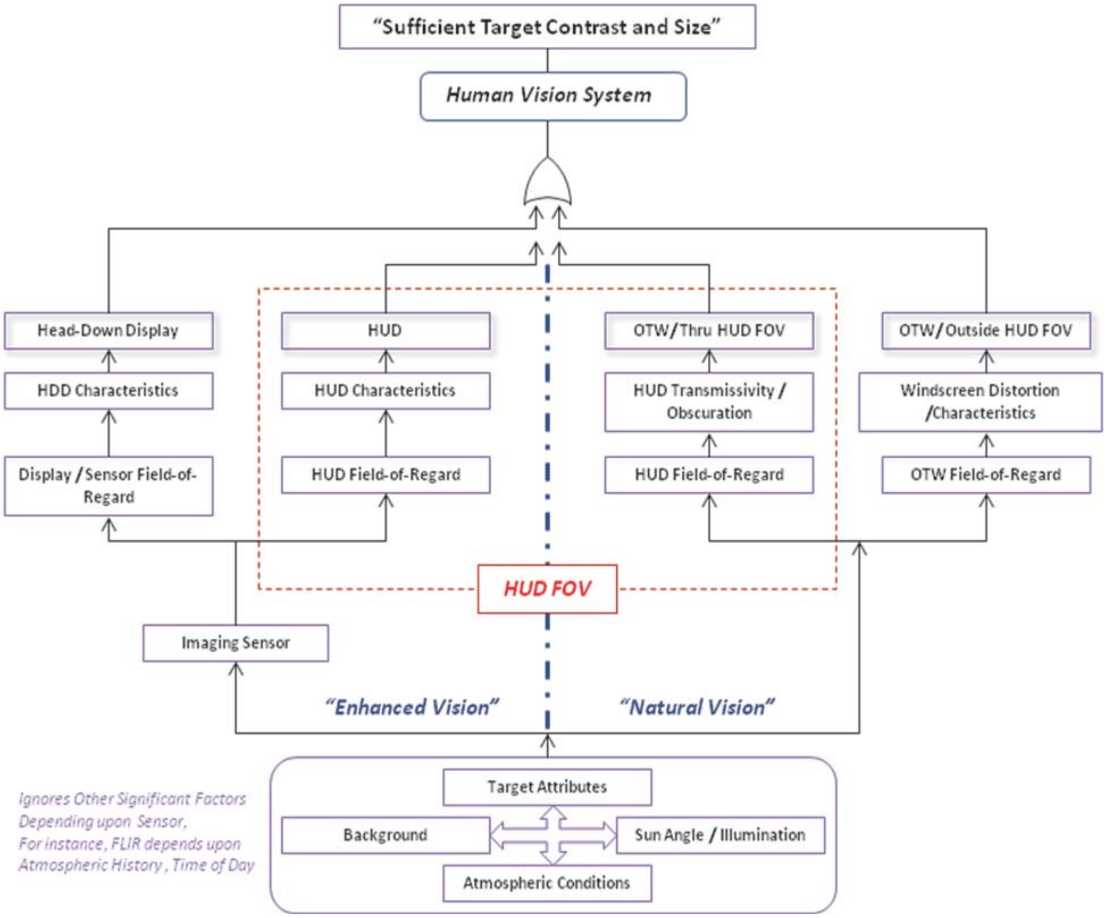

Figure 3: **Target Detection Diagram**

3.2.1. Source

The perceived target contrast and size is obviously driven by the contrast and size of the "source information." In Figure 3, this source information, shown in a bottom-up paradigm, drives the perceptual paths (i.e., "Enhanced Vision" or "Natural Vision")

The target angular size and the apparent target-background luminance ratio (contrast) of the "source information" depend primarily on four factors (see Boff and Lincoln, 1988):

- the target attributes
- the attributes of the target background
- the medium through which it is viewed (i.e., the atmospheric properties such as, fog, haze, moisture content, etc.)
- and the characteristics that illuminate the target, background, and atmosphere (i.e., sun angle, moon phase, etc.).

3.2.2. Detection Mechanisms

This "source information" flows into two possible perception mechanisms:

1. Using Enhanced Vision
2. Using Natural Vision (i.e., the out-the-window (OTW) view)

(The use of SV or CDTI is not considered in this process since this section is concerned with unaided visual target detection by a human observer.)

The perception of the target – whether the target is of sufficient size and contrast - is thus affected by how this source information (i.e., the target-background-medium attributes) is modified along these paths before it is presented to the human observer.

In the case of EV, these modifications include how this source information is "perceived" by the EV sensor and what image transformations or distortions are introduced in the process. Present-day FLIRs transform the radiated thermal energy into gray-scale level (monochromatic) imagery; that is, the thermal signature.

The first-principle involves the sensor detector characteristics including its wave-length, resolution, sensitivity, noise, and image processing characteristics. Target detection is critically dependent on how these image properties are "matched" to the imaging sensor and the characteristics of the environment in which the imaging occurs. For EFVS applications, the FLIR sensor typically provides a wide bandwidth of detector wavelengths, designed to provide a best-case compromise between thermal sensitivity and transmissivity through atmospheric moisture content for runway, terrain, and airport/approach lighting systems.

Analytical tools have been developed to predict infrared sensor system performance in this task. Moderate resolution atmospheric transmission simulations (Beier and Gemperlein, 2004) model the atmosphere and can predict the radiative properties for a wide range of wavelengths and spectral resolutions, enabling the calculation of transmittance and radiance from a target. It uses different climate models, geographical latitudes, time of year (i.e., seasons influencing, for example, sun angle and prevailing atmospheric temperature) and with each climate model, different aerosol types. However, the conditions of the atmosphere alone aren't enough to predict performance. The size of the target and the radiated/reflective/emitted differences against the background as well as the spatial resolution and sensitivity of the optics and the detector, and the noise of the detector and signal processing alter the target prominence against the background.

3.2.3. Detection Avenues

Visual target detection is shown through any of four possible avenues:

1. Using EV on a HDD
2. Using EV on a HUD
3. Using the OTW view, through a HUD
4. Using the OTW view

These four avenues subtend different fields-of-regard/fields-of-view (FOV) and also, invoke different transformational processes of the source information to the pilot perception of the image. For instance:

- Using the OTW view: Target detection using natural vision OTW occurs by the pilot/crew looking through the aircraft windows. The field-of-regard for which this detection is possible is the extent of the windows and the range of head/eye movement available by the crew to look around any aircraft structure. Guidance for this field-of-regard (i.e., window size) for target detection (i.e., collision avoidance) is given under Advisory Circular (AC) 25-773. In this detection task, the "source image" properties are modified by the optical characteristics of the windscreen. Although the goal in the design and development of the windscreen optical characteristics is to provide no modification, perfection is not possible. Under 14 CFR §23.773, "The windshield and side windows forward of the pilot's back when the pilot is seated in the normal flight position must have a luminous transmittance value of not less than 70 percent." Testing has shown that these optical performance requirements has generally been achieved and maintained through an aircraft's service life (Quinn et al, 1996). The influence of canopy distortion in a target detection task for civil transport aircraft should not be a factor, unlike military/fighter aircraft (Task and Goodyear, 1999).
- Using the OTW view, through a HUD: Target detection using natural vision OTW can also occur by the pilot/crew looking through the HUD and aircraft windows. In this case, the target must be located within the HUD field-of-regard. In this detection task, the "source image" properties are modified by the optical characteristics of the windscreen as well as the optical characteristics of the HUD (i.e., transmissivity) and any symbology or imagery that may obscure this detection. SAE Aeronautical Standard AS-5088, "Minimum Performance Standard for Airborne Head Up Display (HUD)" specifies that the light transmissivity of the HUD combiner shall be greater than 70%. This degradation is in addition to possible canopy transmissivity losses, resulting in some potential visual performance degradation. The issues of obscuration due to symbology and attentional influence of HUD operations are discussed in following sections.
- Using EV on a HUD: Target detection using EV can occur by the pilot/crew looking at the HUD. EV shown on a HUD is, by EFVS definition, conformally drawn (i.e., the field-of-regard of the sensor and the HUD are matched and the imagery overlays the real world as seen through the HUD combiner); thus, for a target to be detected using an EV-HUD, the target must be located within the HUD FOV.
- Using EV on a HDD: For the EV detection task shown on the HDD, the field-of-regard of the EV sensor and whether it is fixed or slewable to the aircraft affect whether the target is visible to the EV sensor. Also, the effects from minification and magnification of the imagery (i.e., non-conformal display) must be considered in the detection task. Both the display as well as the sensor, dictate the image resolution presented to the human for the target detection task. In addition to resolution, the magnification and minification of the information affects human performance.

The detection of targets and obstacles using EV imagery critically depends on the display device characteristics. The distinction between head-up and head-down displays is not only important for their spatial location but also due to their optical characteristics.

- HDDs afford much greater resolution, more gray scales, luminance, and contrast sensitivity than HUDs. HUD gray shades, defined as an increase in brightness by a factor of 1.41 (square root of 2), are typically no greater than 7 and rapidly reduce as the ambient background luminance increases toward 10,000 ft-Lamberts (Karim, 1992). This loss of apparent contrast degrades human performance (Lloyd and Reinhart, 1993). 6 shades of gray are typically required for imagery (i.e., video) (Rash, 1999). HDDs do not have to contend with a variable visual background, they employ much higher luminance and contrast optical properties and can use glareshields and other optics to shade the displays from direct and diffuse sun light effects (Karim, 1992).
- Chromaticity can be put into effect on HDDs unlike monochromatic HUDs (e.g., see Scribner, Warren, and Schuler, 2000). Typically, EV imagery is monochromatic, but the HDD may highlight data aspects using false color cueing (e.g., see Toet, 2002).

3.3. Johnson's Criteria

Numerous and sometimes elaborate analyses have been developed to predict human detection performance, essentially quantifying whether the perceived target is of sufficient contrast and size (e.g., to name just a few: Aviram and Rotman, 2000 and 2001, Vollmerhausen, Jacobs, and Driggers, 2004; Watson, Ramirez, and Salud, 2009; see also Boff and Lincoln, 1988).

Instead of using these models, a rough-order-of-magnitude criterion, for comparative analysis only, is used here. Johnson's criteria attempts to quantify minimum resolution requirements for human awareness, detection, recognition and identification of traffic or objects/obstacles.

A series of experiments (Ratches et al, 1997) were conducted to quantify target detection probability as a function of the resolution of the sensor/display system (i.e., the target angular size). This work showed that, whether using an unaided eye or other sensors, such as night-vision goggles or thermal imaging systems, four tasks were involved in the target acquisition process:

1) Detection: correctly discriminating an object in the image from background and system noise.
2) Orientation: correctly determining the detected target aspect or direction of movement.
3) Recognition: correctly determining the class membership of the target. For example, is it a truck? A tank? etc.
4) Identification: correctly determining the exact identity of the target, e.g., for automobiles, is it a Ford or Chevrolet?

These same and similar processes in detection, recognition, and identification for air-to-air target acquisition tasks have also been found (e.g., see Rohrer, 1996).

These experimental data led to the development of Johnson's criteria for target acquisition. Johnson's work presumed that the ability of the observer to detect, recognize and identify a target were a function of how well a critical dimension of the target could be resolved by the sensor-display system. An example of the data is shown in Figure 4, indicating the probability of detection and recognition (of a man or a vehicle) is a function of the number of sensor-display cycles (sensor/display line pairs or roughly pixels) depicting the object.

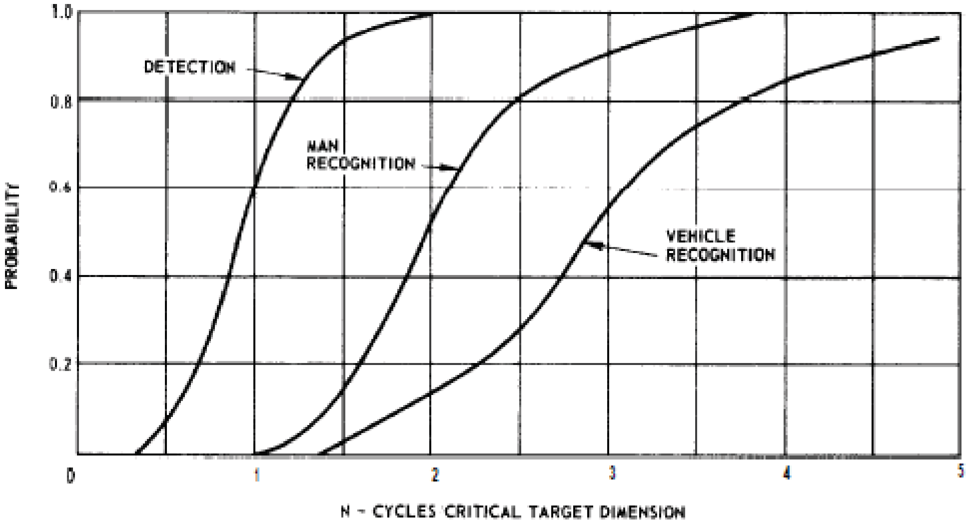

Figure 4: **Probability Of Detection And Recognition As Function Of Resolution Across Critical Target Dimensions (from Ratches, 1997).**

Johnson's work evolved into straight-forward criteria for display and sensor requirements for visual acquisition as shown in Table I. The "critical target dimension" was based on intuition and was usually chosen to be the minimum dimension.

Table I - Johnson's Criteria - Resolution Requirements

Task	**Line Resolution per Minimum Dimension**
Detection	1.0 ± 0.25 line pairs
Orientation	1.4 ± 0.35 line pairs
Recognition	4.0 ± 0.8 line pairs
Identification	6.4 ± 1.5 line pairs

These criteria only pertain to the target size of the problem; that is, the angular extent of the target and the associated resolution of the display and sensor to generate the image for human visual acquisition. The other components of the visual acquisition task – e.g., the apparent target-background contrast - are dependent upon innumerable other factors such as atmospheric conditions (clouds, fog, haze, moisture content, etc.), target color/material, background illumination and color, sun angle, background (sky/ground), etc and sensor/display contrast performance. Even though these are critical issues to the task, these are not influenced by the display resolution directly.

Johnson's criteria has been shown to be a rough, first-order approximation as numerous analyses have shown it to be flawed in several respects (McDonald and Vorst, 2002); however, for comparative analyses associated with angular extent and resolution of a target, Johnson's criteria is applied herein to evaluate EV and display sensor resolution effects on visual target acquisition.

3.4. Visual Search and Gaze

Whether a target, in a visual detection task, is of sufficient contrast and size can be considered as a necessary but perhaps not sufficient prerequisite for successful target detection by a human observer. However, most of the elements that dictate this prerequisite - other than the design characteristics of the EV sensor and display system - are not directly a function of the SEVS technologies. They are a function of the task, the proximity of the aircraft to the obstacle or traffic, or the weather and time of day.

The other critical element required for visual target detection is that of the pilot/crew's visual search and gaze.

Wickens et al (2001) hypothesized that visual gaze was a function of:

(1) the salience of objects that affect attention capture

(2) the effort required to move attention,

(3) the expectancy that information will be obtained; and,

(4) the value of the information to be found there.

These characteristics that govern visual gaze are defined by the roles and responsibilities of the pilot/flight crew and are possibly influenced by CDTI or the presence of traffic/obstacle indications, cautions, or warnings. These elements are to various degrees influenced by the design of and technologies on the flight deck, as described in the following sections.

4. Head-Down and Head-Up Operations

The crew/pilot tasking and their roles and responsibilities during SEVS operations are explored as they impact the pilot's/crew's workload, the available time to perform object and traffic detection, and their visual scan patterns.

The detection of traffic and obstacles is not the only tasking of a pilot or crew member. Within the operating paradigm of "aviate, navigate, and communicate,“ detection of traffic and obstacles is certainly one of the tasks contained within the "navigate" element. However, the concept of "see-and-avoid" is engrained within all FAA operations under both Instrument Flight Rules and VFRs and certainly is of critical importance. "See-and-avoid" requires that each person operating an aircraft maintains vigilance at all times.

During crewed operations, the flight duties of the crew members are dependent upon many factors, and tasking can be distributed, with certain crew members having more or less responsibility for "see-and-avoid." For single pilot operations, vigilance for "see-and-avoid" must be attended to as part of all required pilot duties.

In all cases, the cockpit display of traffic information greatly influences the pilot's ability to perform the task of traffic/obstacle awareness and detection.

4.1. "See-and-avoid"

The FAA requires under 14 CFR Part 91.113, *across all classes of airspace,* that "when weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see-and-avoid other aircraft."

Pilots are trained, and through experience, adopt visual scanning procedures both in their use of instruments (i.e., a visual scan pattern of the cockpit displays) and in scanning out-the-window for other traffic and/or objects (Bellenkes, Wickens, and Kramer, 1997). The FAA's Aeronautical Information Manual (Section 8-1-6) emphasizes that "the time a pilot spends on visual tasks inside the cabin should represent no more than ¼ to ⅓ of the scan time outside, or no more than 4 to 5 seconds on the instrument panel for every 16 seconds outside." The criticality of outside scanning to meet the see-and-avoid safety principle and how to effectively scan for outside traffic is explained in numerous areas (see FAA AC 90-48C, "Pilot's Role In Collision Avoidance"). Unfortunately, studies (e.g., Colvin, Dodhia, and Dismukes, 2005) have shown that pilots do not adhere to these recommendations and spend considerably more time head-down than head-out. VFR pilots in small GA aircraft have been shown to be preoccupied with in-cockpit duties and are head-down at least 40% of the time (Sulzer and Skelton, 1976). Significant individual differences have been noted (e.g., see Wickens et al, 2001).

Measured flight performance for aircraft detection is remarkably poor, often casting doubt on the effectiveness of the see-and-avoid principle (see Graham and Orr, 1970; Andrews, J,W., 1991a, 1991b) In particular, Andrews showed that only 56% of 64 near-collision encounters were sighted by GA pilots during en-route operations. Although some studies show an eight to nine times improvement in detection when alerted, others have still shown relatively poor performance (Moore, 1998).

The merit of see-and-avoid operations and the associated human visual, human attention, and operational issues have been studied extensively (e.g., see Australian Transport Safety Board, 1991; Graham, 1989). Whether see-and-avoid is actually effective or not is immaterial. The FAA requires, under 14 CFR Part 91.113, across all classes of airspace that see-and-avoid shall be conducted. This work examines the influence of SEVS technologies on traffic and obstacle detection which forms part of "see-and-avoid." It should be noted that most of the research cited above for see-and-avoid were almost exclusively conducted enroute or outside of the airport terminal maneuvering area. This analysis of SEVS technologies focuses instead on low visibility approach, landing, departure, and surface operations.

4.2. Visibility Conditions and Manual Control

The weather conditions in which the operation is conducted obviously affect the usable visual cues outside the aircraft (i.e., OTW visibility). These weather conditions typically also affect the visibility of an imaging sensor in an EFVS.

Less obvious is that the weather conditions also dictate (by FAA regulations) the on-board and off-board systems required to conduct the operation. These systems significantly alter the degree to which the pilot must "aviate;" that is, how much the pilot manually flies the aircraft. These requirements, thus, impact the crew duties and the associated workload and attention demands of the pilot during low visibility approach and landing operations. The general assumption is that a pilot who is manually flying would have less spare attention to devote to target/obstacle detection and avoidance.

The landing minima classifications of Category I, II, and III are defined as follows:

- Category (Cat.) I is an instrument approach or approach and landing with a decision altitude (height) or minimum descent altitude (height) not lower than 200 ft and with either a visibility not less than 1/2 statute mile, or a runway visual range (RVR) not less than 1800 ft.
- Cat. II is an instrument approach or approach and landing with a decision height lower than 200 ft but not lower than 100 ft and a runway visual range not less than 1200 ft.
- Cat. III is an instrument approach or approach and landing with a decision height lower than 100 ft, or no decision height, or a runway visual range less than 1200 ft.

Guidance for US approval of low visibility approach, take-off and surface operations are contained in AC120-29A ("Criteria For Approval Of Category I And Category II Weather Minima For Approach") and 120-28D ("Criteria For Approval Of Category III Weather Minima For Takeoff, Landing, And Rollout"). These works do not contain the latest regulatory changes associated with EFVS, such as 14 CFR §91.175 (l) and (m), or special authorizations/changes provisioned through FAA Order 8400.13 ('Procedures for the Evaluation and Approval of Facilities for Special Authorization Category I Operations and All Category II and III Operations"). These materials show that:

- Cat. I approaches can be manually flown with reference to raw data or to flight director commands *or* automatically with the autopilot engaged.
- Cat. II/Cat. III approaches are flown using an automatic landing system. For Cat. II minima, a flight director, autopilot, or HUD with approved flight guidance is used but the landing *can* be manually-flown.
- For Cat. III minima, an autopilot or HUD with approved flight guidance is used to fly the approach, landing, and roll-out. The HUD system provides head-up guidance to the pilot so, by manual control, an equivalent level of performance (and safety) to an auto-land system is demonstrated. A Decision Height not less than 50 ft. height above Touchdown Zone Elevation (TDZE) is used.

4.3. Visual References

The concept of visual flight references creates an important distinction for automatic and manual landing systems, as well as EFVS operations. For Cat. I and Cat. II approaches, visual reference means *being able to see to land* (i.e., being able to conduct a hand-flown landing). For Cat III approaches, visual reference means *being able to see to verify aircraft position,* if ever so briefly. It's important to understand the use of visual references to appropriately gauge pilot workload and attention demands during low visibility approach and landing operations.

At DA(H) or prior to the MDA on an instrument approach in other than Cat. III conditions, the pilot makes a decision whether to continue descending below DA(H) or MDA. This decision is made using natural vision or using an EFVS if equipped. The decision and the subsequent "visual segment" is based on this visual information, the comprehension of its meaning, and the projection of its status in the near future.

Regulations in effect as 14 CFR §91.175 and its companion regulations under §121 and §135 identify the required visual references which, from a historical basis, support the flight crew's informational needs to safely complete this operation. In Table II, the required visual landing references for §91.175 (c) (Non-EFVS flight operations) and (l) (EFVS flight operations) are detailed to descend below the published DA(H) or MDA and to descend below the 100 ft Height Above TDZE (HAT).

From an equivalent performance perspective, the required visual references in Cat I/II conditions must provide information sufficient to:

- Portray the present descent rate, its status with respect to normal operations and normal maneuvering limits and provide trend information that the descent rate and aircraft position will continually allow a safe descent to landing.
- Provide status and trend information that may indicate if, with normal maneuvers, a touchdown can occur with acceptable descent rate and within the intended touchdown zone.

Ideally, during this visual flight segment, the pilot would be able to visually identify that the path toward the intended touchdown point is free of all obstacles, charted or otherwise. This task is typically performed today by operational procedure. By Terminal Instrument Procedures (TERPS) design, obstacle protections are provided to the landing runway in the visual segment of a standard instrument approach procedure and Air Traffic Control (ATC) procedures are in effect to keep vehicles and other aircraft clear of the landing runway. However, there is no instrumentation or display currently in use that annunciates or informs the pilot/crew that they are in the 'approved' visual segment although the use of published vertical and lateral guidance may provide this type of information.

A missed approach/go-around is executed at the DA(H) or the charted missed approach point or so as to not descend below the MDA if the required visual references are not visible and distinctly identifiable or if the aircraft is not in a position to land safely.

The task demands for the flight crew/pilot – i.e., to pick up the required visual references, and successfully complete their flying duties – greatly influences their time, workload, and ability to be aware of and detect traffic or obstacles. These task demands and by inference, the display designs, are affected by the assigned roles and responsibilities for the flight crew.

Table II - Required Visual References, 14 CFR 91.175 (c) and (l)

Required Visual References Using Natural Vision (14 CFR 91.175 (c))	**Required Visual References Using an Enhanced Flight Vision System (14 CFR 91.175 (l))**
For operation below DA/DH or MDA – At least one of the following visual references for the intended runway must be distinctly visible and identifiable: Approach light system Threshold Threshold markings Threshold lights Runway end identifier lights Visual approach slope indicator Touchdown zone Touchdown zone markings Touchdown zone lights Runway Runway markings Runway lights	**For operation below DA/DH or MDA –** The following visual references for the intended runway must be distinctly visible and identifiable: Approach light system ***OR*** Visual references in **BOTH** paragraphs 91.175(l)(3)(ii)(A) and (B) -- (l)(3)(ii)(A) The runway threshold, identified by at least one of the following – -- beginning of the runway landing surface, -- threshold lights, or -- runway end identifier lights **AND** (l)(3)(ii)(B) The touchdown zone, identified by at least one of the following – -- runway touchdown zone landing surface, -- touchdown zone lights, -- touchdown zone markings, or -- runway lights.
Descent below 100 feet height above TDZE – At least one of the following visual references for the intended runway must be distinctly visible and identifiable: Approach light system, as long as the red terminating bars or red side row bars are also distinctly visible and identifiable Threshold Threshold markings Threshold lights Runway end identifier lights Visual approach slope indicator Touchdown zone Touchdown zone markings Touchdown zone lights Runway Runway markings Runway lights	**Descent below 100 feet height above TDZE –** The following visual references for the intended runway must be distinctly visible and identifiable: The lights or markings of the threshold ***OR*** The lights or markings of the touchdown zone

4.4. Crewed Procedures

The roles and responsibilities for the pilot/flight crew are identified by the Standard Operating Procedures (SOPs) in effect. SOPs are universally recognized to promote safe flight operations (see AC120-71A, "Standard Operating Procedures for Flight Deck

Crewmembers" 27 Feb 2003). This AC provides general guidance for the development of SOPs for crew sharing of responsibilities and duties in low visibility approach and landing operations. Further guidance is available for taxi operations (AC120-74A, "Parts 91, 121, 125, and 135 Flight Crew Procedures During Taxi Operations," 26 Sept 2006 and AC91-73A, "Part 91 and Part 135 Single Pilot Procedures During Taxi Operations"). These SOPs generally define who is responsible for the specific "aviate, communicate, and navigate" functions and how they are performed. These SOPs may change based on company/air carrier, but more typically, the SOPs change based on cockpit display configuration. The ACs do not, however, consider the impact of SEVS technologies and how roles and responsibilities may be modified by the introduction of these technologies.

4.4.1. <u>Pilot-Monitored Approach</u>

The pilot-monitored approach (PMA) is commonly employed for head-down low-visibility approaches.

As noted in the Commercial And Business Aviation Advisory Circular No. 0239 (dated 8 Sept 2006) "proper use of the PMA permits the left seat pilot to improve safety related to making the decision to transition from instrument conditions to visual conditions for the landing. During a PMA, the left seat pilot has significantly more 'heads-up' time for visual scanning outside the flight deck. This extra time permits the pilot conducting the landing to determine whether sufficient visual references exist to judge the position and rate of change of position of the airplane in order to decide to continue the approach visually to a safe landing."

This operating policy minimizes the problem of visually transitioning from instrument flying to visual flying. Unfortunately, this operating policy involves a change of control.

The left seat pilot (PNF or pilot-monitoring, PM) handles communications with the ANSP and makes decisions, while monitoring the flying performance. The right seat pilot (PF) may fly the approach with or without the engagement of autopilot or auto-thrust.

The PF is engaged directly in either:

- Hand-flying the airplane, by flying the raw data (Cat. I)
- Actively following the flight director commands and monitoring the raw data (Cat. I or Cat. II); or,
- Supervising autopilot operation and being ready to take manual control of the aircraft, if required.

The PNF scans alternatively inside and outside, calls flight parameter deviations (i.e., excess deviations in airspeed, pitch, bank, track, glideslope, altitude and vertical speed) and altitudes (e.g., "one hundred above" then "minimums").

Before or upon reaching the DA(H) or MDA,

- If visual references are acquired, the left-seat pilot calls "landing" takes over the controls and lands; or,

- If visual references are not acquired, the left-seat pilot calls “go-around” and the right seat pilot initiates the go-around and flies the missed approach.

If the left seat pilot commands a go-around, the right seat pilot (PF) flies the go-around procedure and missed approach as briefed.

If the left seat pilot takes control for landing (now the PF), the right seat pilot (now the PNF) continues to monitor the aircraft performance on instruments (i.e., head-down) and calls out deviations.

In this procedure, the PNF recognizes and identifies the required landing visual references, assesses the suitability of the landing zone, and then is tasked with flying the approach, landing and roll-out *without* the assistance of the (formerly) PF (i.e., they are asked to remain head-down in the event of a go-around). The PNF does not have a visual transition from head-down to head-up at the instantaneous moment control is transferred.

4.4.2. Pilot-In-Active Control Loop

The so-called “Pilot-in-Active Control Loop” assumes that there is only one HUD and it is equipped on the left-hand pilot side. The left-hand seat pilot flies the entire approach (as PF) with or without the engagement of autopilot or auto-thrust.

The right-seat pilot (PNF or PM) handles communications with the ANSP, monitors the approach, and assists in the acquisition of outside visual references. The PNF scans alternatively inside and outside, calls flight parameter deviations and altitudes.

The PF confirms the acquisition of visual references and calls “landing” (or “go around” if visual references are not adequate).

If “landing” is called, the PF progressively transitions from instrument flight conditions to external visual references using the HUD.

There is no transfer of control and the PF is head-out through the entire approach and landing obviating the need to visually accommodate or re-focus. The PNF is both head-out and head-down monitoring all systems and functions. With this procedure, two pilots are involved in identifying the required landing visual references and assessing the suitability of the landing zone.

4.5. EFVS Procedures

4.5.1. EFVS Crew Procedures

Adaptations of the Pilot-In-Active Control Loop procedure have been created for EFVS operations. Since the regulation permits descent below the published DA/DH or MDA if the pilot distinctly identifies the required visual references (see Table II), additional call-outs and procedures are used to distinguish between EFVS required visibility and natural vision and the fact that only the PF, using the EFVS, can positively identify and use the required EFVS visual references.

In a crewed experiment, various display formats for the PF HUD and the PNF repeater display of EV imagery were experimentally tested while using these crew procedures (see Bailey, Kramer, Prinzel, and Wilz, 2009). In Table III, the crew call-outs are shown, indicating that an aditional step – the call-out and identification of "EV Lights" – was required to descend below the published DH. If the "EV Lights" was not called out, a go-around was executed at the DH. If "EVS Lights" was called, the next decision altitude was at 100 ft HAT where the lights or markings of the threshold or the lights or markings of the touchdown zone had to be distinctly identified by the PF to continue the approach to landing.

The PF was responsible for flying the aircraft, confirming the acquisition of visual references; first, the EFVS visual references and then, the natural vision references (or "go around" if visual references are not adequate). The PF had the option to declutter the HUD and not use EV imagery for the landing; although the PFs thought the procedure to identify the landing references with natural vision was awkward (e.g., they would momentarily declutter the HUD to remove the EV imagery or look around the HUD), the PFs kept the EV on the HUD and used this information to complete the landing and roll-out (Kramer, Bailey, and Prinzel, 2009b).

The experiment generally showed the effectiveness of EFVS and the EFVS crew procedures. Improvements to the procedures and call-outs were suggested, but in general, the roles and responsibilities of the crew using EFVS procedures extended from current Pilot-in-the-Active Control Loop were validated.

Head-position and orientation tracking data was collected of the PM to quantify display usage and visual gaze/attention. The data showed that attention was divided between a repeater display of EV information, the normal flight instruments, and the forward, OTW view from 1000 ft AFL until 200 ft AFL. The PM scanned alternatively inside and outside, called flight parameter deviations and altitudes. Below 200 ft AFL, the PM was almost exclusively head-up, looking OTW, searching and clearing the landing runway area (Bailey, Kramer, and Prinzel, 2007).

Table III - EFVS Crew Procedures

Altitude-Based Events	PF Tasks / Callouts	PNF Tasks / Callouts
500 feet HAT	Response: "*Systems Normal, EV Normal*"	Call "*500 feet*"
100 feet Above Minimums	Response: "*Check*"	Call "*100 feet Above*"
Published Minimums (200 ft HAT)	With EV Visual Cues, Call "*EV Lights*"	When Visual Cues Appear, Call "*Lights*" or "*Field in Sight*"
	Without EV Visual Cues, Call "*Going Around*"	Without PF Call of 'EVS Lights', Call "*Go Around*"
EFVS Decision Altitude (100 ft HAT)	When Actual Visual Cues, Call "*Landing*"	When Visual Cues Appear, Call "*Lights*" or "*Field in Sight*"
	Without Actual Visual Cues, Call "*Going Around*"	Without PF Call of 'Landing', Call "*Go Around*"

4.5.2. EV Head-Down Crew Procedures

Head-down EFVS operations are not currently authorized by the FAA; however, since HDDs are cheaper and more widely available than HUDs, evaluation of their potential for EFVS has been explored.

Two variations of the PMA crew procedures have been tested. In both cases, the PF was using a HDD of EV information and guidance to descend to the published DA/DH. Two different piloting procedures were tested once the required landing visual references were identified:

1) The PF transitions from EV head-down to head-up, using natural vision; or,
2) Aircraft control is transferred from the head-down PF to the head-out pilot, who continues the approach to landing using natural vision.

Four subject pilots flew these two HDD EFVS procedures and in comparison, a standard head-down PMA to 200 ft Instrument Landing System (ILS) minimums and an EFVS Pilot-in-Active Control Loop procedure using a HUD.

This work showed that there were no performance differences between the procedures.

No problems were reported in immediately identifying the runway OTW after transitioning from head-down to head-up. The depiction of the runway in the EFVS guided them to the right location to look for the runway. The post-flight debriefings indicated that the pilots had "good and comprehensive transition from EV head-down segment to visual flight without impairing flight path."

However, the results for the PMA procedures using a control transition at the EV transition height evoked some controversy among the pilots. Two pilots liked this switching from PNF to PF and vice versa whereas the other two stated that this was not a good idea below the DA(H). One pilot had a "crash" where the landing sink rate exceeded acceptable structural limits.

4.5.3. EV Single-Pilot Procedures

Single pilot EFVS operations are not currently approved or authorized by the FAA. The pilot in this operation would have to successfully fulfill all required duties and complete all tasks currently conducted by two pilots, with acceptable pilot workload and safety margins.

5. Traffic/Obstacle Detection Using SEVS Technologies

Within the context of the crewed and single pilot procedures for low visibility approach and landing operations, the influence of SEVS technologies are discussed as they pertain to pilots performing the role of PM or of PF.

Visual target detection using SEVS technologies can be achieved through any of four possible avenues:

1. Using EV on a HDD
2. Using EV on a HUD
3. Using the OTW view, through a HUD
4. Using the OTW view

5.1. Automatic Target Detection and Recognition

This work does not currently consider concepts for fused or combined EV and SV systems although they have been studied and some of the results are germane to this discussion.

Several studies (Parrish et al, 2003; McKay et al, 2002) have shown that the optimal combination of SV and EV technology is one that provides the direct display of SV to the flight crew without direct display of EV. Instead, EV technology is used “behind the glass” for automatic navigation error detection, database integrity monitoring, and real-time obstacle/object detection. Image processing performs these functions automatically without intervention by the flight crew.

This arrangement provides a highly usable display presentation (i.e., SV) that is unaffected by the actual weather and visibility conditions, yet if un-charted obstacles, traffic, database errors or navigation errors are detected by the EV running in the background, the situation is annunciated, and almost “perfect” decision-making by the pilot occurs. This advantage was also shown by Jennings and Powell (2004) where runway incursion scenarios were detected during simulated instrument conditions much more quickly using Automatic Dependent Surveillance-Broadcast (ADS-B) transmission of traffic data and graphical representation on an SV display than OTW visual detection.

While degrees of success in developing these decision aids have been met, technology for “perfect” object detection and database/navigation error detection does not yet exist. Further, there may always be gaps, such as minimal radar cross-section objects or ‘below-detection’ threshold errors, which may still warrant flight deck procedures and human interventions for integrity and error monitoring. *Research should be conducted to determine the desired/required missed detection and false alarm rates for a SV which utilizes ‘behind the glass’ processing for automatic database, obstacle/object, and navigation error and omission checking (R-4).*

5.2. Resolution Influence of Detection and Recognition

In the absence of "behind the glass processing," EV imagery has been touted as providing an element of traffic detection above and beyond unaided natural vision. While this seems intuitive, the capabilities of the imaging sensor and the prevailing weather, target and background determine the level of success. Detection and recognition is dependent upon the sensor resolution and its sensitivity to the environment and "target," the size and contrast of the obstacle/object against the image background, and the display resolution (Mendez, Freitag, and Zinn, 1972; Arthur et al, 2005)

To illustrate technological capabilities and limitations, Johnson's criteria is used. The hypothesized scenario is a Cessna-172 holding short for take-off the runway threshold. Computer-generated images of the scenario are shown in Figure 5 at 500 ft height above the TDZE (HAT), Figure 6 at 300 ft HAT, Figure 7 at 200 ft HAT, and finally, Figure 8 at 100 ft HAT. The C-172 is 27 ft in length and 36 ft in span. The images show 43 degrees horizontal field-of-view with a 4:3 H:V aspect ratio. A 'best-case' scenario is considered in these examples, where the larger dimension (span) is used to predict the detection and recognition range. Also, no degradation in target contrast is implied due to atmospheric effects or background characteristics.

Using Johnson's criteria (see Table I) and computing the number of pixels required as being twice the number of line pairs plus one, 3 and 9 pixels are required for detection and recognition, respectively, of the C-172. Using these assumptions, the number of pixels that the C-172 subtends in an image is computed in Table IV.

Two different resolutions are shown comparing a typical EV system performance and a hypothetical sensor system could theoretically provide eye-limiting resolution. Present-day commercial FLIRs (for EFVS applications) employ approximately 320 x 256 pixel resolution, spanning a typical HUD Field-of-View (FOV) of 32^{o} H x 24^{o} V for the conformal image. This provides approximately 10 pixels per degree visual resolution. In comparison, the Snellen visual acuity equivalent to 20/20 of 60 pixels per degree is also shown. The sensor in this latter case would employ 1920 x 1440 pixels.

Table IV– Pixels Subtending the Lateral Extent (36 ft) of C-172

Altitude	320x256 pixel EV (10 pixels per degree)	20:20 Snellen Equivalent EV (60 pixels per degree)
500 ft HAT	2 pixels	14 pixels
300 ft HAT	4 pixels	26 pixels
200 ft HAT	7 pixels	43 pixels
100 ft HAT	22 pixels	136 pixels

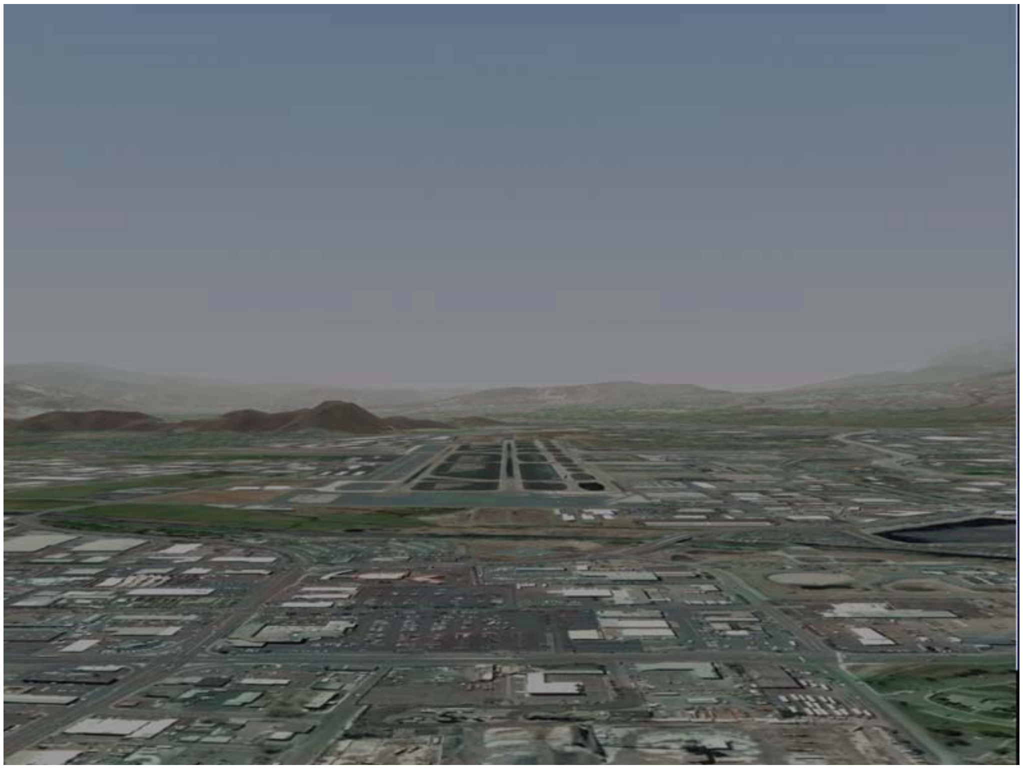

Figure 5: View of C-172 Holding Short From Aircraft at 500 ft HAT

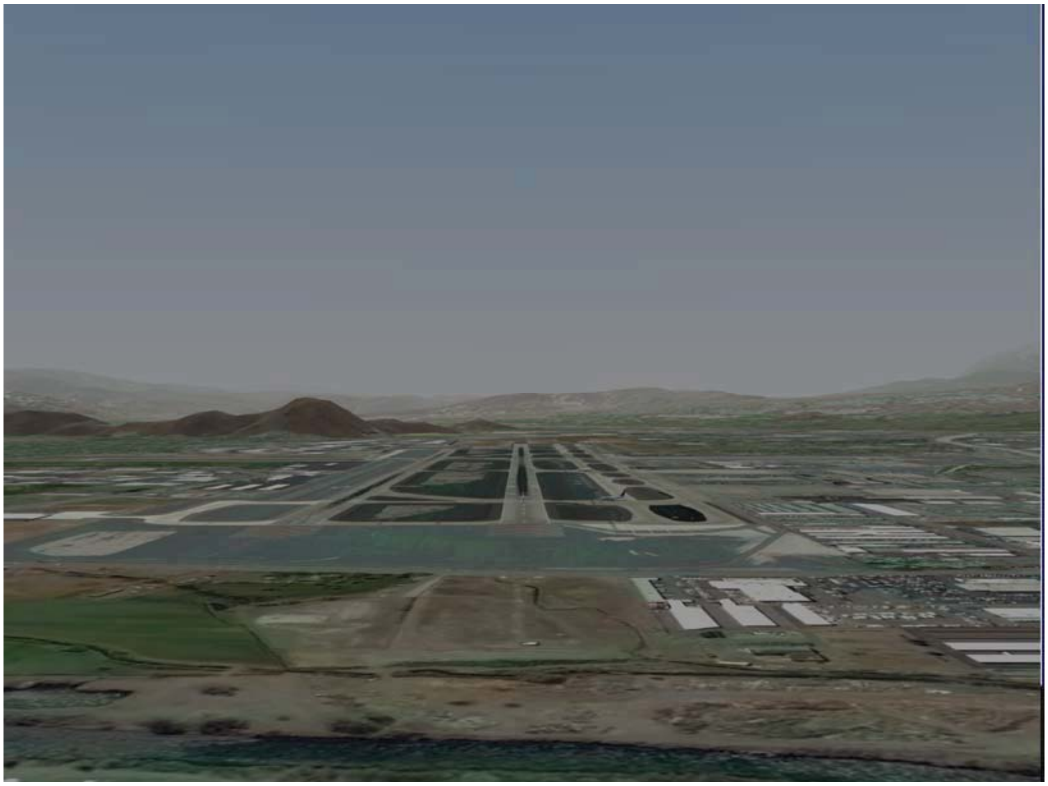

Figure 6: View of C-172 Holding Short From Aircraft at 300 ft HAT

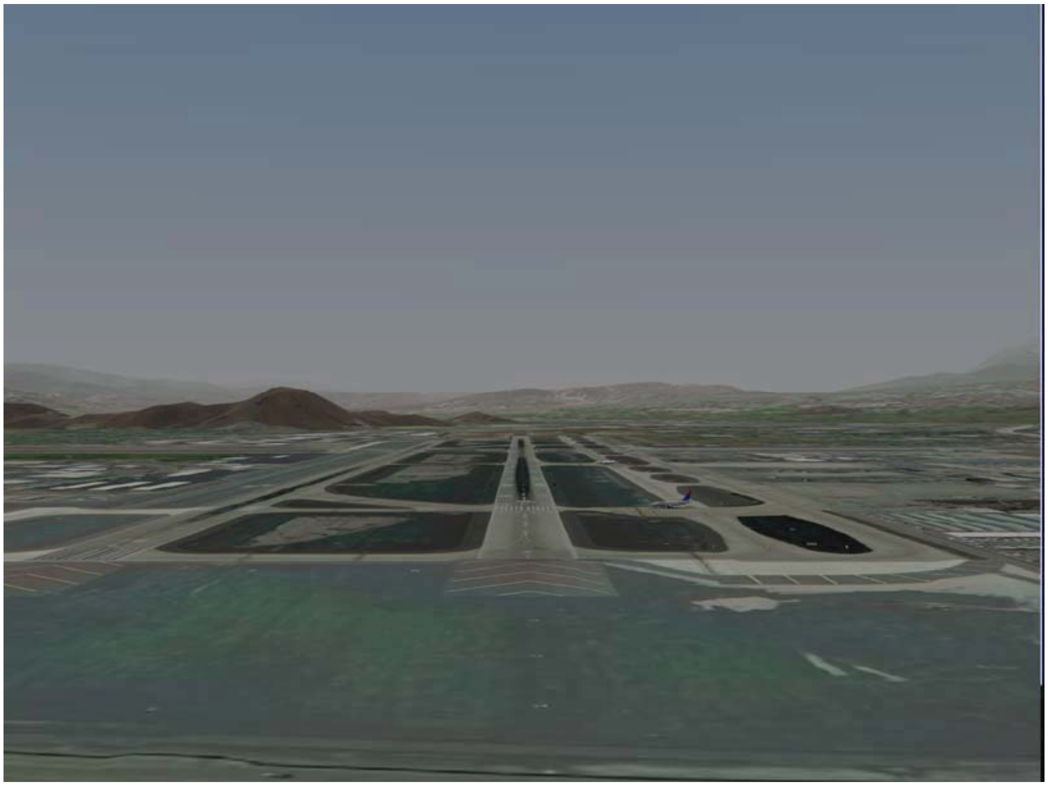

Figure 7: View of C-172 Holding Short From Aircraft at 200 ft HAT

Figure 8: View of C-172 Holding Short From Aircraft at 100 ft HAT

These numbers highlight that a typical EV resolution is relatively poor and the range for target detection is typically much closer than if the human were viewing OTW. The C-172 will only subtend sufficient angular size in the EV for detection at approximately 300 ft HAT and for recognition only after descending below 200 ft HAT. The performance, based on resolution comparisons, is 6 times worse than a human observer looking out the window.

This is not to say that the EV can't provide detection of the target. The advantage of an EV system is that it may provide a higher contrast image than the out-the-window view (e.g., a hot C-172 imaged against a cold runway background). It may also be that the EV can penetrate the atmosphere whereas the human's natural vision is obscured.

However, this simple example highlights that resolution is just one ingredient – but an important prerequisite - to traffic/obstacle detection. Performance data for target detection tasks must colored by the resolving capabilities of the EV and the OTW visual system especially when flight simulation is used. The resolution capabilities of simulators are typically much, much less than that of the human vision system.

5.3. Traffic/Obstacle Detection by PM With SEVS Technologies

In a crewed experiment, the presence and absence of symbology on a head-down repeater display of EV imagery for the PNF was experimentally tested while EFVS approaches were flown (see Bailey, Kramer, Prinzel, and Wilz, 2009). Runway incursions were introduced on two occasions unbeknowst to the crew and interspersed in a large number of nominal data runs.

As noted by Kramer et al (2009b), almost all obstacle detections were made by the PNF using their natural OTW vision.

It was hypothesized that the PNF made almost all of the detections because the PF is primarily focused on flying the aircraft, while the PNF, serving as a PM, had the primary responsible responsibility of monitoring and verifying flight path performance, cross-checking guidance and raw data indicators, and identifying the visual runway environment and clearing the landing area.

This work also suggests that the PNF could not effectively use the repeater display of EV information for "clearing" the runway for obstacles. Johnson's criteria, applied to the EV system and the runway "targets," indicated that the EV information was not of sufficient resolution to be useful at 400 to 500 ft HAT for target detection, in the area where the PNF was using the repeater display (Bailey, Kramer, and Prinzel, 2007). Below 200 ft HAT, the EV repeater would be effective at showing traffic on the runway, but by this altitude, the PNF had transitioned to OTW and was not using the repeater display.

This work showed that the PM has the attentional resources and innate responsibilities for runway incursion detection (i.e., target detection). However, the HDD of EV imagery was not tailored for this obstacle/object detection task. To detect obstacles using this device required higher sensor resolution to detect objects at the altitudes and ranges where the PM desired to use the display (above 200 ft HAT). A zoom (magnification) capability would be needed to effectively increase the resolution of the sensor/display image before the aircraft transitioned into the visual segment. Magnification was also shown to be desirable in a study by Theunissen (2004).

This work had some limitations which influence the global applicability of the data:

1) This work did not look at the presence or absence of a repeater display. In the US, a repeater display of EV information is not required during EFVS applications; however, in Europe, a repeater display is required.
2) This work did not look at variations in size or display minification/magnification effects for the repeater display of EV information.
3) CDTI influences were not evaluated.
4) Variations in the repeater display location were not evaluated. The PNF display was located outside of the primary field-of-view of the crew (see AC25-11, "Electronic Flight Deck Displays," 27 June 2007) to the outboard and right of the forward instrument panel. A forward primary location may have enabled the PNF to quickly glance at the repeater display at lower altitudes and still maintain vigilance OTW.

An evaluation of EV/SV information for the PM to perform navigation integrity, obstacle detection, and runway incursion detection resulted in relatively mediocre performance (McKay, Guirguis, Zhang, and Newman, 2002). The evaluations were flown as a single pilot, with the lone pilot serving as a PM. During low-visibility auto-flight landings where all runs included an "anomaly" (e.g., SV database misalignment, runway incursions, or uncharted obstacles), the evaluations showed that (see Figure 9):

- The best performance - fewest missed detections - were found when the PM had automatic, 'behind-the-glass' detection capability (i.e., "Threat Icons").
- Using an EV-only HUD ("EVS HUD" in Figure 9), 57% of the obstacles were undetected and 50% of the runs with the database misalignment went undetected 38% of the runway incursions went undetected. Despite this relatively poor performance, the pilots subjectively preferred this implementation overall.
- A Primary Flight Display concept, showing SV with a pilot-controllable EV inset image ("EVS Insert" in Figure 9), exhibited the worst performance for anomaly detection. The PFD inset concept "missed" 100% of the uncharted obstacles and a 33% rate of missed detections for the database misalignments. Detection of runway incursions showed a missed detection rate of 33%. The poor performance and low-acceptance of the head-down EV insert concept was attributed to the clutter of the image, the small EV image size, and confusion between the SV/EV images. A preference for control of the EV sensor image in an inset display has been shown elsewhere (Theunissen et al, 2004), but pilot workload was shown to increase because of the additional pilot control for display management.

- With EV-only shown on a HDD ("EVS HDD" in Figure 9), all uncharted obstacles were successfully detected but 33% of the runs missed the database misalignment. A missed detection rate of 22% for runway incursions was found. This concept was well liked for its large image size and minimal display clutter, but disliked because of the workload in transitioning from head-down to head-up flight.

The data suggests that a head-down display without imagery provides the best opportunity for obstacle and traffic detection. The larger the display the better, but a HUD presentation was preferable, especially if all symbology could be decluttered and if the full dynamic range of the EV image could be presented. *Research should be examine head-down vs. head-up performance for the PM, with experimental variations in display size, location, and minification/magnification (R-5)*

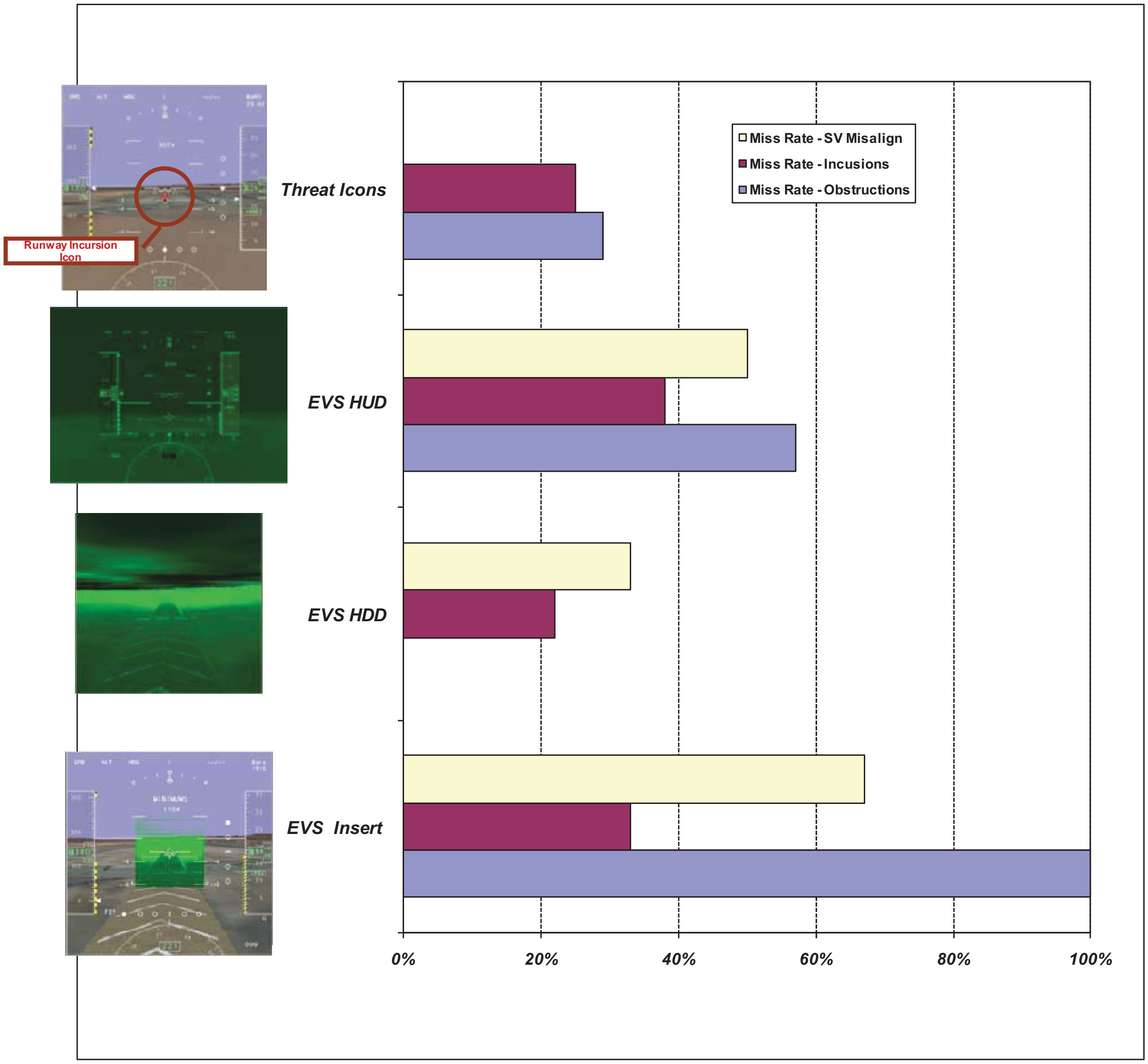

Figure 9: **PM Evaluations Using SEVS Technology**

5.4. Traffic/Obstacle Detection by PF With SEVS Technologies

The use of a HUD is deemed an essential "characteristic and feature" of the EFVS operation (FAA, 2004a) and as such, HDD implementations for EFVS are currently not allowed. The "essential features" of the HUD were described as follows:

- The display should provide the EV image and spatially-referenced flight symbology so that they are aligned with and scaled to the external view (i.e., conformally drawn).
- The display should be located so the pilot is looking forward along the flight path (i.e., looking at and through the imagery to the out-of-the window view) to readily enable a transition from EFVS imagery to the out-the window view.
- The display should not require the pilot to scan up and down between a head down display of the image and the out-the-window view looking for primary flight reference information. This transition would be hindered by repeatedly re-focusing from one view to the other.

In contrast to this mandate, the feasibility of an EFVS head-down procedure has been examined in simulation (Korn, Lenz, and Biella, 2007). This work was a follow-on to previous experimentation on crew coordination which focused principally on head-down displays and the application of a millimeter-wave radar sensor for EFVS (and its idiosyncrasies associated with transformation from an azimuth and range data to an egocentric, perspective display) (Lorenz and Korn, 2004). This work suggested that head-down operations in low visibility conditions was feasible, although not necessarily without potential limitations, especially if a change in aircraft control, from PF to PM, was necessary at low altitude.

Head-down to head-up transitions from instrument to visual flight conditions without a HUD - the process of looking up from a head-down instrument panel, refocusing and accommodating to the outside visual field, and perceiving and reacting to visual stimuli in the external scene - may take as long as 2 to 5 sec (Fisher, 1979). Pilots were observed to make from 4 to 14 separate head-down to head-up transitions during low visibility approaches, dependent on the simulated visibility and ceiling height. More transitions were made for higher ceiling heights and visibility conditions as the pilot's maintained a continuing cross-check between the head-down instruments and external visual cues.

The advantages of a HUD by minimizing visual scanning, accommodation, and re-focusing when transitioning from instrument to visual flight conditions are well founded in research (Wickens and Long, 1994; Lauber et al, 1982; Martin-Emerson and Wickens, 1997; Weintraub and Ensing, 1992; and Newman, 1995). The HUD visual transition effects have even been shown in ground vehicle transportation studies (e.g., Liu and Wen, 2004). These perceptual advantages were felt to contribute toward superior lateral touchdown performance using a HUD compared to HDDs for a transition to visual references, although no improvement in longitudinal touchdown performance was shown (Goteman, Smith, and Decker, 2007).

Wickens and Long (1994) also reported a significant improvement in tracking performance prior to breakout when GA pilots flew a HUD in an ILS approach task. The improvement was attributed to the fact that pilots didn't have a need to "divert attention away from the symbology" when head-up to find the runway at the break-out from instrument conditions. This observation was also supported by an (non-significant) improvement to recognize and confirm when the runway first became visible.

An attempt was made to quantify how these perceptual demands might impact quantitative approach performance. Performance-based approach standards from the Joint Aviation Authorities Joint Aviation Requirement All Weather Operations were applied to capture the effects of transition from head-down to head-up using natural vision or head-up EFVS to head-up natural vision (Kramer, et al, 2009a; Kramer et al., 2009b). These analyses showed that eliminating any visual transition improved tracking performance. However, the differences were not large and not statistically significant. Nonetheless, the trends make intuitive sense. By allowing the pilot to concentrate on the task and display information, improved flight tracking performance results. The HUD-visual segment transition allows the pilots to simultaneously perform glideslope corrections and acquire the required landing visual references through normal vision. If the pilots did not have to shift their attention, tracking performance improved.

These HUD advantages are not, however, provided without complications, limitations, or penalties as discussed in the following. When using HUDs (or other virtual displays), the pilot's accommodation and cognition are influenced by numerous complex and interacting HUD factors, creating sometimes contradictory findings (Edgar, 2007). From Edgar (2007), these factors include:

1. The HUD image occludes parts of the background;
2. The HUD image is displayed proximal to the use (i.e., the HUD combiner), near an individual's accommodation distance;
3. The user's attention is directed to the HUD image;
4. The HUD presents information to be processed by the user;
5. The HUD image is monochromatic;

These factors have been historically, but not necessarily accurately, lumped into two issues: clutter and attention capture. These are discussed in the following in reference to obstacle and traffic detection.

5.5. Clutter

Display clutter, especially for HUDs, has historically been a concern (e.g., Newman, 1980) and the increased use of EFVS for HUDs pushes this issue to the forefront (e.g., see Zuschlag, 2001). The goal of a display design should always be to minimize visual clutter. Only graphical elements that "add useful information content, reduce flight crew access or interpretation time, or decrease the probability of interpretation error" should be used (AC 25-11).

One universal definition of visual clutter is not available. Various clutter definitions have been proposed which typically group by (Kaber et al, 2008):

- Content or format of the data
- Degraded performance of the operator using the display
- Irrelevant information to the task at hand

The current clutter definition under AC25-11 ("Electronic Flight Deck Displays") includes each of these properties:

- "A cluttered display presents an excessive number or variety of symbols, colors, and/or other unnecessary information and, depending on the situation, may interfere with the flight task or operation. A cluttered display causes increased flight crew processing time for display interpretation, and may detract from the interpretation of information necessary to navigate and fly the airplane."

Note that the use of a "de-cluttering" function is also formalized for the express purpose "to enhance pilot performance" under AC25-11. In fact, under the EFVS rule within §91.175(m), the "displayed imagery and aircraft flight symbology do not adversely obscure the pilot's outside view." Under the MASPS for EFVS and SV (RTCA DO-315), requirements are contained such that "a control shall be provided which permits the pilot flying to deactivate and reactivate the display of the EFVS image on demand without removing the pilot's hands from the primary flight controls (yoke or equivalent) and thrust control."

Display clutter contains two critical aspects.

- First, clutter exists from a "bottoms-up," data-driven aspect, addressing the effect of clutter to confuse or obscure visual information in terms of the "physical" attributes of the display due to the number of display elements, their size, form, proximity, and luminance (Alexander et al, 2008). These issues are influential both in a local domain, referring to the area immediately surrounding "critical" display areas and in the global domain, associated with entire display and display area, in general.
- Display clutter also includes a "top-down," knowledge-driven aspect, addressing the effect of visual information on human cognitive processing and attention. The issues of particular interest are the relevancy and redundancy of the displayed information. Clutter involves the display content and its influence/relevancy to the piloting task at hand (Kaber et al, 2008).

Display clutter, therefore, involves the physical attributes of the display and its content and its influence/relevance y to the piloting task and cognitive/attentional demands (Kaber et al, 2008). Experimental evidence suggests that pilot experience modulates the perceptions of clutter with high-time, HUD experienced pilots being more accurate and consistent in judging the occurrence of clutter. Pilots with prior HUD experience also appear to be more consistent in relating display clutter to perceptions of cognitive load.

Clutter is linked – as discussed below – with attention capture.

A key element that is missing in this foundational work is the influence of actual HUD operations in relevant weather and operational contexts especially considering the inherent luminance limitations of the HUD and the seemingly unlimited luminance and coloration of the real-world. *Research should be conducted evaluating qualitative and quantitative metrics of clutter in actual flight conditions (R-6).*

5.6. Attention Capture

Attention capture is the phenomenon wherein a pilot fixates their attention to one task/element at the expense of ignoring other potentially critical task information. This phenomenon has been reported in human factors and aviation psychology research literature and attributed to several accidents, particularly associated with the use of a HUD (e.g., see Crawford and Neal, 2006; Prinzel and Misser, 2004). In those cases where it was observed, the authors typically concluded that pilots flying with a HUD were less likely to detect an unexpected "event" in the "far domain" because of their fixation on the HUD and its symbology (i.e., the "near domain").

Because of the great emphasis on attention capture with HUD usage, and its potential role in traffic/object awareness and detection, pertinent literature are reviewed.

The most often cited case of HUD attention capture was a simulation experiment using 8 pilots (Fischer, Haines, and Prince, 1980) flying a low visibility approach and landing task. Four runs were flown without expectancy for the runway incursion with the HUD; four runs without HUD. The simulated weather had a 180 ft cloud deck, in 2000 ft RVR. With this weather, if the aircraft were on glideslope, the pilots might be able to first detect the incursion at approximately 160 ft HAT.

The data, at first glance, makes a compelling case for HUD attention capture. In all of the non-HUD runs, the flight crew noted the incurring vehicle. In half of the HUD runs, the runs "resulted" in an incursion.

Upon closer inspection, however, the data (shown in Figure 10) contained many unintentional confounds and it isn't nearly as neat as described as above. First, two of non-HUD runs were spoiled by experiment protocol. The confederate FO inadvertently contaminated or terminated the runs. Thus, two out of four non-HUD runs did not result in an incursion; the other two didn't count. Second, one of the HUD runs which was claimed to "result" in a runway incursion was actually terminated at an altitude *higher* than one of the "detected incursions" in the no-HUD condition (i.e., the HUD run terminated at 67 ft HAT, whereas the pilot in a non-HUD run spotted the incursion at 63 ft HAT). Finally, inspection of the data showed that the non-HUD pilots had relatively poor ILS tracking performance and were *significantly* below the glideslope, resulting in a longer time for "visual conditions" than the HUD pilots who flew on glideslope. As a rule of thumb, the pilot only had ~10 seconds from 160 ft HAT to 60 ft HAT to see the traffic and initiate a go-around or the confederate FO would terminate the run.

(Note that their second runs – with full expectancy of an incursion event – resulted in better detection performance with the HUD. The pilot's were flying head's up and therefore, had better performance since they didn't have to transition from head-down to head-up.)

Despite these confounds, the "attention capture" conclusion from this work spawned numerous other research efforts to identify its physical and/or psychology mechanisms.

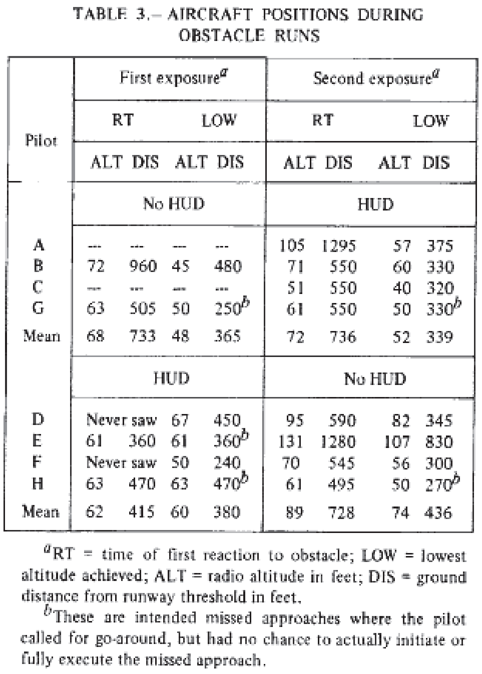

TABLE 3.– AIRCRAFT POSITIONS DURING OBSTACLE RUNS

Pilot	First exposure[a]				Second exposure[a]			
	RT		LOW		RT		LOW	
	ALT	DIS	ALT	DIS	ALT	DIS	ALT	DIS
	No HUD				HUD			
A	---	---	---	---	105	1295	57	375
B	72	960	45	480	71	550	60	330
C	---	---	---	---	51	550	40	320
G	63	505	50	250[b]	61	550	50	330[b]
Mean	68	733	48	365	72	736	52	339
	HUD				No HUD			
D	Never saw		67	450	95	590	82	345
E	61	360	61	360[b]	131	1280	107	830
F	Never saw		50	240	70	545	56	300
H	63	470	63	470[b]	61	495	50	270[b]
Mean	62	415	60	380	89	728	74	436

[a] RT = time of first reaction to obstacle; LOW = lowest altitude achieved; ALT = radio altitude in feet; DIS = ground distance from runway threshold in feet.

[b] These are intended missed approaches where the pilot called for go-around, but had no chance to actually initiate or fully execute the missed approach.

Figure 10: **Data From Fischer et al (1980) For Runway Incursion Event**

Excellent summaries of attention capture and associated research are contained in Prinzel and Risser, (2004), Crawford and Neal (2006), and Edgar, 2007. Weintraub and Ensing (1992) suggest that cognitive switching is "impeded by: a) optical clutter; b) the conformal aspects of the symbology; c) the lack of physiological change (e.g., in accommodation, in convergence, in gaze angle) to serve as cognitive signals to switch attention." The cognitive switch might also be impeded by the compelling nature of the HUD flight-director/command symbology.

With 20/20 hindsight provided by the many years and the numerous studies conducted since on this subject, six factors seem to emerge as profoundly influential in HUD attention capture research:

1. OTW Visual Fidelity
2. HUD Optics
3. Conformal Symbology
4. Brightness, Contrast, and Declutter

5. Type of Event
6. Pilot Experience and Training

These factors follow Edgar's list of confounding factors (Edgar, 2007) in accommodation and cognition using virtual displays and include some of what is already known about perceptual grouping and attention capture for virtual displays and HUDs (see for example, McCann, Foyle, and Johnson, 1993).

More importantly, these factors are expanded upon as they are not often considered or factored into the empirical/applied aviation research which identified "attention capture" as a safety factor in the use of HUDs. These factors possibly describe how attention capture "problems" found in laboratories, run counter to operational data:

- A study by the Flight Safety Foundation (2009) found that HUDs prevented or positively influenced 38% of accidents overall in modern glass cockpits. Of these accidents where the pilot was directly involved, such as takeoff or loss-of-control, the "safety advantage" of the HUD became much higher (69% and 57%, respectively).
- Development and certification flight testing of Head-up Guidance Systems for manual Cat. III landings (Green, 1988) initially included concerns for HUD attention capture. However, test experience noted that "a pilot can become engrossed with any control task. Fixation, or a narrowing of his horizon of perception to extraneous cues, can occur heads-down in a tracking task as well as heads-up." The flight data noted that "at no time in the flight program did any pilots comment about a fixation problem associated with the HUD, or notice any reduced capability to either scan for traffic or detect unexpected traffic while maneuvering in a terminal area."

5.6.1 OTW Visual Fidelity

A critical aspect of attention capture is the saliency or similarity between the HUD ("near field") and OTW visual field ("far field"). As noted by Crawford and Neal (2006), "if the HUD is more salient of the two domains, these elements of the external world, especially those that are unexpected, may be more difficult to detect."

The OTW visual fidelity in laboratory or simulator evaluations creates a critical difference of HUD attention capture compared to the flight environment. Notable laboratory / simulation tests showing attention capture (e.g., Hofer et al, 2000; Fischer, Haines, and Prince; 1980; Wickens and Long, 1995) provided 20:60 visual acuity at best. Based on acuity alone, with these degraded visuals, pilots must be twice to three-times as close to an incurring vehicle for detection as could be expected in-flight. As noted in Section 5.2, the visual acuity of present-day EFVS HUDs provides only 10 pixels per degree resolution – one-sixth of a human's normal visual acuity. Therefore, in-flight, there is a significant difference in acuity between the HUD and the OTW, promoting salient differences. In laboratory or simulator evaluations, these acuity and saliency differences may not be present.

Because of degraded OTW visuals, pilots were deprived of or received degraded OTW visual cues critical to the task. In the absence of OTW visual cues, pilots can become reliant on the HUD guidance symbology for flight control, drawing attention and focus unnaturally toward the HUD at the expense of the OTW (Weintraub and Ensing, 1993).

Another notable component in far-field/near-field saliency is the visual cueing/fidelity of the OTW target depiction and lighting. Especially in low-visibility and night operations, airport and traffic lighting is a critical visual cue. Calligraphic lighting is critical simulation tool to mimic realistic lighting effects; these point light source effects were notably absent in almost all instances of HUD attention capture research. Their absence degrades the saliency of the OTW scene and thus, promotes HUD attention capture. One could argue that not all "targets" of interest have lights. However, even though a target may not have lights, the fact that a repeatable pattern of lights is absent due to obscuration or shadowing also provides visual cues (e.g., see AC91-73A).

Emerging technology trends suggest possible trending toward HUD attention capture:

- State-of-the-art Liquid Crystal Display HUDs are moving to much higher resolutions, nearing eye-limiting acuity. This trend would suggest a reduction in saliency differences between the HUD and OTW visual fidelity.
- Fortunately, the underlying resolution of FLIRs are remaining, for the foreseeable future, at approximately 320 Horizontal x 240 Vertical pixel resolution because higher FLIR resolution would trigger unwanted export restrictions associated with International Trafficking Acquisition Regulations. (The lower resolution FLIR signals are being mapped to the higher resolution HUD video formats.)
- EFVS HUD operations would suggest a trend toward HUD attention capture given that, by definition, the HUD imagery contains more information than provided in the natural vision spectrum. The HUD attention capture literature is also devoid of this effect, as discussed in Section 5.3.

Research should be conducted using high fidelity simulation and flight testing; evaluating HUD attention capture effects in very low visibility operations (visibilities less than 700 ft) where the saliency becomes less distinct (R-7).

5.6.2 HUD Optics

A vast majority of HUD attention capture research didn't, in fact, use a real HUD, but instead, simulated HUD operations by embedding the HUD imagery into the OTW visual scene (e.g., Fischer, Haines, and Prince, 1980; Weintraub, Haines, and Randle; 1985; Wickens and Long, 1995; Ververs and Wickens, 1998; Hofer, et al, 2000). The simulations created the case where the OTW and HUD imagery were at the same optical distance. Using this simulation methodology, unfortunately, masks the perceptual differences of the HUD and the OTW. It also emphasizes obscuration of the OTW by HUD symbology.

HUDs also include other critical factors which optically promote the differentiation between the HUD and the OTW visual scene:

1. Real HUDs are *not* focused at infinity (Gibson, 1980).
   The design goal of a HUD is to provide a virtual image at optical infinity but HUD optical systems are not perfect; there are residual uncompensated optical errors in the optical system. As such, HUDs are typically focused inside of optical infinity. (As described in SAE AS8055, minimum acceptable errors in monocular positional accuracy are specified. The complication arises that these errors can cause binocular parallax errors. Stringent requirements are in place to limit optical errors which might cause a pilot's eyes to angle outward (divergent errors) because pilots cannot easily accommodate these errors (Gibson, 1980). As such, HUD optics are typically biased toward convergent errors (apparent display depth to vary inside of optical infinity across the field-of-view) but beyond resting-eye focus. The net effect is that *perfect* conformal overlay is not provided by a real HUD. Head movement will generate some degree of differential motion between the HUD symbology and the OTW visuals, thus, promoting attention switching.)
2. Pilots don't have perfect vision:
   Disparity between the HUD virtual image and the OTW imagery is further differentiated by pilots not having perfect vision. Any disparity in visual performance between a pilot's left and right eye will exacerbate the imperfection from an ideal "optical infinity" design.
3. HUDs have distinct eye boxes:
   HUD optics have a distinct eye box over which the exacting design requirements for monocular and biocular performance are specified. However, outside of this eye box, the pilot can view an unobstructed, uncluttered view of the world by head movement, which clearly separates the "near domain" and "far domain" information.
4. Real HUDs have limited luminance and distinct coloration:
   P-43 phosphor provides a unique green color which is almost unique in the outside world, so the probability of "color obscuration or clutter" with an object in the real-world is improbable, lending support that the HUD will be perceived as a separate entity from the OTW, supporting attention switching (McCann, Foyle, and Johnson, 1993).

Emerging technology trends are, again, trending toward HUD attention capture principles:

- Color HUDs are not yet a present-day reality but if they come to fruition, very careful color coding will be necessary to ensure a minimum of color-obscuration and to support attention/domain switching by color differentiation.
- Optics designs are emerging to create much larger design eye boxes. Increasing the size of the eye box would lessen the perceptual switch between the "near domain" HUD and "far domain" OTW visual information.

Research should be conducted evaluating the impact of color HUDs (and head-worn display or virtual display) on attention capture, clutter, and target detection (R-8).

5.6.3 Conformal Symbology

Human information processing is constrained by attention limitations. Scene-linked symbology has been shown to be a necessary but perhaps not sufficient means to support simultaneous processing on instrument information and far domain information. (McCann and Foyle, 1995). This use of "scene-linked symbology" - where these symbolic references are located such that they overlay a real-world position and move and transform as though they were actual objects in the world - facilitates efficient cognitive processing and mitigates problems of attention tunneling and symbology fixation.

Real HUDs are composed of conformal and non-conformal elements. This mix of symbology types emphasizes attention/domain switching via differential motion (McCann and Foyle, 1995).

HUD symbolic changes and aural cues are employed by design and/or standard operating procedures to ensure attention/domain switching. For instance, HUD systems may use conformal runway edges for visual momentum and acquisition on the approach, but they disappear at 50 ft, creating a visual change - a visual vacuum as it were - that is filled by the outside runway edge environment (Green, 1985). Automatic or crew call-outs of altitudes and runway status aid this attention switch.

Perfectly conformal symbology in real HUDs is not possible. In Section 5.2.2, the optical distortions of real HUDs were discussed and these negatively impact conformality. Further, the latency involved in signal processing to sense, compute, and draw conformal HUD imagery creates inaccuracies in its representation against a real-world object. Excessive delay creates symbology "swimming" which, as the latency increases, eventually becomes unacceptable (Bailey et al, 2004).

Research should be conducted evaluating the impact of imprecision in conformal HUD symbology (statically and dynamically) on attention capture effects and the ability of the pilot to use EFVS imagery especially as it is the predominant source of visual information for landing in very low visibilities (<700 ft visibility) (R-9).

5.6.4 Brightness, contrast, and declutter

HUD attention capture (and clutter) has been shown to be dependent upon the symbology contrast (Ververs and Wickens, 1996 and 1998). This result is intuitive, given that the apparent contrast (luminance of the "near domain" symbology against the background "far domain" background) directly impacts saliency.

Unfortunately, this degree of freedom has too often been an experimental confound in the attention capture research. It was noted in Hofer et al (2000) that "one of the pilots commented that the HUD was worse for switching and would induce tunneling, when the tactical symbology was too bright; this is why it was suggested to turn down the symbology brightness to make it less compelling and to detract less of the pilot's attention." Ground simulation is notoriously poor at reproducing real-world HUD operations - critical in the evaluation of cognitive switching (and the potential for cognitive capture) and occlusion.

While real-HUDs may be used in simulation – simulating eye box effects and imperfect optics - the evaluations are compromised by the very limited luminance output of the external scene, out-the-window projectors. The limited luminance (less than 50 ft-L typically) of the OTW often creates a biased evaluation between the HUD imagery and the OTW – critical for object and obstacle detection – especially without experimental control of the HUD brightness settings. The transmissivity of the HUD combiner also corrupts the contrast and brightness of objects when looking through the HUD to the point where they may not be perceptible. "Burn-through" of landing lights is an important visual element of HUD low visibility EFVS operations which is not often simulated because of the limited luminance output of the OTW visuals and the HUD combiner transmissivity. Thus, the low luminance of the OTW background may bias the perception of the HUD imagery as it depends upon the background illumination.

Emerging technology is trending toward HUD attention capture concerns:

- Emerging Liquid Crystal Display HUDs replacing CRT-based systems can provide much higher luminance outputs, enabling full sunlight-readable imagery. Moving toward much higher luminance levels would suggest: a) a possible reduction in saliency differences between the HUD and OTW visual fidelity; and b) a higher propensity for symbology obscuration of OTW visual information.

Research should be conducted evaluating the impact of HUD brightness as well as simulated OTW visual luminance (apparent target contrast) on attention capture effects and the ability of the pilot to detect target (R-10).

5.6.5 Type of Event

A meta-analysis found that, although improved tracking performance can obtained with HUDs, "detection performance was found to be worse when a HUD was used during the landing phase of flight, a HUD cost that is amplified when events are unexpected" (Fadden, Wickens, and Ververs, 2000).

Hofer et al (2000) also found that HUD performance was inferior to HDDs in *expected* event detection, and far inferior in the detection of *significant* events leading to a possible incident or accident (i.e., runway incursion). (Nevertheless, the subjective results revealed that the pilots judged the HUD as being lower in overall workload and more usable than the HDD. The perception also was that it is easier to switch between the displayed information on the HUD and the outside scene, than it is to switch between the HDD and the outside scene.)

As noted by Wickens and Alexander (2009), "the implications are not that HUDs are problematic, but rather than imposing an event or visual item within the foveal vision does not guarantee its detection, if it is unexpected and not salient."

In contrast, in terms of responding to unexpected occurrences, the detection rates and response times were comparatively higher and faster, respectively, when subjects used a HUD (Weinrauch et al., 1989; Sojourner and Antin, 1990); however, reaction times were faster using the HUD only in a low-workload situation. When the workload condition was high, on the other hand, the HUD users had longer reaction times when compared to the HDD (Fischer et al., 1980; Iarish and Wickens, 1991; Wickens et al., 1993).

Automotive HUD research (Wolffsohn, McBrien, Edgar and Stout, 1998) has shown that response times to and detection of changes in the HUD image and outside world scene were significantly worse with increased cognitive demand. Response times to and detection of changes in the HUD image and outside world scene also increased with age.

Research should be conducted evaluating the impact of experience and training in HUD operations for runway incursion detection and attention capture effects (R-11).

5.6.6 Pilot Experience and Training

Another unfortunate confound in the HUD attention capture literature is the experience base of the subjects. HUD experience has been found to be critical in understanding and correct use of HUDs (Kaber et al, 2008).

Many of the subjects in attention capture research were General Aviation (GA) pilots, (e.g., Wickens and Long, 1993) without prior HUD experience and even in those tests that used highly experience flight crews, HUD experience was limited or non-existent (e.g., Hofer et al, 2000; Atkins et al, 2001). As Hofer (2000) noted, "it was commented that a major training effect is to be expected with the HUD. That is, it is felt that pilots can be trained at what they need to do and get significantly better at performing all required tasks at a desired level of performance. To rely solely on the HUD is considered a learning curve, but the learning curve is expected to be moderately steep."

HUD experience brings two key points:

- Understanding of HUD brightness and implications for clutter and how to declutter the HUD effectively;
- Understanding of HUD attention capture and transition to the OTW. Hofer et al, 2000 theorized that pilots are "trained to make a physical switch between the two planes of information (head-up OTW and head-down) in a non-HUD aircraft;" whereas, using a HUD, a deliberate "attention" switch is required of the pilot to shift from information gathered from the HUD-symbology (near field) to the OTW visual (far field). As noted (Weintraub and Ensing, 1992), "when switching from a head-down display instrument panel to the outside world, there are three strong cues conveying the message that a switch is in progress from display information to outside scene information: The pilot looks up, the pilot changes

> focus, and the pilot changes convergence form the outside world. They are powerful reminders to switch attention."

A pilot can become engrossed with any control task. Fixation, or a narrowing of their perception to other cues, can occur heads down as well as heads-up. This attention switch during HUD operations is promoted by judicious use of HUD brightness. For instance, the importance of HUD brightness and declutter controls are commonly trained in HUD operations (G. Saylor and R. Moreau, personnel communication, 29 May 2010) although standard operating procedures (SOPs) are not in place nor are SOPs expected since straight-forward rules for SOPs aren't possible or practical. Training emphasizes the influence of HUD brightness, clutter/occlusion, and declutter controls. It stresses that the HUD brightness should be set as low as possible to keep the pilot looking through the HUD, yet still being able to see the HUD information. Pilot experience directly influences HUD brightness usage, with more experienced pilots tending to use less brightness as they have learned and become proficient in the HUD, its symbology and usage.

6. Cockpit Display of Traffic Information with SEVS

The ability of a human to detect obstacles and traffic visually has been discussed and the impact of using a HUD or SEVS information on HUDs and HDDs has been discussed. This ability is also modulated by the roles and responsibilities defined for the flight crew (pilots). The emergence of ADS-B for Cockpit Display of Traffic Information (CDTI) creates the potential for significant improvements in traffic awareness and detection.

Four tactical and strategic capabilities/operational benefits (McAnulty and Zingale, 2005) are envisioned by use of CDTI:

- traffic awareness for the flight crew;
- airborne spacing where the flight crews achieve and maintain a given spacing with a designated aircraft, but controller remains responsible for separation;
- airborne separation where controller delegates separation relative to designed aircraft to the flight crew; or,
- airborne self-separation where a controller delegates separation relative to all known aircraft in accordance with applicable airborne separation minima.

Numerous references describe potential applications for employment of CDTI (e.g., see McAnulty and Zingale, 2005; RTCA DO-289, MASPS for Aircraft Surveillance Applications). This technology is clearly one of the foundational enabling technologies for NextGen. These works have been expanded into government and industry consensus leading to Minimum Operational Performance Standards and Safety, Performance, and Interoperability Requirements for numerous CDTI-based operational capabilities.

All of these works are pertinent but in this report, the use of CDTI for awareness of surface traffic is examined. In particular, research are reviewed as to how CDTI supports and/or modifies the pilots' task of traffic detection and collision avoidance in the terminal maneuvering area (i.e., runway and low altitude safety) and during surface operations.

6.1. Object/Traffic Detection and Use of CDTI

The process of "visual scanning" by a pilot (crew) is greatly influenced by the search importance, vigilance, and localization, such as:

1) The current tasking of the pilot (crew) – i.e., what are the roles and responsibilities of the flight crew in the operation which dictates the time and attention available to perform a visual search.
2) Whether the pilot's search is localized or directed to look for a "target" in a certain area or location, as compared to very large, generalized area.
3) Whether the pilot is alerted to potential collisions or conflicts with traffic or objects, thereby, increasing the pilot's motivation and urgency in conducting a success search.

CDTI has been shown to be an effective enhancement for visual acquisition of traffic (e.g., see Battiste, Ashford, and Olmos, 2000; Bone, Helleberg, and Domino, 2004;

Moore, 1997; Andrews, 1984 and 1991). CDTI creates an "alerted" search situation and also provides localization for the visual search.

Some studies show an eight to nine times improvement in detection when alerted (Andrews, 1991; Boff and Lincoln, 1988). Un-alerted pilots were noted to concentrate their gaze in the forward direction (within 30° of straight ahead), but when informed that they were on a collision course, spread their glances more evenly over the visible area (Howell, 1957). Flight deck observations noted that, when available, CDTI was the first method used in the process of visually locating traffic (Joseph, Domino, Battiste, Bone, and Olmos, 2003), providing information for the pilots to localize their OTW visual search. CDTI provided increased positive visual acquisitions (Prinzo, 2003). However, dedicated studies in the use of CDTI (without collision detection and alerting) for traffic awareness and detection on the runway are few.

For target detection using CDTI, operational differences (e.g., Part 91 versus Part 121/135 operations) and airspace class differences likely influence CDTI usage, modulating the amount of head-down time caused by CDTI (Wickens et al, 2001). For instance, significant time is already required for head-down attention to the instruments for aircraft control - some aircraft and operations more than others. Airspace class dictates equipage and operational procedures so pilots may not have to attend to OTW scanning as much in controlled airspace as VFR airspace. These changes affect the "value" that the pilot places on OTW scanning viz-a-viz CDTI and head-down scanning. If the aircraft is operating in higher traffic density conditions or in uncontrolled airspace, OTW and CDTI vigilance changes because the "value" of scanning is significantly higher.

Wickens et al (2001) found that pilots used CDTI to guide them as to where to look to detect traffic, providing 5 seconds faster detection of non-conflict traffic than were pilots in the non-CDTI condition. However, during traffic conflict trials, pilots allocated relatively more attention to the CDTI, in order to plan their avoidance maneuvers, and this led to slower OTW detection times than in the baseline.

Head-down time is a recurring, significant issue for CDTI suggesting that the use of CDTI draws pilots into the cockpit at the expense of scanning OTW for traffic (e.g., see McAnulty and Zingale, 2005; Battiste, Ashford, and Olmos, 2000). For instance, less head-down time and better integration of CDTI into the operation was found (Bone et al, 2003) when using a forward, primary FOV CDTI versus a CDTI display located near the center aisle-stand/throttles. Pilots may be able to effectively integrate CDTI into this head-down scan. Workload was also found to be lower for the forward, primary FOV CDTI, but these differences were not considered to be operationally significant. An earlier study by Abbott and Moen (1981) had essentially reached the same conclusions.

General design principles have recently been developed for 2-D traffic display symbology as part of RTCA SC-186 (Zuschlag, Chandra, Helleberg and Estes, 2010) with emphasize on how the symbology promotes intuitiveness, ease of learning, and ease of remembering. The additional of directional information to CDTI traffic symbols during airborne collision encounters was shown to not negatively affect pilot response to

TCAS resolution advisories (Olsen et al, 2009). The directional information also didn't affect pilot scanning.

Research should be conducted evaluating the use of CDTI for traffic awareness and detection on the runway without traffic collision detection indications or alerting. This work would be complementary to research on indications, warnings, and alerting methodologies to establish the cognitive and human-centered and engineering design trade-offs of Terminal Maneuvering Area Conflict, Detection, and Resolution systems (R-12).

6.2. Object/Traffic Detection and Use of CDTI with SEVS – Exo-Centric

The criticality of head-down time significantly influenced the development of airport moving map concepts (i.e., exocentric view of a synthetic airport layout, geo-referenced to ownship and CDTI) especially for the Taxiway Navigation And Situation Awareness (T-NASA) concept (Foyle, Andre, McCann, Wenzel, Begault, and Battiste, 1996). The T-NASA moving map was designed to promote eyes-out navigational awareness rather than eyes-in control functionality.

Eye-gaze tracking and analysis indicated that the amount of time dwelling on the moving map was significantly different depending upon the visibility condition (Graeber and Andre, 1999) but the operational significance of these differences (ranging from 38% to 41%) is questionable. Pilots who were instructed on the intended use of the moving map gazed at the map less (35%) as opposed to those that were not instructed (44%). Using audio or visual "head-up" callouts as to the pilot's visual attention to an airport moving map reduced the visual attention demand of the airport moving map display, without significant performance degradation relative to the no-callout condition (Purcell and Andre, 2001).

As NextGen operations emerge - including concepts for 4D surface operations requiring runway to gate time-of-arrivals - the influence of CDTI, moving map concepts, and head-down time warrants renewed investigation. A study of these concepts (Shelton et al, 2010) using "non-normals" to assess safety-critical scenarios showed that pilots were actively using and interacting with the surface map display concept only when there was valuable surface traffic and intent information. When flying ownship-only display concepts, the map was useful to support route and navigation awareness, but it was not often needed. But as traffic intent information and cleared route information was added, additional head-down time was attracted (Prinzel et al, 2010). The non-normals results showed the value of surface traffic CDTI and surface traffic 'intent' information but many of these potential incidents or accidents in the non-normals were also effectively mitigated by an EV-equipped HUD. Another study showed very similar results where four non-normals, involving taxiway or runway incursions studying the effect of the presence or absence of 'party-line' information were effectively mitigated by an EV-equipped HUD instead (Prinzel et al, 2010). The role of the crew (pilots) and the fact that the pilot-flying must remain vigilant and head-out during surface operations significantly modulates the effectiveness of CDTI and how effective CDTI can be depends upon the display location and its content.

The integration of CDTI with SEVS technologies must consider the presentation format and especially, the potential for clutter as traffic and terrain/flight reference information must be effectively integrated and quickly interpretable. Co-planar CDTI formats suffer from scanning-related integration that increases with conflict density. However, perspective CDTI formats suffer from perceptual ambiguity, such as range-to-traffic estimation difficulties (Alexander, Wickens, and Merwin, 2005). The use of highlighting can be useful but must be appropriately tailored (Johnson, Liao, and Tse, 2003).

A runway incursion prevention system has been created to add another “safety wrapper” around the pilot/crew awareness provided by the airport moving map (such as T-NASA). The system adds aural and visual alerting of the incurring traffic to create awareness and localize the visual search. The importance of an ‘alerted’ search was highlighted in a test of incursion prevention concepts for GA pilots. An airport moving map with traffic was found to be only marginally beneficial without alerting. One pilot experienced a severe runway incursion despite having the traffic displayed on an airport moving map (Jones and Prinzel, 2006). The incursion resulted because the pilots had transitioned to out-the-window and were not focused on the head-down display to locate incurring traffic. It was hypothesized that the utility of the surface map would be more effective if the display was located higher on the instrument panel, closer to the pilot’s head-up eye gaze.

Continued enhancements for traffic awareness on airport moving maps are emerging, including initiatives under SC-186 Surface Indications and Alerts (SURF-IA) providing obvious and direct indication of runway occupancy and potential safety/runway traffic implications (Moertl and Nickum, 2008). Further, NextGen concepts for 4D trajectory based operations, including required time of arrivals in airborne and surface operations, are spawning new CDTI such as the explicit depiction of cleared taxi routes for ownship and traffic with their required and actual taxi performance graphically drawn (see Figure 11).

The importance of CDTI and advisory, caution, and warning systems for NextGen include low altitude operations where desires for increased airport throughput will dictate more closely spaced arrivals. In an experimental simulator study (Pritchett and Hansman, 1996), traffic displays with increasing amounts of traffic information were evaluated in closely-spaced parallel approaches. The results generally support the contention that with more and better trend information, improvement in performance for conflict detection can be attained.

Research should be conducted evaluating the optimal methods for integration of CDTI within SEVS ego-centric display concepts (R-13).

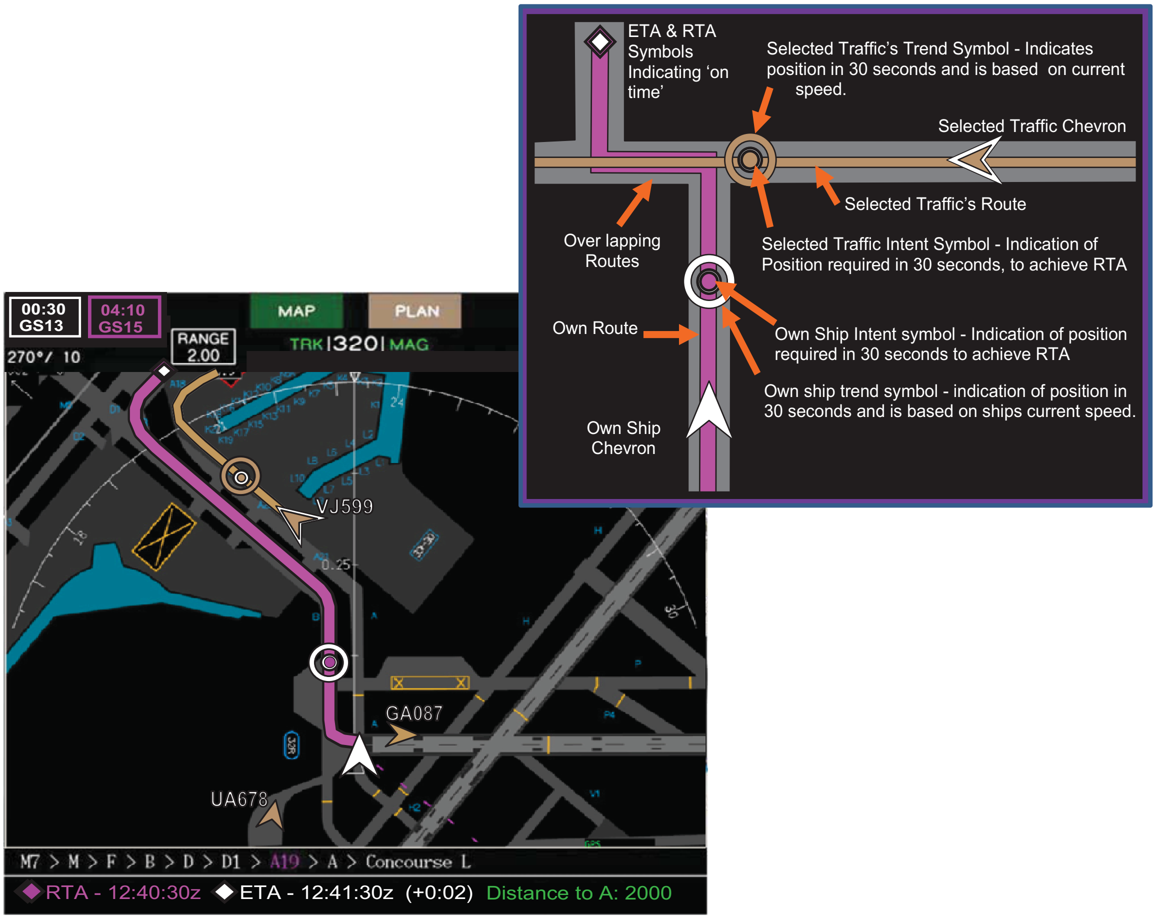

Figure 11: 4D Surface CDTI Concepts

6.3. Integration of CDTI with SEVS – Ego-Centric

CDTI research has predominately focused on exo-centric presentations of traffic (CDTI) and synthetic vision (airport moving maps) on a navigation display; that is, electronic moving map concepts.

However, objective and subjective data from an empirical study suggested that CDTI should be presented both head-up and head-down rather than just head-down (Kramer and Norman, 2000). Pilot workload for traffic surveillance was lower and it made for quicker and easier visual acquisition when the CDTI information was presented both head-up and head-down. Traffic locator box icons on the head-up displays allowed for quick visual and therefore, much easier detection and assessment of traffic. Clutter was a concern but not significantly so. Range filtering of traffic data was shown effective in reducing clutter yet retaining critical CDTI information head-up (Wong, Kramer, and Norman, 2002).

Representation of traffic location by icons within an ego-centric perspective display (i.e., a "traffic locator box") creates localization cueing with minimal clutter (Jones, 2002;

Kramer and Norman, 2000). Questions emerge as to whether improvement in situation awareness can be gained by instead using virtual models of the traffic aircraft, in SV presentations. A virtual model, driven from ADS-B 'In' information, would theoretically provide a more intuitive representation of the traffic and could include aircraft type, heading, bank angle, etc. Preliminary evaluation of head-worn display concepts during surface operations have evaluated virtual models (see Figure 12) for traffic representation, but conclusive results are not yet available.

Research is needed to identify and quantity the design trade-offs between intuitive traffic representation and the potential increases in display clutter or occlusion for ego-centric SEVS display concepts (R-14).

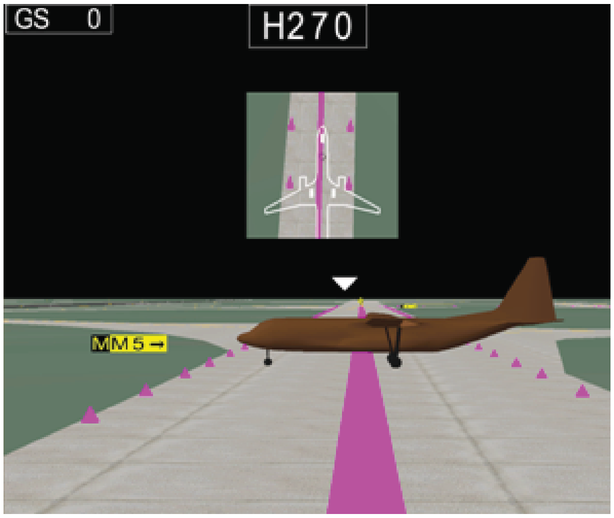

Figure 12: Head-Worn Display Concept With Traffic Represented By A Virtual Model

Viewpoint considerations must be tailored to the application. Studies in closely-spaced parallel approach tasks, suggests that "virtual" viewpoints at other than the pilot eye point make a significant difference in traffic awareness and blunder detection (Azuma and Furmanski, 2005). In fact, they suggest that "the view that a pilot would normally see out of a cockpit was by far the worst option."

Research has been conducted to determine minimum relevant traffic information for strategic traffic awareness during closely-spaced parallel approach tasks (e.g., Pritchett and Hansman, 1996). Others suggest that additional cues (traffic roll and heading) are also required to detect traffic blunder (Jennings, Charafeddine, and Powell, 2002). Their work suggested that a single synthetic vision display is insufficient to convey traffic information. The difficulties arise from an insufficient field-of-view of the PFD (or HUD) and that the distance cues are too weak in an ego-centric perspective display to precisely convey the location of the other aircraft. While the PFD does show traffic elevation and azimuth, additional display concepts have been evaluated to complement the SV PFD for traffic awareness, including exo-centric views.

7. Concluding Remarks And Recommendations

NASA LaRC and the FAA are conducting collaborative research activities to ensure effective technology development and implementation of regulatory and design guidance to support introduction and use of SEVS technologies in NextGen. SEVS technologies have the potential to provide an additional margin of safety and aircrew performance to enable the implementation of operational improvements for low visibility surface, arrival, and departure operations in the terminal environment with equivalent efficiency as visual operations.

In this report, the research literature is reviewed to assess pilot awareness and detection of traffic and obstacles when using SVS and EFVS systems.

Research was reviewed as to how the visual traffic and obstacle detection task is, in essence, a human observer performing "target acquisition." The cognitive and physical mechanisms for acquisition and detection using natural vision and EV using head-down or head-up displays is discussed. The critical issues influencing the time required, accuracy, and pilot workload associated with recognizing and reacting to potential ground collisions or conflicts with other aircraft, vehicles and obstructions related to the use of SEVS technologies are described. In particular, the importance of sensor resolution and the relative contrast of the "target" are paramount.

This work also discusses the effect of head-down and head-up operations with SV and EFVS, respectively, as well as the influence of single and dual pilot operations. The pilot's role in the operation is a significant contributor to the attention directed to and the importance of the search task.

Finally, research is reviewed in the methods and strategies of adding CDTI with head-down SVS and head-up EFVS in low-visibility landing and surface operations and their effect on time required, accuracy, and pilot workload for recognizing and reacting to potential ground collisions or conflicts.

7.1. Recommendations

Based on this review, numerous knowledge gaps have been identified and form the following recommendations for continued research and also, for specific empirical pilot-in-the-loop ground and flight testing activities to support SEVS for NextGen:

Future work should investigate the vision system technology (SEVS) requirements for an equivalent visual operational capability (R-1).

- To achieve the equivalent visual operations, one could assume that the vision system technology must meet the same performance as that provided by aircraft windows with a human observer. Is our knowledge of human visual performance sufficient and/or correct so as to design and create a vision system which meets equivalent visual capabilities? Is this assumption valid? Are these requirements too strict? Too lax?

- Are head-worn displays required to create this functionality? If so, what are the requisite cognitive and engineering issues? If not, what are the requisite cognitive and engineering issues with using HUDs and/or HDDs?

Future work should explore the impact, if any, of SEVS in changing the roles and responsibilities of the ANSP (R-2).

- Will new and expanded "operating credit" from the use of SEVS technologies require changes in ANSP roles or responsibilities? What impacts?

Future work should explore the potential for SEVS to replace the need for or functional elements currently required for Surface Movement Guidance and Control Systems and for approach lighting systems (R-3).

- Can equivalent visual capability on the flight deck obviate the need for certain requirements currently stipulated for Surface Movement Guidance and Control Systems and for approach lighting systems? What are the system characteristics required for these credits?

Research should be conducted to determine the desired/required missed detection and false alarm rates for a SV which utilizes 'behind the glass' processing for automatic database, obstacle/object, and navigation error and omission checking (R-4).

- Research suggests that the 'ideal' vision system is a SV presentation with processing 'behind-the-glass' to support integrity and accuracy requirements. What level of human interaction with this process is required/desired? What type of interaction is required/desired?

Research should be examine head-down vs. head-up performance for the PM, with experimental variations in display size, location, and minification/magnification (R-5)

- During EFVS operations, the PM has specific roles and responsibilities. Research is needed to identify the display characteristics required to best support these roles and responsibilities for current and emerging operational capability.

Research should be conducted evaluating qualitative and quantitative metrics of clutter in actual flight conditions (R-6).

- Display clutter is critical. Qualitative and quantitative metrics have been proposed but they have only been tested in ground simulation.

Research should be conducted using high fidelity simulation and flight testing; evaluating HUD attention capture effects in very low visibility operations (visibilities less than 700 ft) where the saliency becomes less distinct (R-7).

- Emerging trends suggest that HUD attention capture could be on the increase. Research is needed to develop counter-measures and establish guidelines/requirements to ensure that attention capture is mitigated.

Research should be conducted evaluating the impact of color HUDs (and head-worn display or virtual display) on attention capture, clutter, and target detection (R-8).

- Only a very limited research basis is available regarding the application of color virtual displays, head-worn displays, and HUDs. Research is needed in "augmented reality" scenarios, especially for attention capture, clutter, and target detection, where the interaction of displayed information and real-world visual cues are paramount.

Research should be conducted evaluating the impact of imprecision in conformal HUD symbology (statically and dynamically) on attention capture effects and the ability of the pilot to use EFVS imagery especially as it is the predominant source of visual information for landing in very low visibilities (<700 ft visibility) (R-9).

- What are the static conformal and dynamic response requirements for an EFVS system to conduct operations in very low visibilities where the EFVS provides the vast majority, if not the sole source of usable visual cues for the pilot?

Research should be conducted evaluating the impact of HUD brightness as well as simulated OTW visual luminance (apparent target contrast) on attention capture effects and the ability of the pilot to detect target (R-10).

- Data are needed to guide the use and training of the HUD controls to ensure its effective operational use.

Research should be conducted evaluating the impact of experience and training in HUD operations for runway incursion detection and attention capture effects (R-11).

- The human factors research data on HUD effects do not adequately or appropriately reflect trained HUD operators and these influences. Selected data should be collected to quantify these impacts.

Research should be conducted evaluating the use of CDTI for traffic awareness and detection on the runway without traffic collision detection indications or alerting. This work would be complementary to research on indications, warnings, and alerting methodologies to establish the cognitive and human-centered and engineering design trade-offs of Terminal Maneuvering Area Conflict, Detection, and Resolution systems (R-12).

- SURF-IA and other initiatives are creating significant safety enhancements using ADS-B traffic information and attendant CDTI in exo-centric applications. However, several gaps in this research and application are apparent, including:
    - Is CDTI on head-down displays sufficient if the pilot's attention (i.e., roles and responsibilities) are directed elsewhere? What display concepts / alerting will help this scenario? Display location effects?
    - How does the use of CDTI and instantiations of traffic information (including trend information, cleared traffic route, and intent) modulate head-down time and attention?

    - How do pilot roles and responsibilities modulate head-down time and attention?

    - Most CDTI studies have assumed "perfect" traffic position reporting. What are the influences of realizable/realistic ADS-B accuracies? What are the influences of these accuracies on the task and performance? What about mixed equipage? ADS-B faults or failures?

Research should be conducted evaluating the optimal methods for integration of CDTI within SEVS ego-centric display concepts (R-13).

- What methods and presentation formats for ego-centric CDTI are optimal? What display concepts / alerting will help this scenario?

Research is needed to identify and quantity the design trade-offs between intuitive traffic representation and the potential increases in display clutter or occlusion for ego-centric SEVS display concepts (R-14).

- Display clutter is critical. Is symbolic representation of traffic on a head-up or head-down display sufficient or preferable to actual traffic models?

- Ego-centric CDTI presentations are likely impacted by "imperfect" ADS-B accuracies. What are the influences of these accuracies on the task and performance? What methods can be used to compensate for realizable/realistic ADS-B accuracies?

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14. ABSTRACT

Research literature are reviewed and summarized to evaluate the awareness and detection of traffic and obstacles when using Synthetic Vision Systems (SVS) and Enhanced Vision Systems (EVS). The study identifies the critical issues influencing the time required, accuracy, and pilot workload associated with recognizing and reacting to potential collisions or conflicts with other aircraft, vehicles and obstructions during approach, landing, and surface operations. This work considers the effect of head-down display and head-up display implementations of SVS and EVS as well as the influence of single and dual pilot operations. The influences and strategies of adding traffic information and cockpit alerting with SVS and EVS were also included. Based on this review, a knowledge gap assessment was made with recommendations for ground and flight testing to fill these gaps and hence, promote the safe and effective implementation of SVS/EVS technologies for the Next Generation Air Transportation System.

15. SUBJECT TERMS

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