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HEAD-UP DISPLAYS FOR AUTOMOTIVE APPLICATIONS

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16. Abstract

This report reviews the literature on automotive head-up displays (HUDs) from a human-factors point of view. Four major topics are covered in this review: HUD display parameters, the designs of available HUDs, popular appraisals of HUDs, and human performance with HUDs.

The most important display parameters are HUD location and HUD contrast with respect to the roadway. Several assessments of optimal HUD location have been made, and there is a consensus that HUDs should be located in the region where drivers make the majority of their eye fixations. Appropriate HUD image contrast levels with respect to the roadway have also been assessed, and it has been recommended that the HUD image be between 15 percent and 50 percent as bright as the background for daylight luminance conditions, and about 300 percent as bright as the background during nighttime luminance conditions.

The second section of the review is dedicated to the description of HUD hardware and available HUD systems. It is evident that technology is available to produce a HUD that meets all of the display criteria discussed in the first section, with the exception of optimal HUD image contrast with the brightest backgrounds.

Popular perceptions of automotive HUDs are discussed in the third section of the review. People believe that HUDs would be beneficial for performing the driving task, but will require more experience with HUDs before being comfortable with them in their automobiles.

Human performance with automotive HUDs is discussed in the final section of this review. Most assessments have investigated the effects of displaying speedometer information head-up. It has been found that people can monitor and extract information from a HUD speedometer more rapidly and frequently than from a conventional speedometer, but that HUD speedometers do not affect speeding behavior. The most significant benefit of HUD speedometers is that they allow for quicker and more accurate reactions to roadway obstacles because the driver's eyes do not leave the road.

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EXECUTIVE SUMMARY

Head-up displays (HUDs) have been available for aircraft for quite some time and they are now finding their way into automotive applications. Because many of the issues associated with using HUDs for automotive applications are different than those associated with aircraft HUDs, a significant amount of literature specifically pertaining to automotive HUDs has been generated in the past several years. This literature has addressed a diverse array of concerns, including the appropriate display parameters of HUDs, the actual design of HUDs within automobiles, peoples' opinions towards HUD technology, and human performance with HUDs.

This literature review is an attempt to organize and integrate the variety of work conducted on automotive HUDs from a human-factors standpoint. Because the application of HUD technology to automobiles is a relatively new idea, it is hoped that this review will serve not only as an assessment of the current state of automotive HUDs, but also as a foundation upon which future work can be based. While the primary focus throughout the review is to summarize previous research, it also provides criticism of the methods used in that work, and suggests possible improvements in these methods.

The review is divided into four major topics: human factors issues in HUD design, descriptions of available HUDs, popular perceptions of automotive HUDs, and human performance with automotive HUDs. These topics are covered in four separate sections, such that the reader may survey any one of these topics by reading the section pertaining to that topic in isolation. While the sections are written so that each can be read independently, the individual sections may be more meaningful if this review is read in its entirety.

Several HUD display parameters are discussed in the first section of this review, with the most important being HUD location and HUD contrast against the background of the roadway. Many assessments of HUD location have been made, but there still is not a complete consensus concerning one optimal HUD location. Whether HUDs should be on the average line of sight assumed while driving or at a location slightly eccentric to this line of sight is still a point of contention, but there is consensus that HUDs should be located near a point upon which drivers frequently fixate. There is also consensus in the literature that the optical distance from the driver's eyes to the HUD virtual image should be between 2.0 and 2.5 m, about at the end of the automobile's hood.

Another important display parameter still under examination is the appropriate HUD image contrast with respect to the roadway. Several studies have addressed this issue, and it seems appropriate that the HUD image be between 15% and 50% as bright as

the roadway for daylight conditions, and about 300% as bright as the roadway during nighttime conditions. While these recommendations are fairly well established, they have been difficult to follow in certain situations. One such situation involves viewing the HUD against a background of sunlit snow. Sunlit snow is so bright that current HUD technology has not produced a HUD image that is bright enough to be seen against such a background. Because of problems of this type, it has been difficult for designers to achieve optimal HUD image contrast with respect to the roadway, and stricter contrast levels may be set when it is possible to produce brighter HUD images.

The second section of the review, which is dedicated to the description of HUD hardware and available HUD systems, illustrates that most of the technology necessary to produce acceptable HUD systems is already available. This section is primarily intended to chart the evolution of HUD technology, as well as to illustrate the role that human-factors work on HUDs can play in providing further direction to the engineering of HUD hardware and systems. It is currently possible to produce a HUD that is inexpensive and meets all of the established display criteria, except for the problem of producing a HUD image that is bright enough to be seen against very bright backgrounds. Further work will need to focus on designing systems that allow for higher HUD image contrast with respect to bright backgrounds.

Popular perceptions of automotive HUDs are summarized in the third section of this review. People believe that automotive HUDs could be beneficial for performing the driving task, but they may require some experience with them before being comfortable enough to want them in their own automobiles. Because peoples' comfort with automotive HUD technology is an important influence on HUD design, and few surveys of peoples' attitudes towards HUDs have been conducted, it seems necessary for future work to focus on their opinions towards more specific aspects of HUD technology. These surveys could ease the transition to automotive HUD technology by allowing for the design of HUDs over which people could feel a sense of mastery.

Human performance with automotive HUDs is discussed in the final section of this review. The majority of human performance assessments of HUDs have investigated the effects of displaying speedometer information with a HUD. A common finding has been that people can monitor and extract information from a HUD speedometer more rapidly and frequently than they can from a conventional head-down display (HDD) speedometer. While HUDs afford quicker access to speedometer information, they do not have a significant effect on speeding behavior. People using HUD speedometers have been found to make speed violations as frequently as people using HDD speedometers. The most significant benefit that HUD speedometers have demonstrated over HDD speedometers is that people using HUD speedometers have been shown to have quicker and more accurate reactions to roadway obstacles than people using HDD speedometers.

Because displaying information at a head-up location seems to foster improved environmental monitoring, but does not necessarily save any of the effort expended in order to monitor the information displayed, the safety benefit of HUDs might lie in increasing awareness of the roadway environment, rather than in reducing monitoring effort. Thus, it is reasonable to consider the possibility that HUDs could be used to display information other than speed and still demonstrate their safety benefits. Some possibilities include displaying navigation information, cellular phone status, or cassette deck status with a HUD so that people could monitor these types of information without looking down from the roadway for long periods of time. These possibilities are likely to become the focus of HUD research in the near future, as there has been little discussion about what should be displayed with a HUD, and such discussion will ultimately be necessary in order to decide how best to utilize HUD technology for improving driver safety and information access.

CONTENTS

INTRODUCTION

The concept of pilots using an out-of-the-window display of information was suggested in the technical literature at least as early as 1946, when Lt. Col. Paul Fitts noted that, "It has been proposed ... to throw the image of certain instruments onto the wind screen so that they might be viewed while looking out of the plane" (Fitts, 1946, p. 272). HUDs moved from this early theoretical conception to become actual display devices shortly after this recommendation was made. The first HUD-equipped aircraft, the Hawker-Siddeley Buccaneer, was flown in 1960 (Weintraub & Ensing, 1992).

Since then, advances in HUD technology have allowed the widespread use of HUDs in aircraft. There has been considerable progress with respect to aircraft applications of HUDs, and the HUDs that are now used in aircraft are quite sophisticated. The issues associated with aircraft HUDs have not all been solved, though, as even the most sophisticated of aircraft HUDs have yet to meet rigorous human-factors requirements. Weintraub and Ensing (1992), in their review of human-factors issues associated with HUD design, appraise the situation as somewhat precarious: "It would be reassuring if human-factors theory, data and answers to practical questions were catching up with display technology. In our view, although both are advancing, technology is advancing more rapidly, raising new questions faster than the human-factors community can generate answers" (p. 5).

The popularity of HUDs for aircraft has driven research on HUDs for automobiles. Although there are some similarities between the design parameters of aircraft and automotive HUDs, automotive HUDs need to be designed in accordance with the different demands that are placed on the driver. Kiefer (1991) suggested that because automotive HUDs differ from aircraft HUDs in several essential characteristics, data from studies on aircraft HUDs must not be applied uncritically to automotive HUDs. Because the visual environments for driving and flying are quite different, automotive applications place different demands on the display characteristics of HUDs.

Aircraft HUDs have been used in order to provide pilots with information about the location of their aircraft with respect to the environment through which they are flying. This information is often necessary for pilots to determine whether they are properly guiding their planes. Because the environment itself does not always provide reliable visual navigation cues to pilots, aircraft HUDs are designed primarily as sources of location information. Automotive HUDs need not provide information about driver location with respect to the road, though, because the driving environment usually is sufficiently information-rich for drivers to guide their vehicles through it without additional indications of location. Thus, automotive HUDs should display information either about the automobile's operations (e.g., speedometers, turn signals, or warning gauges) or about the extended environment (e.g., map displays) that is not already available to drivers. By using automotive HUDs to display information about the driving situation that is not already available to drivers, such as the internal operations of the automobile, or the characteristics of the external environment which the driver cannot see, it may be possible to improve the safety of the driving task.

HUDs have been installed in aircraft at a cost of about $100,000 per unit, but with some alterations they can be produced at $100 per unit for automotive applications (Enderby & Wood, 1992). This cost reduction is mostly attributable to the reduced field of view necessary for automotive HUDs (from 20° by 30° for aircraft to 1.5° by 3° for automotive HUDs) and the image source used, which is a vacuum fluorescent tube display (VFD) in automobiles as opposed to a cathode ray tube (CRT) in aircraft. Another cost reduction can be realized by using the windshield glass as the final projection surface (combiner) in an automotive HUD. The image combiners in aircraft HUDs are expensive because of the requirement that they project the HUD images at optical infinity. This constraint need not be applied to automotive HUDs. Many researchers have recommended that automotive HUDs project virtual images at a distance between 2.0 and 2.5 m from the driver's eyes (Inzuka, Osumi, & Shinkai, 1991; Kato, Ito, Shima, Imaizumi, & Shibata, 1992; and Weihrauch, Meloeny, & Goesch, 1989), a more easily satisfied requirement in terms of equipment costs.

Because automotive HUDs can be much cheaper than aircraft HUDs and because they should present different types of information (operating characteristics of the automobile or information about the extended external environment), designers of automotive HUDs face different problems and different options. Although the technology used to design aircraft HUDs has been easily applied in the design of the physical structure of automotive HUDs, some of the human-factors issues associated with automotive HUDs have not been adequately addressed. Because the technology is readily available for automotive companies to start producing HUD-equipped automobiles, the apprehension that Weintraub and Ensing (1992) voiced about human-factors research lagging behind engineering research for aircraft HUDs also seems justified with respect to automotive HUDs.

This review addresses the state of our current knowledge about human-factors issues that are critical for the best implementation of automotive HUDs. It is organized into four topical sections followed by an integrative conclusion:

1. **Human Factors Issues in HUD Design** - A description of the hardware of which a HUD is composed and the display parameters established for automotive HUDs. This section is divided into two subsections.
    - An overview of how an automotive HUD image is produced and displayed in a form that the driver can monitor along with the roadway.
    - A summary and critique of the empirical work conducted to optimize the display parameters of HUDs, including where the image should be displayed (in-plane location, and virtual-image distance from the driver's eyes), contrast issues (brightness, display color, and windshield transmittance), and legibility issues (character size, stroke width, and display-pattern complexity). It includes assessments of the degree to which researchers agree or disagree on certain parameter values, as well as recommendations for future work on display parameters.

2. **Descriptions of Available HUDs** - A discussion of several of the already available automotive HUDs, illustrating the state of available HUD technology.

3. **Popular Perceptions of Automotive HUDs** - A discussion of and commentary on popular media coverage of HUDs. The contrasting comments of people who have and have not used HUDs are included in this section. Their appraisals and concerns with respect to automotive HUDs are described and recommendations for improving HUD design are offered.

4. **Human Performance with Automotive HUDs** - The fourth section treats two types of human performance assessments of automotive HUDs:
    - Experiments that have compared human performance while drivers were using either head-up display speedometers, or head-down display (HDD) speedometers. These experiments have employed a variety of methods. Implications of each of the methods are discussed, including critiques of the generalizability of each study. A more general critique of the benefits of displaying automobile speed with HUDs is also included in this analysis, in order to assess the justification for installing HUD speedometers in vehicles.
    - Assessments of the desirability of displaying information other than speed with HUDs. Work on navigation HUDs is summarized, as well as the justifications for displaying navigation information in a HUD format.

Issues of display complexity are raised with respect to navigation HUDs, including whether HUDs are likely to capture drivers' attention and thereby degrade driving performance. It is here that the basic question, "Why should we install HUDs in automobiles?" is addressed.

5. **General Discussion and Conclusions** - The concluding section is an attempt to tie all of the findings together, illustrating the progress that has occurred in the engineering of automotive HUDs and the extent to which human-factors research has lagged behind engineering accomplishments. It includes an assessment of the current state of automotive HUDs, the directions that research on HUDs needs to take in order to prepare for the possibility of their widespread introduction into the automotive market, and whether automotive HUDs hold promise for facilitating driver performance and safety.

HUMAN FACTORS ISSUES IN HUD DESIGN

What is a HUD? How does it work?

The defining characteristic of an automotive HUD is that it can be monitored simultaneously with the roadway. Thus, traditional instruments could properly be called HUDs when they are mounted very high on instrument panels, or perhaps on hoods. However, the common understanding is that HUD refers to a display produced by special optics that superimpose a translucent image on the driver's view of the environment. An automotive HUD projects a virtual image on a windshield, which is usually specially treated, or on a combiner. This virtual image is often projected such that it appears near the center of the driver's visual field, approximately at the end of the automobile's hood. The image is usually fairly small, covering only a few degrees of the driver's visual field. Automotive HUDs are used to display a variety of information to drivers, typically speedometer and warning-light information. They could, however, be used to display any type of information that might facilitate better driving.

The actual components of an automotive HUD can vary a great deal, but all HUDs contain three essential elements: (1) an image source, (2) a system of lenses and mirrors that reflect, refract, focus, and magnify the HUD image, and (3) a combiner surface.

The image source is the component of a HUD that produces the initial pattern of light energy that will eventually be viewed by the driver. A variety of image sources have been proposed, and will be discussed in this review.

The reflective and refractive systems serve to transfer the HUD image from its source to the combiner. These systems vary based on the overall design of the HUD. Because the human-factors issues associated with reflective and refractive systems are seldom discussed by the designers of HUDs, they will not be discussed in this review.

Combiners, the third basic component of a HUD system, serve as a final surface onto which the HUD image will be projected. The windshield of an automobile is typically used as the combiner, and it is often treated in some manner in order to allow for high image contrast and clarity for the area in which the HUD image is projected. As the optical element that will be viewed directly by the driver, combiners are selected so that they serve the function of setting the distance of the HUD virtual image. The distance is often set so that the driver will see the HUD image at or near the end of the hood of the automobile.

In order to design a HUD that will be functional in the wide variety of situations that a driver might encounter, the desired display parameters of that HUD must be known. The issues associated with display parameters are discussed in the following three sections. The first section addresses the question of the optimal location of the HUD image, the second section is dedicated to contrast issues, HUD image brightness and color, and combiner treatment processes. The third section focuses on legibility and treats issues associated with character size, stroke width, and display pattern complexity.

Optimal HUD location

One of the most important display issues associated with HUDs is the appropriate location of these displays with respect to the driver's eye fixations. Because location is one of the defining features of HUDs, it is important to determine whether displaying information in a head-up location will allow better performance than if the same information were displayed in a head-down location. In addition to answering the question of whether any performance benefits could be expected with a HUD versus a HDD, it is also important to decide where the HUD would be optimally located if it did demonstrate such benefits.

A few recurring methodological issues are best discussed before turning to specific empirical studies. One of these issues arises from the frequent confounding of display location and display format in comparisons between HUDs and conventional panel HDDs. While both HUDs and HDDs may display information in an analog or digital format, HUDs typically use a digital format. Thus, in empirical tests of HUDs versus HDDs, it is important to consider whether display format may play a role in producing any observed performance differences.

Even when the HUDs and HDDs display information in the same format, it is possible that the processes used to extract information from them differ. Design conventions so far have dictated that HUDs be projected against a dynamic background and HDDs against a static background. In order to assess whether any differences in performance with HUDs and HDDs are attributable to display location, it is necessary to control for possible effects of background types on people's performance. Fortunately, most of the research reviewed here meets this constraint, such that the HUDs and HDDs were both viewed against either a static or a dynamic background. Studies in which the effects of background and location are confounded (i.e., HDD presented against a static background compared with a HUD presented against a dynamic background) should be considered with a greater degree of caution.

Many studies of optimal HUD location have used subjective evaluations. Special care should be taken in evaluating the methods applied in these studies. Although these studies may help assess the attitudes of potential users about HUD location, the full range of factors that may affect participants' responses should be considered. Surveys have shown that laypeople hold significant prejudices with respect to HUDs and other new automotive technologies that are likely to affect their initial interactions with HUDs (Brand, 1990; Johnson, 1990; and Siuru, 1990). These prejudices will be discussed in greater detail in the section of this review titled, "Popular Perceptions of Automotive HUDs."

The empirical work that follows has been divided into two sections. The first section includes studies that have relied upon subjective data in order to assess appropriate HUD location. It is organized chronologically, and this organization incidentally reflects the evolving complexity of methods used. The second section treats performance-based assessments of HUD location, and it is also organized chronologically. Both sections are summarized in Table 1, which compares the relative merits of the various methods used.

Assessments including a subjective component

Weihrauch, Meloeny, & Goesch (1989)

This group assessed the optimal location of a head-up display as a part of research that they conducted in order to design the 1988 Cutlass Supreme HUDs. They selected the optimal location of the HUD by assessing driver preferences, although they do not describe how they made these assessments. They came to the conclusion that the image should be approximately 8° below the normal line of sight, centered directly in front of the driver in azimuth, and at an optical distance of at least 2.4 m in front of the driver's eyes.

Okabayashi, Sakata, Furukawa, & Hatada (1989)

Okabayashi, Sakata, Furukawa, & Hatada (1989) also assessed the optimal display parameters for an automotive head-up display using only subjective measures. They determined the optimal display position in the windshield plane using a rudimentary method that would later be refined by Inzuka, Osumi, and Shinkai (1991) and Kato, Ito, Shima, Imaizumi, and Shibata (1992). They asked people to give subjective ratings of both visibility and annoyance on a five-point scale. They then set critical levels on each measure that had to be met in order for a given location to be considered acceptable. However, because they did not describe their method very well, it is difficult to interpret their findings.

Inzuka, Osumi, & Shinkai (1991)

Inzuka, Osumi, & Shinkai (1991) also investigated the best location of an automotive HUD. They decided on the optimal location by using both objective and subjective measures. By determining the eye-fixation distributions for drivers in different contexts and assessing the regions in which a HUD would annoy drivers, they were able to decide upon an appropriate area in which a HUD could be displayed.

They measured the eye-fixation distribution by using an eye-mark camera and a videotape recorder to record driver eye movements on a busy, straight, urban road and on an expressway. They found that 90% of the eye fixations for the urban road condition fell within a region that ran from 6° above the drivers' normal line of sight to 5° below it, as well as from 12° to the left to 11° to the right of the normal line of sight. For the expressway condition, the area covered during 90% of eye fixations was significantly smaller, running from 4° above the normal line of sight to 4° below it, and from 11° to the left to 5° to the right of the normal line of sight.

The annoyance of the display was assessed in a laboratory. A simulated HUD speedometer was projected on a viewing screen along with a target that was intended to simulate a common roadway object. The distance and orientation of the simulated HUD with respect to the target was varied systematically. The position of the target within the participants' field of view was approximately where roadway objects might be located in an actual driving situation, in order to simulate the annoyance different HUD locations could cause in an actual driving situation. The subjective annoyance experienced was assessed over several locations with respect to the target, and the region within which annoyance ratings exceeded a criterion of distraction was determined. This annoyance region took the form of a heptagon, and this heptagon covered a fairly large portion of the previously mapped 90% distribution of eye fixations.

After the annoyance region was subtracted from the 90% distribution of eye fixations, there were only a few acceptable locations left, from which the investigators selected a range of locations that they judged to be optimal. This range was chosen so that the HUD could be viewed together with the road surface, and spanned from 6°-10° below the normal line of sight and from 8° to the left to 5° to the right of the normal line of sight.

The recommendations of Inzuka et al. (1991) should also be considered tentative because the annoyance assessment that they performed did not simulate viewing a HUD against a dynamic background. It is possible that doing so would reduce the annoyance effects for many of the positions that fell within their annoyance region. Because the experimental participants had little experience with HUDs, their high annoyance ratings could be attributable to their initial prejudices about the HUD technology. Actual experience with the automotive HUD in a realistic driving context might yield quite different annoyance regions. This issue deserves further investigation, but at this point in the understanding of human performance issues associated with HUDs, it seems appropriate to remain wary of subjective measures as diagnostic criteria for HUD parameter specification.

Kato, Ito, Shima, Imaizumi, and Shibata (1992)

Kato, Ito, Shima, Imaizumi, and Shibata (1992) conducted a study using the same method as Inzuka et al. (1991). They also determined the distribution of eye movements during normal driving using visual recording equipment, determined an area of subjective annoyance, and determined an appropriate range of possible HUD locations. Based on this range and some functional constraints, they suggested that the HUD image be located 8.4° to the right of the normal line of sight (drivers are seated on the right side of the vehicle in Japanese automobiles), as well as 6.7° downward from the normal line of sight of the driver.

The findings of Kato et al. (1992) are subject to the same criticisms as Inzuka et al. (1991). The participants in their study were no more informed than those in the study performed by Inzuka et al. (1991). Nonetheless, the work that both groups of researchers conducted represents the state of the art in the use of subjective measures to determine an appropriate HUD location. Significant improvements need to be made in the training of annoyance evaluators (experimental participants) before subjective assessments will prove to be a useful source of data. Because people's evaluations may be biased by the influences of prejudice on their initial interactions with HUD technology, their comfort with HUDs should be assessed after they have already had some experience using them.

Performance-based assessments

Sakata, Okabayashi, Fukano, Hirose, & Ozono (1988)

Sakata, Okabayashi, Fukano, Hirose, & Ozono (1988) conducted a series of studies that would later be replicated in greater detail by Okabayashi, Sakata, Furukawa, and Hatada (1989). These studies were conducted using a dual-task method (see Okabayashi et al. (1989) for a description of this method) in which participants monitored both a HUD and objects in the forward field of vision for a short time period, ranging from 0.3 to 0.5 s.

They assessed the optimal HUD location using this method, and found that people were best able to recognize the information in the HUD while accurately monitoring objects in their forward field of vision when the HUD was displayed between 0° and 10° from the "central horizon of sight" (which was defined as the mean vertical position at which the eyes would be fixated during a driving task).

Okabayashi, Sakata, Furukawa, and Hatada (1989)

Okabayashi, Sakata, Furukawa, and Hatada (1989) also made performance-based assessments of several display parameters, including display location and the effect of the optical distance of the HUD image on its legibility. They compared their HUD, which was displayed 10° to the left and 8° down from the normal line of sight, with a head-down display (HDD), which was displayed 20° below the normal line of sight.

The investigators used a dual-task method in which the participants performed a Landolt ring task and random-number identification task for each type of display. The two-digit random numbers were displayed at two different locations, one head-up location very close to, but not overlapping the Landolt rings, and one head-down location which was relatively further from the Landolt rings. The Landolt rings and the random numbers were simultaneously displayed on the same screen and participants were told to monitor both the Landolt rings and the random numbers. Participants who viewed the random numbers at the HUD location demonstrated better digit identification performance as well as fewer errors on the Landolt ring task than the participants who viewed them at the HDD location. These results were interpreted by the authors as evidence of the relative superiority of the HUD display legibility and visibility.

Okabayashi and colleagues subsequently measured recognition time for the information displayed in HUDs versus HDDs. By using visual recording equipment in a real driving situation, they found that fixation times were 20-40% shorter on average for people using a HUD that met their previous specifications (10° left and 8° down from the normal line of sight) than for people using a conventional display panel HDD. This fixation time advantage varied with the type of road upon which people were tested. The HUD advantage was greater on straight roads than on curved roads, and greater at higher speeds than at lower speeds.

The investigators hypothesized that the lower fixation times for the HUD were attributable to the fact that the HUD was closer to the distribution of eye fixations made while driving, thus reducing the size of the required eye movements. They also explained the interactions of display type with road curvature and speed in terms of this hypothesis. The larger HUD advantage for straighter roads and higher speeds was attributed to drivers shifting their fixations closer to the horizon at higher speeds and on straight roads. Such a shift causes the eyes to be positioned closer to the HUD than to the HDD.

In a critique of Okabayashi et al. (1989), Weintraub and Ensing (1992) questioned the validity of the argument that the smaller eye movements required with a HUD lead to improved performance over a HDD. They also questioned the data because participants showed high error rates for both types of displays, and because there was no control for the different characteristics of the two display types. At the degrees of eccentricity that Okabayashi and colleagues tested in their study, they argue that increasing the amount of eye movement required to shift between displays will undoubtedly result in longer eye movement times, but that eye movement times should not be used alone as an index of performance. Weintraub and Ensing (1992) claim that the time it takes to shift visual attention from one location to another is a more appropriate index of performance, because visual attention shift times are composed of eye movement times as well as cognitive components.

Okabayashi, Sakata, Furukawa, & Hatada (1990)

Following their 1989 work, Okabayashi, Sakata, Furukawa, and Hatada (1990) performed an on-the-road study, also aimed at determining the optimal location for a HUD. As a part of this latter study, they assessed drivers' forward fields of view by monitoring their eye movements under city driving conditions for speeds ranging from 10 km/hour to 50 km/hour. They then examined the distribution of eye fixations in order to determine the size of the areas containing 70% and 95% of fixations. Seventy percent of the drivers' eye fixations fell within a 4° radius of their normal line of sight and 95% of their eye fixations were within a 15° radius of their normal line of sight. Based on these results, they defined a, "field of forward view," as falling within a 15° radius of the normal line of sight. This conclusion seems well justified, as the urban conditions under which drivers were tested probably required what might be deemed an upper limit in the spread of eye movements.

The 1990 study also included measurement of the fixation periods of drivers during a normal driving task. Seventy percent of the fixation durations fell between 0.2 and 0.6 s. Based on these data and some prior sources of information, they determined that 0.5 s could serve as a maximum estimate (it is probably too high) of the average length of fixations made while driving.

After collecting this information on eye fixations, they conducted an experiment in which participants simultaneously monitored HUD images and objects in a simulated driving environment. Participants were to identify Snellen figures (capital Es of varying orientations) as a simulated environmental monitoring task, and to read a HUD that displayed two-digit numbers. The Snellen figures were projected on a screen that was located 5 m from the participants' eyes. These figures appeared at one of nine random locations between 15° to the right and 15° to the left of the participants' normal line of sight. The HUD images were randomly generated, two-digit numbers, and they were displayed at locations that ranged from 0° to 20° below the normal line of sight.

The procedure was as follows: the participants fixated on a letter "N" located at a position intersected by the normal line of sight while both the Snellen figure and the HUD images were presented for 0.5 s. The participants then reported the orientation of the Snellen figure as well as the random numbers that were displayed. Results showed a linear relationship between the angular separation of the HUD image from the normal line of sight and percent correct, with participants demonstrating increasingly better performance as the HUD image appeared closer to the normal line of sight.

In a second laboratory experiment that employed essentially the same dual-task method, the investigators tested recognition accuracy for two different HUD locations in order to determine which of these locations resulted in better performance. One of the display locations was intersected by the normal line of sight and the other was 7° down and 11° to the right of the normal line of sight, the display location of a HUD that was installed in the Nissan Silvia. The Nissan Silvia was a Japanese vehicle in which the driver was seated on the right. The investigators noted two important effects. One was that performance was much better when the HUD images were displayed closer to the normal line of sight, and the second was that performance was better when the HUD images were displayed at points nearest to the environmental objects. Based on these findings, they concluded that HUDs should be displayed as close to the normal line of sight as possible in order to facilitate environmental monitoring. This conclusion is a bit questionable, though, as the environmental monitoring task (identifying Snellen figures) was highly artificial. It seems appropriate to test whether HUDs are best displayed close to the normal line of sight when the environment is an actual driving scene. It is possible that an actual driving scene might be so complex that the HUD image would better be displayed at a greater angular separation from the normal line of sight. This is something that should be pursued in future research.

Table 1 summarizes methods, recommended HUD locations, and some critical comments for the studies that bear on optimal location of automotive HUDs.

Table 1 - Summaries of Studies Relevant to HUD Location

Study	Method	Recommended location of HUD image	Criticism - Benefits and Drawbacks
Weihrauch, Meloeny, and Goesch (1989)	Assessment of driver subjective preferences for HUD location.	8° down from the normal line of sight.	While subjective assessments address the interface between drivers and a HUD, this completely subjective assessment is probably artificial and subject to driver prejudices towards new technology.
Okabayashi, Sakata, Furukawa, and Hatada (1989)	Subjective assessment of HUD visibility and annoyance caused by HUD in several locations. Range of acceptable HUD positions was determined by subtracting out annoyance region from the visibility region.	Recommendation was cryptic. While an optimal HUD location is recommended by the authors, the value they report is not explained well enough to use.	This method allows for more informative subjective assessments of HUD performance, as the optimal HUD location is determined with respect to both subjective visibility and annoyance. However, this improvement does not address the issues associated with using only subjective measures to determine an optimal HUD location.
Inzuka, Osumi, and Shinkai (1991)	Measured visibility through an objective performance assessment, and annoyance through a subjective measure. Optimal HUD location was defined as the region that was visible, yet not rated as annoying.	The region of appropriate display locations was defined as 6° - 10° below the normal line of sight, and between 5° to the left and 8° to the right of the normal line of sight.	This is an interesting approach, as it assesses the optimal HUD location with respect to an objective measure of visibility and a subjective measure of annoyance. This study represents an improvement over the methods employed by Okabayashi et al. (1989), as it allows for convergent objective and subjective descriptions of optimal HUD location.
Kato, Ito, Shima, Imaizumi, and Shibata (1992)	Essentially the same methods as those employed by Inzuka et al. (1991).	6.7° below and 8.4° to the left of the normal line of sight.	This study is subject to the same criticism as the Inzuka et al. (1991) study. It does not represent any methodological improvement over that study. The values suggested for the HUD location are based on the intersection between the optimal region for displaying a HUD and a range of locations that the authors deemed convenient.

Study	Method	Recommended location of HUD image	Criticism - Benefits and Drawbacks
Sakata, Okabayashi, Fukano, Hirose, and Ozono (1988)	Performance-based assessment of optimal HUD location. Dual-task monitoring of simulated HUD and simulated environmental figures.	Within 10° of the normal line of sight.	First objective assessment of optimal HUD locations. Simulates the parallel processes that occur when a driver uses a HUD and monitors the roadway. Method could be improved upon by using more realistic HUD or environmental stimuli.
Okabayashi, Sakata, Furukawa, and Hatada (1989) (Study 1)	Dual-task method, HUD and environment monitored simultaneously. Compared performance for two HUD positions, one at 10° left and 8° down from the normal line of sight, the other at 20° down from it.	Performance with HUD at 10° left and 8° down was better than at 20° down.	Assesses optimal HUD position in terms of performance, and serves to compare a possible HUD location with one that is more similar to the display location of HDDs.
Okabayashi et al. (1989) (Study 2)	Performance was assessed in the field with the two HUDs studied in Study 1. Visual task recording equipment was used to monitor eye movements.	The display at 10° left and 8° down took 20-40% less time to recognize than the display at 20° down. More benefit was found for the higher of the two display locations when driving on straight roads and at higher speeds.	Field study with high face validity. It represents a source of evidence for the relative superiority of HUDs over HDDs.
Okabayashi, Sakata, Furukawa, and Hatada (1990) (Study 1)	Laboratory study, dual-task method. Participants monitored both simulated environmental events (Snellen figures) and a simulated HUD. The simulated HUDs were located between 15° left and 15° right and between 0° and 20° down from the normal line of sight.	As close to the normal line of sight as possible. Recognition performance linearly increased as the HUD was displayed closer to the normal line of sight.	A good laboratory study because it assesses performance with HUDs in several different locations. The environmental stimuli could be improved, though, as Snellen figures are quite artificial representations of the environment. Using richer environmental stimuli would make this study more generalizable.
Okabayashi et al. (1990) (Study 2)	Similar to study 1, but using only two locations, one that was intersected by the normal line of sight, and the other at 11° right and 7° down from the normal line of sight.	HUD should appear as close to the normal line of sight and environmental stimuli as possible.	Same as Study 1. This study serves to demonstrate that a HUD located at a point intersected by the normal line of sight is easier to use than a HUD at the location selected for the Nissan Silvia.

By examining Table 1, we can see that some advances have been made with respect to the methods used to assess the optimal display location of a HUD, but that these methods could be further improved. Subjective assessments of the annoyance that a HUD would cause at different locations have been refined to a minor degree. An appropriate HUD location can now be determined by using convergent measures of eye fixation distributions and subjective annoyance. This represents a significant improvement over the purely subjective measures used by Weihrauch et al. (1989). Nonetheless, there are still some theoretical issues that need to be addressed with respect to the use of subjective measures in assessing optimal HUD location.

The methods used so far have not taken account of the strong effects that the novelty of a HUD could have on drivers' ratings of the annoyance caused by that HUD. It is reasonable to believe that drivers' initial appraisals of annoyance are manifestations of their reactions to the novelty of HUD technology, rather than an informed assessment of the annoyance or inconvenience that HUDs in varying locations might actually cause.

Several remedies are readily available to improve the validity of these subjective assessments. One of these remedies would be to permit people to practice the driving task (or a simulation thereof) while using a HUD on several occasions before asking for their appraisals of the annoyance that a HUD in differing locations would cause. This practice would allow participants to adapt to HUD technology and to overcome their initial prejudices with respect to HUDs, which would allow them to provide more informed ratings of annoyance.

Because a changing background might draw attention away from the HUD, viewing a HUD against a dynamic background, rather than the static backgrounds used in laboratory studies, could cause less of a sense of annoyance or distraction. Using an actual driving task (or a dynamic driving simulation) would address this issue and allow for more valid subjective assessments of annoyance.

The dual-task method used to assess optimal HUD location has a high degree of face validity, but it could be improved by changing the stimuli used in the simulated HUD and environmental monitoring tasks so as to better simulate actual driving. The HUD monitoring task could be improved by simulating a HUD that more closely approximates the display format of a HUD that might actually be installed in an automobile. So, rather than simply displaying random two-digit numbers as Okabayashi et al. (1990) did, more elaborate simulated HUDs could incorporate other forms of information, such as warning lights, headlight beam status, or turn signal indications. By using more elaborate simulated HUDs, future research could more closely approximate the attentional load that an actual HUD might cause.

Simulations of environmental information could be improved to reflect more accurately the complexity of the driving task. Although using Snellen figures and Landolt rings may allow for easily interpreted data, the visual processes required to identify Snellen figures or Landolt rings are likely to differ from those necessary to detect objects that might actually be seen while driving. In order to simulate better the processes involved in extracting information from an actual driving scene, it seems appropriate to use driving scenes or something analogous to them as stimuli for the environmental monitoring task. Under ideal circumstances, computer-generated images of driving scenes could be used as for the environmental monitoring task. These driving scenes could be controlled in such a manner that experimental participants would have to react to simulated hazards as an environmental monitoring task. While this level of simulation may not be readily available, future research should strive towards incorporating more realistic simulations of the driving environment when HUD display characteristics are established through assessments of peoples' performance.

HUD virtual image distance

In addition to determining the optimal location of a HUD with respect to the normal line of sight, it is also necessary to determine the appropriate virtual image distance at which to display it. There has been considerable agreement that the HUD image should appear at a distance of about 2.0 to 2.5 m away from the driver's eyes. A representative sample of research addressing the issue of HUD virtual image distance follows.

Okabayashi, Sakata, Furukawa, and Hatada (1989)

Okabayashi et al. (1989) addressed the effect of image distance on drivers' ability to extract information from a HUD. In a simulated driving task, they determined the optimal location of HUD images relative to a screen upon which roadway images were projected. The HUD image distances varied with respect to the screen, such that the HUD image would be projected at distances ranging from a point close to the driver's eyes (about 1 meter) to the screen distance. Over several sets of trials the screen distance was varied between 4.8 and 12.8 meters. For this range of roadway image distances, they found that participants made fewer monitoring errors as the HUD image was projected closer to the roadway images. Based on this result, they concluded that HUD images should be displayed as close as possible to the average focal distance assumed while driving.

Because they found that focal distance increases as a function of automobile velocity, and HUD images are optimally displayed at a driver's focal distance, Okabayashi et al. (1989) recommend that HUD virtual image distance increase along with driving speed. This recommendation has not been followed, though, as it is impractical in terms of HUD design, and because there is no appreciable benefit in performance for increasing HUD virtual image distances beyond 2.5 m (see the next study).

Inzuka, Osumi, and Shinkai (1991)

Inzuka et al. (1991) tested both younger and older people in order to determine whether image distance would affect the performance of older individuals. Since older individuals usually have a diminished capacity to accommodate, it was expected that they might benefit from the HUD image being located at a greater distance from their eyes.

As a part of a simulated driving task, the investigators required both older and younger participants to monitor a simulated HUD speedometer. They found that the performance of the older participants was facilitated as the HUD image was moved from 1 meter to 2.5 m away from their eyes, but that for distances greater than 2.5 m, there was not any significant improvement in the performance of older participants. Because increasing the HUD image distances beyond 2.5 m resulted in no performance benefits for older or younger drivers, this study recommended that HUD images be located at 2.5 m away from drivers' eyes.

Kato, Ito, Shima, Imaizumi, and Shibata (1992)

Kato et al. (1992) suggested that the HUD image be located 2.0 m away from the driver's eyes. They used the same method as Inzuka et al. (1991) and found that 2.0 m was the point at which increasing HUD image distance no longer resulted in performance benefits to older or younger drivers.

Based on the findings of Inzuka et al. (1991) and Kato et al. (1992), it seems reasonable to accept a HUD image distance of about 2.5 m from drivers' eyes. Displaying HUDs at this distance will optimize performance for drivers of all ages. Displaying HUD images 2.5 m away from drivers' eyes should also allow drivers to simultaneously monitor both the HUD and the roadway without the HUD ever appearing to be farther away than objects that might lie on the road ahead. Displaying the HUD at a shorter focal distance than any objects on the roadway will insure drivers that using a HUD will not cause them to collide with an object in the roadway simply because they are focusing at a greater distance than that object.

Contrast issues

Brightness/Luminance contrast ratio (LCR)

There is little consensus with respect to appropriate HUD brightness and contrast levels. Several authors have made recommendations for maximum HUD brightness or luminance contrast ratios [$(\text{luminance}_{HUD} + \text{luminance}_{environment}) / \text{luminance}_{environment}$], but there is little convergence in the methods employed in order to assess the optimal HUD brightness or luminance contrast ratios (LCRs).

Kato et al. (1992) recommend a maximum HUD luminance of 3000 cd/m^2, and they claim that a HUD would still be visible against a background of sunlit snow if its luminance was set at 3000 cd/m^2. Weihrauch et al. (1989) recommend that the LCR should range between 1.2/1.0 and 1.5/1.0. While these recommendations would be useful if they were elaborated upon more thoroughly by their authors, they are not particularly useful because they are unsubstantiated by empirical evidence.

Weintraub and Ensing (1992)

Weintraub and Ensing (1992) offered a thorough, yet concise treatment of HUD contrast issues. They recommended that HUD symbology be visible against a variety of backgrounds, and that the HUD should be discriminable when viewed against a background of sunlit snow, which has a luminance level of 34,000 cd/m^2. For acceptable visibility, they recommend a maximum daytime LCR of 1.5/1.0, and a minimum acceptable LCR of 1.15/1.0. With respect to the constraint that the HUD should be visible against a background of sunlit snow, the maximum HUD brightness necessary can be determined by the formula:

$$\text{MAXIMUM HUD BRIGHTNESS} = 34{,}000\ \text{CD/M}^2 * (\text{LCR} - 1.0).$$

For the minimum acceptable LCR of 1.15, this translates to a HUD brightness of 5100 cd/m^2, and for the preferred LCR of 1.5, this translates to HUD image brightness of 17,000 cd/m^2.

For the lower luminance backgrounds that will be encountered during nighttime, Weintraub and Ensing (1992) recommend that the HUD brightness be adjustable to much lower levels, as the luminance difference between the HUD and the roadway could cause it to be difficult to identify objects in the visual field. They recommend a LCR of about 4.0/1.0 for situations of low ambient illumination.

This recommendation is based on an aircraft HUD study conducted by Rogers, Spiker, and Cincinelli (1986). This study addressed the issue of appropriate HUD LCRs for pilots flying in low, moderate, and high ambient illumination conditions. They found that raising the LCR above 4.0/1.0 in conditions of low ambient illumination did not result in any facilitation of pilot performance. Since conditions of low ambient illumination should have about the same effect upon driving performance as they do upon flying performance, it is reasonable to extend these findings to night driving situations. Thus, the LCR of a HUD should be adjustable between the limits of 1.15/1.0 and 4.0/1.0 to accommodate for the range of conditions between high and low ambient illumination. While it would be reasonable to replicate the Rogers et al. (1986) experiment for automobiles, their range of LCRs should be adopted for the time being. Based on this recommendation, it seems reasonable to suggest that the operator of an automotive HUD have the capability to adjust HUD luminance level. This should be allowed in order to facilitate optimal performance for the wide range of environmental luminance levels that drivers will encounter while using their HUDs.

Display color(s)

There is a consensus that HUDs be green if only one color of display is to be used. Hasebe, Ohta, Nakagawa, Matsuhiro, Sawada, & Matsushita (1990) recommend a green with a dominant wavelength of 540 nm as the best display color for an automotive HUD. They recommend this color because they determined it to be most easily distinguishable from the variety of backgrounds against which the HUD image would be projected.

Hasebe et al. (1990) discuss multicolored HUDs, and note that red or yellow could serve as secondary colors for an automotive HUD in which green is being used as the primary display color. Although they recommend red and yellow as appropriate secondary colors of display, Hasebe et al. (1990) do not offer empirical evidence supporting the use of multicolored HUDs.

Weintraub and Ensing (1992) recommend that HUDs remain monochromatic, arguing that multicolored HUDs could cause significant distraction to drivers. The use of multiple colors of display for automotive HUDs is open to further research, but until evidence is offered demonstrating the relative superiority of multicolored HUDs, HUDs should remain monochromatic.

Combiner tinting & transmittance

HUD designers have attempted to moderate the effects of varying environmental luminance on HUD visibility by treating the combiner windshield. By altering the amount and type of light from the environment that reaches the driver's eyes, the perceptual salience of the HUD with respect to the environment can be controlled.

Weintraub and Ensing (1992) recommend that, "Combiner transmittance should be as high as possible" (p. 20). Sakata et al. (1988) are among the few groups of researchers who tested people's performance with HUDs that incorporated tinted combiners. They found that people were just as able to detect objects appearing in the forward field of vision for tinted combiners that had transmittance levels of 40% or greater, but that at lower levels of transmittance, detection performance suffered. This value seems rather low, though, considering that Weintraub and Ensing (1992) recommend that combiner transmittance be as high as possible. This issue should be settled by further empirical work.

Legibility issues

A third class of issues associated with HUD display parameters concerns HUD legibility. Little work has been done in order to establish appropriate legibility criteria for automotive HUDs, but this subsection will summarize what empirical work has been reported in the literature.

Character size

One legibility issue is the proper character size of automotive HUDs. A few studies have addressed this issue, including that by Inzuka et al. (1991). They found that people were best able to read HUD images that covered larger proportions of their visual fields when they were projected at shorter distances. They also found that people were best able to read HUD images that covered smaller proportions of their visual fields when they were projected at longer distances. Based on these findings, Inzuka et al. (1991) proposed that HUD image size and projection distance should be inversely related, such that HUD images appear larger at closer distances and smaller at further distances. After mapping the relationship between HUD image size and projection distance, they recommended that HUD characters located at their previously determined optimal image distance of 2.5 m should subtend a visual angle of 0.8°.

Kato et al. (1992) also assessed optimal character size, and the method that they used was the same as that described by Inzuka et al. (1991). They recommend a character size of 31 mm, which corresponds to a visual angle of 0.9° at the virtual image distance of 2.0 m. Based on the similarity of these recommendations, it seems reasonable to recommend that automotive HUD character size should range between 0.9° of visual angle for an image distance of 2.0 m and 0.8° of visual angle for an image distance of 2.5 m.

In addition to the recommendation that the major axis (height) of automotive HUD characters should subtend an angle of about 0.8° to 0.9°, Weintraub and Ensing (1992) recommend that character width be 75% of character height Although this recommendation was made with respect to aircraft HUDs, it should transfer to automotive HUDs. Thus, the width of automotive HUD characters should subtend about 0.6° of visual angle.

Virtual image distance, stroke width, and complexity

Another set of legibility issues are associated with the virtual image distance, stroke width, and display pattern complexity of automotive HUD images. These issues are necessarily related, and only one study has really addressed them in concert (Okabayashi et al., 1990).

The dual-task method they used has been previously described in the section covering the effects of HUD position on performance and will not be reiterated here. The stroke width of the HUD images was set at three different levels: 2', 5', and 13.2' of visual angle (the stroke width used in the Nissan Silvia). The viewing distance was also varied over a range from 0.8 to 5.0 m. They found that the correct response rates on an environmental monitoring task (Snellen figure identification) increased as a function of increasing stroke width, as well as a function of increasing viewing distance. The stroke width differences were significant at the shorter viewing distances, but were relatively unimportant as the viewing distance approached 5.0 m (which was the distance at which the Snellen figures were projected). They concluded from these results that if a HUD image is to be fine (stroke width = 2') then it should be located as close as possible to the location of the foreground objects upon which the driver is focusing.

Following their study of the effects of HUD image display fineness on environmental monitoring performance, Okabayashi et al. (1990) examined the interactions between display complexity, virtual image distance, and luminance contrast, and the effects of these interactions upon dual-task monitoring performance. They displayed Snellen figures side-by-side at a distance of 5.0 m from people's eyes for use in a simulated environmental monitoring task. They tested the effects of displaying a HUD image of varying complexity in front of the Snellen figures on people's ability to monitor both the Snellen figures and the HUD images. The HUD image consisted of a checkered pattern of pixels, some percentage (0-100%) of which would be illuminated in a random fashion at any given time. As the percentage of squares illuminated approached 50%

(from either the lower or upper bounds of 0% and 100%, respectively), the investigators considered the HUD image more complex. The luminance of this HUD image was adjusted so that the contrast between it and the Snellen figures would range between 1.15:1 and 1.63:1. The distance of the HUD image from participants' eyes was also varied over a range of 0.8 m to 5.0 m.

In the experiment, there was an LED located 15° to the upper left of the normal line of sight, and this LED was used as a fixation point for the participants. They were to look at the LED until it disappeared, after which they were to fixate on the two Snellen figures as quickly as possible. The Snellen figures would be visible for 1 s after the LED disappeared. This allowed participants an average of 0.5 s to react to the disappearance of the LED and to shift their focus to the Snellen figures, after which they could stare at the Snellen figures for approximately 0.5 s.

Both luminance contrast ratio and HUD complexity had significant effects on people's ability to correctly identify the Snellen figures. It was easiest for viewers to distinguish the Snellen figures when the LCR between the HUD and the Snellen figures was at its lowest (0% of the simulated HUD pixels were illuminated). As the LCR increased (more simulated HUD pixels were illuminated), it became increasingly difficult to distinguish the HUD from the Snellen figures. As the HUD images became more complex (the proportion of HUD pixels illuminated approached 50% from the lower limit of 0% and the upper limit of 100%), it also became more difficult for people to distinguish the Snellen figures. Because HUD complexity and LCR were both determined by the percentage of pixels illuminated, there were significant interactions between these two variables. HUD complexity was found to have stronger effects on performance than LCR, such that it was easiest for drivers to distinguish the Snellen figures when 0% of the pixels were illuminated (low complexity, low LCR), more difficult to distinguish them when 100% of the pixels were illuminated (low complexity, high LCR), and most difficult to distinguish them when 50% of the pixels were illuminated (high complexity, moderate LCR). Because of these findings, the investigators concluded that as the complexity of the HUD images increases, the LCRs of these images will need to be restricted to a lower range in order to allow for accurate environmental monitoring to be possible.

Okabayashi et al. (1990) claim that it is imperative that HUD images of high complexity should be displayed at LCRs of no greater than 1.2:1.0. They also noted that HUD image distance from the foreground appeared to have a significant effect on performance, with participants experiencing a slightly greater degree of difficulty identifying the Snellen figures when the HUD images were displayed closer to the Snellen figures.

In accordance with their earlier findings, though, they recommend that HUD images be displayed as close as possible to environmental images. In order to accommodate displaying HUD images at the same distance at which environmental images might appear, they recommend that the contrast range for the HUD image be further constrained, possibly with an LCR as low as 1.15:1.

Although these studies on display parameters are complex, we can still extract a few simple guidelines from them: If HUD images are to be complex, displayed close to the foreground, and fine-grained (of thinner stroke width), then the luminance contrast ratio needs to be carefully constrained to a lower range in order to facilitate acceptable environmental monitoring performance.

The series of studies performed by Okabayashi et al. (1990) leave some questions unanswered. One is whether an image composed of randomly illuminated pixels is an appropriate analog for a complex HUD image. It is arguable that the random HUD image may cause more distraction than a HUD image of equal luminance that is more easily coded and understood by its viewers. If there was a simple way in which HUD images could be interpreted, they might cause less distraction than the random images used by Okabayashi et al. (1990). But if the information in the organized HUD images is more complex, then they might require more processing capacity than the random images, and thus cause a greater level of distraction. While Okabayashi et al. (1990) offer a good approximation of the types of effects we might see with complex HUD images, it seems important to devote future research to examining the appropriate display parameters for images that might be used in actual HUD applications.

Table 2 summarizes the information that has been reviewed in this section. This table may be used to generate approximations of the optimal display parameters for an automotive HUD.

Table 2 - HUD Display Parameters

Display Parameter	Recommendations
Virtual image distance	Between 2.0 and 2.5 m from the driver's eyes.
Brightness/LCR	Weintraub and Ensing (1992) recommend a maximum LCR of 1.5/1.0 for daytime conditions, but posit that LCRs above 1.15/1.0 are acceptable for these conditions. For nighttime driving conditions, Weintraub and Ensing (1992) recommend that LCRs be close to 4.0/1.0. Okabayashi et al. (1990) recommend LCRs of no greater than 1.2/1.0 for HUD images of high complexity.
Display color	Hasebe et al. (1990) recommend a 540 nm dominant wavelength green as the primary color of display for HUDs. They also recommend that red and yellow be used as secondary colors of display if a multicolored HUD is desired. Weintraub and Ensing (1992) recommend that HUDs be monochromatic only, and that they should be green.
Windshield tinting and transmittance	Weintraub and Ensing (1992) recommend that windshield transmittance should be as high as possible and that the hues of the environment should be altered as little as possible by the combiner. Sakata et al. (1988) found that performance did not decrease as a function of windshield transmittance until transmittance levels dropped below 40%.
Character size	Inzuka et al. (1991) recommend that characters subtend a visual angle of 0.8° at a virtual image distance of 2.5 m. Kato et al. (1992) recommend that characters subtend a visual angle of 0.9° at a virtual image distance of 2.0 m. Weintraub and Ensing (1992) recommend that character width be 75% of character height.
Display fineness, stroke width, and display pattern complexity	Okabayashi et al. (1990) recommend that if HUD images are to be complex, displayed close to the foreground, and fine-grained (of thinner stroke width), then the LCR needs to be carefully controlled in order to facilitate acceptable performance.

DESCRIPTIONS OF AVAILABLE HUDS

Engineering innovations to HUD technology are being generated at a much faster rate than basic human-factors research on automotive HUDs. This has led to problems in the design of several HUD systems (Weihrauch, Meloeny, and Goesch, 1989; Nakagawa, Ohta, Hasebe, Akatsuka, Matsuhiro, and Sawada, 1989; Hasebe, Ohta, Nakagawa, Matsuhiro, Sawada, and Matsushita, 1990; Sugita and Suzuki, 1992). Although these HUDs were designed in accordance with the engineering innovations available at the time of their release, many human-factors considerations have been overlooked in their design.

While there is little reason to criticize the designers of HUDs, it is important to consider the implications of the disparity in advancement of human-factors and engineering technology used in HUD design. Whereas it is relatively simple to apply the technology used in aircraft HUDs to automotive HUDs, the human-factors issues associated with automotive HUDs are very different from those associated with aircraft HUDs. This has led to a precarious state of affairs, as the surface appeal of well-engineered automotive HUDs might overshadow possible human-factors design shortcomings of these HUDs. Because the engineering design of automotive HUDs is quite advanced, it is likely that many more HUDs will be released to the market in the next few years, even if the important human-factors issues with respect to them have not been addressed. In order to maximize their effectiveness, it is important that human performance with HUDs be better characterized in the near future.

Weihrauch, Meloeny, & Goesch (1989)

Weihrauch et al. (1989) describe one of the first production HUDs, which was introduced in the 1988 Oldsmobile Cutlass Supremes. This HUD was designed with a vacuum fluorescent display tube (VFD) as its image source, reflective optics (not described more specifically), and the standard production windshield as the combiner. This HUD produced a virtual image of a digital speedometer and selected warnings just above the hood line in the center of the driver's visual field, at approximately front bumper range. The 1988 Cutlass Supreme HUDs were equipped with an adjustment knob that would allow the driver to adjust the vertical position of the HUD image, a glare reduction device, and a HUD image brightness control.

The HUD image in these 1988 Cutlass Supremes covered a 1.5° vertical by a 3.0° horizontal section of the visual field and was projected at a distance of 2.4 m from the driver's eyes. The image was visible within 95% of the visual fixations made while driving.

In order to select an appropriate HUD combiner, the investigators determined the optimal transmission and reflectance qualities of automotive HUDs through laboratory studies. They decided that the transmission of the windshield must exceed 70% at normal incidence of light, and the reflectance of the windshield must be minimized in order to control the detrimental effects of veiling glare caused by environmental sources of illumination. They satisfied these criteria by using the production windshield as a combiner.

They assessed the necessary brightness of the HUD image for an acceptable level of contrast between the HUD and the environment. Based on their investigations, they set the maximum brightness level of their HUD at 1700 cd/m^2.

The investigators noted that a higher image brightness might be desired for conditions of high environmental luminance, such as sunlit snow, and they discussed some ways that image brightness could be increased in order to allow for HUD visibility under these conditions. Some possibilities that would not require changing the standard windshield combiner included using brighter or narrower spectral band image sources, and increasing the optical efficiency of the HUD's internal components. Other possibilities that would require altering the standard windshield included polarizing the combiner projection surface in order to increase HUD image visibility, treating the combiner to filter out undesired wavelengths of light, or increasing the overall reflectivity of the windshield in order to reduce the intensity of the light from the environment impinging upon the driver's eyes. They recommended that these possibilities be examined in future research.

Nakagawa, Ohta, Hasebe, Akatsuka, Matsuhiro, and Sawada (1989)

Nakagawa et al. (1989) introduced an LCD HUD. Their Double-layered Super-Twisted Nematic (D-STN) Liquid Crystal Display (LCD) HUD produces a black and white display with high contrast, and they deem it a promising solution among the several liquid-crystal-display modes. The contrast ratio of the LCD image source "on" units to "off" units is 100:1, and the operating temperature range extends from -20°C to 70°C. The D-STN LCD does not contain its own illumination source and must be illuminated by a backlight. The backlight that they used was a hot-cathode fluorescent tube, which allowed the luminance of the HUD image to be tuned between 40 cd/m^2 and 1,200 cd/m^2. They deemed this an acceptable range given the demand of maintaining a HUD luminance contrast ratio of about 1.3:1.0 for the large range of environmental illumination conditions that might be encountered while driving.

Hasebe, Ohta, Nakagawa, Matsuhiro, Sawada, and Matsushita (1990)

Hasebe, Ohta, Nakagawa, Matsuhiro, Sawada, and Matsushita (1990) designed an D-STN LCD HUD. Since LCDs are non-emissive devices for which the display color depends upon the color of the backlight that is illuminating the LCD, they were able to produce multicolored HUD images by using differently-colored backlights.

Hasebe et al. (1990) determined the most appropriate display colors to use in a multicolored HUD. By assessing the discriminability of a wide range of colors against a variety of backgrounds that might be encountered while driving, they found that green is the best color for a head-up display. If other colors are to be used, red and yellow would also be easily discriminable secondary colors. They used red as the only secondary color in their HUD because it works well for warnings. They did not test people's performance with multicolored HUDs, though, and multicolored HUDs are a display option that requires further investigation.

In addition to discussing multicolored HUDs, Hasebe et al. (1990) provide an overview of LCD technology in order to clarify the advantages of LCDs. They reviewed two available types of LCDs: simple matrix and active matrix LCDs. Because of cost concerns, they decided to use a simple matrix LCD in their designs. They note that simple matrix LCDs have limitations, though, as they offer a maximum of 200 scanning lines, which constrains the possible display size and complexity of the HUD images.

In addition to these problems with the simple matrix LCD HUDs, the investigators also discussed three other possible limitations of the HUD they designed. These limitations include viewing-angle-dependent contrast, temperature-dependent contrast, and temperature-dependent switching time. The first of these, viewing-angle-dependent contrast, was not deemed particularly problematic, and they determined that visibility would not be affected under normal usage conditions. The investigators thought that the temperature-dependent nature of the LCD could limit the acceptable applications of an LCD HUD, as temperature fluctuations were known to affect the contrast ratio between the on and off cells of the dot-matrix LCD. Because of this concern, the investigators tested their LCD HUD over a reasonable range of possible temperatures and found that the contrast ratio was never less than 10:1. Thus, they decided that temperature-dependent contrast was not a significant problem for their HUD.

The switching time was the only truly limiting aspect of their simple matrix LCD HUD. The switching time of their HUD ranged from 200 ms on average at room temperature to 1 s on average at temperatures below freezing. Because switching time affects the frequency at which the displayed information can be updated, the investigators were concerned about displaying time-regulated information with their HUD. Because some forms of hazard information need to be frequently updated, they decided that it may be inappropriate to use their HUD for displaying certain types of warnings to drivers. Other than these limitations, though, the D-STN LCD HUD that Hasebe et al. (1990) designed meets most of the requirements for a practical automotive HUD.

Sugita & Suzuki (1992)

One of the latest developments in the evolving technology of HUD projection systems is described by Sugita and Suzuki (1992). This system incorporates a volume hologram as one of the HUD's optical elements. Because of a surface treatment process, the hologram functions as a concave mirror for a specified range of wavelengths, but allows other wavelengths to pass through it. Thus, the treatment process allows most undesirable environmental illumination to be reflected away from drivers' eyes and eliminates distracting HUD ghost images.

The HUD they describe includes a holographic mirror, along with several elements common to previously described HUD designs. These common elements include a high brightness vacuum fluorescent display (VFD) as an image source, an aluminum concave mirror, and a windshield with a reflective coating that serves as the combiner. Their HUD system projects a virtual image that is located approximately 2 m in front of the driver, has a brightness range of 6 to 1200 cd/m^2, and is green in color.

With respect to other HUD systems, Sugita and Suzuki's system demonstrates several salient advantages. These advantages include its capacity to prevent infrared radiation from affecting the fluorescent segments of the VFD image source, as well as better contrast control than in conventional HUDs. While these are significant improvements, their HUD did not alleviate the problem of image washout under high environmental luminance conditions. This problem remains to be solved in future work.

Table 3 summarizes the four HUD systems discussed in this section. It may be used in order to gain a sense of the current state of HUD technology.

Table 3 - Available HUD Systems

Study	Type of HUD/ What it Displays	Image Source	Combiner Type	Special Features and Benefits	Possible Additional Adjustments
Weihrauch, Meloeny, and Goesch (1989)	1988 Oldsmobile Cutlass Supreme/ Digital speedometer and standard warnings.	VFD, 3000 ft*Lambert brightness limit, which allows a maximum image brightness of 1700 cd/m^2.	Standard production windshield.	Adjustable vertical position of HUD image, glare reduction device, image brightness control.	Use brighter or narrower spectral band image sources, polarize the combiner surface, spectrally selective combiner, improve overall windshield reflectivity.
Nakagawa, Ohta, Hasebe, Akatsuka, Matsuhiro, and Sawada (1989)	Dynamic Super-Twisted Nematic LCD HUD.	Backlight illuminated LCD with a high "on" to "off" unit contrast, operating temperature range from -20°C to 70°C. Display luminance adjustable between 40 cd/m^2 and 1,200 cd/m^2. Luminance contrast ratio > 1.3/1.0 for a wide range of environmental luminance conditions.	Combiner wasn't discussed in detail.	LCD technology, high image contrast.	Lower minimum operating temperature might be desirable for cold weather conditions.
Hasebe, Ohta, Nakagawa, Matsuhiro, Sawada, and Matsushita (1990)	Dot-matrix Dynamic Super-Twisted Nematic HUD (D-STN) with color capability.	Different colors of fluorescent backlights used to illuminate LCD. Primary color was green, secondary color of display was red. Simple matrix LCD with a scanning line limitation of 200 lines.	Treated standard windshield.	LCD technology, multicolored display.	Temperature-dependent switching time as long as 1 second at temperatures below freezing makes this inappropriate for the display of some time-regulated hazard information.
Sugita and Suzuki (1992)	HUD with a holographic optical element that acts as a concave image-focusing mirror.	High brightness VFD with an image brightness adjustable between 6 - 1,200 cd/m^2. Green in color.	Treated windshield that will reflect only certain frequencies of light.	Volume hologram as an optical element in combination with the special combiner eliminates ghost images and allows for excellent contrast control.	Image washout under high levels of environmental luminance is still a significant problem.

POPULAR PERCEPTIONS OF AUTOMOTIVE HUDS

Automotive head-up displays have been receiving an increasing amount of attention in automotive magazines and in surveys of driver attitudes towards new technology for automobiles. Because people's attitudes towards HUDs are fairly positive, it seems likely that they will soon be available as an optional feature in a wide variety of automobiles. In order to describe the status of popular perceptions of automotive HUDs, a survey of relevant publications follows. First, a summary of the treatment of HUDs in popular automotive magazines is given in order to describe the state of the HUD market. This is followed by a compilation of survey responses regarding people's attitudes about HUDs and their preferences for the design of HUDs.

State of the market

Kobe (1988)

Kobe (1988) focused on whether we really need HUDs in automobiles, whether HUDs were expected to enter the automotive market in the 1990s, and what he expected their reception to be. He expressed a good deal of enthusiasm for automotive HUDs and implied that they would soon be available in the automotive market. He mentioned that Oldsmobile and Nissan were already involved in HUD design programs and were in the process of releasing HUD-equipped automobiles at the time of this article's publication. He also noted that Ford was involved in research and development efforts at that time, but had no definite plans for releasing a HUD-equipped automobile.

Gosch (1989, 1990)

Gosch (1989, 1990) described the concept of a head-up display to an audience of car enthusiasts, and he offered a detailed account of a HUD that was installed in a VW. The VW HUD that he described displayed speed, distance traveled, oil level, water temperature, and a fuel gauge.

Plumb (1990)

Plumb (1990) dealt with the changing nature of automobile interior design. Although he showed enthusiasm for a variety of innovations, such as integrated controls and displays that are easier to use and personalized settings for the interior conditions of the vehicle, he spoke somewhat warily about HUDs. He voiced the concern that manufacturers need to avoid the over digitization of automobiles and that they should take care to not scare consumers away with unnecessary features. He reported that while consumers believed that HUDs could render performance and safety benefits, they would still not want HUDs in their vehicles. Because of this, Plumb doubted that HUD-equipped vehicles would sell successfully.

While this is a reasonable concern, Plumb may have ignored the possibility that people's opinions towards HUDs could change rather quickly. While it is reasonable for him to doubt that some people will ever have enough exposure to HUDs to change their opinions about them, it is possible that public opinions towards HUDs could change radically if a relatively small number of people bought HUD-equipped automobiles and openly praised the merits of HUDs. People's opinions could suddenly become quite positive, and this could drive a greater demand for automotive HUD technology.

Driver attitudes & preferences

Several studies of people's attitudes and opinions towards automotive HUDs have been conducted. The responses to these surveys shed a positive light on HUDs and survey trends suggest that the demand for HUDs might expand quickly once a critical mass of people have them in their automobiles.

Brand (1990)

Brand (1990) focused on driver attitudes about a variety of safety features and options for automobiles. The respondents were upscale automobile owners from Los Angeles and New York. They discussed automobile features in small discussion groups with interviewers (i.e., focus groups). Some of his major findings were that these people were not as concerned with new technologies ("bells and whistles") as they were with quality, cost, and comfort. People said that while they used new features at first, they would tire of them quickly and quit using them. People were also wary about relying upon the new features, which they saw as being likely to break down. Rather than having new features added into their automobiles, several people expressed an interest in the standardization of existing features across automobiles.

Brand's survey respondents who owned HUD-equipped automobiles expressed a general liking for them, although they preferred to use the HUDs at night rather than during the day. The people who had HUDs or would consider buying HUDs also said that they would like to have more control over their HUDs. People wanted to control the information displayed, the location of the HUD, and whether the HUD was on or off at any given time. These concerns were raised because people feared that HUDs could cause visual clutter that would distract them from monitoring the road ahead of them.

One particularly interesting finding was that people who had tried or desired navigation systems in their automobiles expressed an interest in having the navigation information displayed head-up. The respondents thought that looking at a map was a dangerous but necessary action that they already took while driving, and they wanted to be able to access navigation information without risking their safety. The option of displaying navigation information with a HUD will be discussed in a later portion of this review titled, "Navigation HUDs and other possible future directions for HUD research."

Siuru (1990)

In an article that puts a different twist on the issue of automotive HUDs, Siuru (1990) discusses the demands that senior-citizen drivers are placing upon Detroit auto makers to develop safety features that can help them avoid collisions. His article suggests ways in which HUD technology can be applied to meet the safety demands of the fastest-growing segment of the driving population, drivers over 65.

Older drivers have slower reaction times and more frequently experience visual deficits. HUDs could alleviate these problems by aiding senior citizens in their visual accommodation and reducing their reaction times to hazards. Siuru believes that it is harder for seniors to extract information from standard dashboard displays, because of the increased amount of time that it takes their eyes to accommodate from the roadway to the dashboard displays and to reaccommodate from the dashboard displays back to the roadway. Because of this, he thinks that HUDs could cause a reduction in reaction time by eliminating the need for senior citizens to look down at the dashboard panel displays. He also thinks that HUDs could aid older drivers by keeping their eyes focused at a location closer to where possible roadway hazards might be detectable, thus allowing more time during which older drivers could react to hazards.

Johnson (1990)

Although the articles by Brand (1990) and Siuru (1990) address many of people's concerns about HUDs, an important issue that they only touch upon is that of visual clutter. The initial reaction of most people to HUDs is that HUDs would make it difficult to monitor the roadway ahead because of the distraction that they would cause. While this issue has not been empirically addressed for automotive HUDs, there is evidence in the literature on aircraft HUDs that this sense of visual clutter is likely to dissipate as the result of experience with HUDs.

Johnson (1990) interviewed pilots about their experiences with aircraft HUDs. These pilots were interviewed over the course of several training sessions with aviation

HUDs and reported that while they initially thought that the HUDs would cause their visual environment to be cluttered, with practice the HUDs actually served to better organize their visual environment and made piloting easier.

It took the pilots several hours of training to experience increased comfort with HUDs, though, and it is important to be aware of such effects of experience when conducting research on automotive HUDs. Most studies of automotive HUDs have not allowed people much practice with the HUDs before they were tested. Thus, the complaints of distraction or visual clutter made by novices using automotive HUDs could be relatively unimportant. These experiences of discomfort could eventually dissipate as people gain experience with automotive HUDs.

In summary, although people believe that automotive HUDs could be beneficial for driving, they may require some experience with automotive HUDs before they will feel comfortable enough with them to want them in their own automobiles. Because people's comfort with automotive HUD technology is an important influence on future HUD design, more surveys of people's preconceptions of HUDs and their experiences with HUDs should be conducted. Such surveys could provide the information necessary to ease the transition to automotive HUD technology and allow for the design of automotive HUDs over which people could feel a sense of mastery.

HUMAN PERFORMANCE WITH AUTOMOTIVE HUDS

This section summarizes research on human performance with respect to HUDs in simulated or actual driving situations. This section addresses two key questions, "Why display information with a HUD rather than a HDD?" and, "What type(s) of information should be displayed with a HUD if a HUD is to be used?" Although most of the research that will be reviewed herein is concerned with whether HUD speedometers are superior to HDD speedometers, the issues associated with other possible applications of HUD technology are also discussed. Following is an assessment of human performance with HUD speedometers, then a survey of the issues associated with using HUDs to display navigation and other types of information.

HUD speedometer studies

Armour (1984)

Armour (1984) was one of the first to address the issue of whether HUD speedometers can be read faster than HDD speedometers. He studied differences in reading times for analog versus digital speedometers in head-up and dashboard-mounted locations. He had drivers perform what he deemed a normal driving task and timed their eye movements and fixations while they were observing the speedometers. The description of method was not very detailed, but Armour did report significant differences in the estimated speedometer reading times for the different types of speedometers. He found that for drivers, reading times were as follows:

HUD digital:	0.95 s
Dashboard mounted digital (25 mm characters):	1.04 s
Dashboard mounted digital (6.4 mm characters):	1.10 s
HUD analog (typical clock dial speedometer):	1.56 s
Dashboard mounted analog:	1.62 s

Based on these results, Armour concluded that the format (digital versus analog) of the display is more important than its location. The average effect of the display format was about 0.5 s, whereas the average effect of the display location was about 0.1 s. Because the benefits associated with HUDs in this situation were minor, Armour concluded that their usefulness remained questionable.

Although Armour's findings do provide some information about the efficacy of head-up displays, they do not disprove the possible worth of HUDs. Armour only monitored the ability of people to extract information from displays, not the effects of these displays on the ability of people to monitor events occurring in the environment. Because improving people's environmental monitoring performance is often the main reason for installing HUDs in automobiles and Armour did not assess this type of performance, his work leaves some important questions about the possible benefits of HUDs unanswered.

Briziarelli & Allan (1989)

Briziarelli and Allan (1989) examined the effectiveness of a HUD speedometer as a means of controlling drivers' speeding behavior. They tested drivers' speeding behavior on a highway and a residential road, and also during the transitions between these two types of roads. They determined whether the HUD affected speeding behavior on constant-speed roads, and whether it minimized the effects of speed adaptation during the transition from highway to residential driving conditions.

In order to investigate the effectiveness of the HUD speedometer in helping control speeding behavior of people, they found 40 people to volunteer for their study, 10 of which had received a speeding summons in the past two years. Each participant was randomly assigned to one of four treatment conditions: (1) using a conventional speedometer, (2) using a conventional speedometer and being speed-adapted on a stretch of highway before being tested, (3) using a HUD speedometer, and (4) using a HUD speedometer and being speed-adapted on a highway before being tested. They found no differences between any of the four groups. All four groups of participants sped while they were driving through the residential test area; they drove at an average rate of about 35 mph even when the posted limit was 25 mph.

Although the HUD speedometers did not seem to affect speeding behavior, 90% of those drivers using the HUD speedometers thought they were more aware of their speed than they would be with a HDD, and 70% of these drivers said that they were comfortable using the HUD speedometers.

Briziarelli and Allan offered several possible explanations for why the speedometer format did not affect speeding behavior. The HUD speedometer had an analog format, which could have made speed information less salient to drivers. Another possibility that they suggest is that the drivers did not have sufficient experience with HUDs to use them to help control their speeding behavior. Two factors unassociated with the method used which might explain drivers' speeding behavior are that the participants in the experiment might have simply been referencing their speed to traffic flow, which was moving at a rate higher than the posted limit, or that these drivers would speed no matter how aware they were of the fact that they were speeding.

Furthermore, Briziarelli and Allan may have explored the wrong range of driving speeds. People tend to speed more frequently in zones with lower posted speed limits, even if they are aware of their speed, simply because they believe that the posted limits are unreasonably low. Briziarelli and Allan might have found effects of HUD speedometers on behavior for roadways that had higher posted speed limits, say between 30 mph and 45 mph.

Kiefer (1991)

Kiefer (1991) discusses the problems associated with what he calls "speedometer use only" studies. These studies (Iino, Otsuka, and Suzuki, 1988; Rutley, 1975; Sakata, Okabayashi, Hirose, and Ozono, 1987; and Sakata, Okabayashi, Hirose, and Ozono, 1988) all assessed speedometer monitoring performance, but failed to control for the confounding effects of factors not essential to the definition of HUDs. He noted that the differences in performance for HUD speedometers versus HDD speedometers could be attributable to differences in speedometer format (analog versus digital) which were not kept constant for both types of displays. So, for example, studies which assessed differences between an analog HDD speedometer and a digital HUD speedometer do not necessarily tell us anything about the effects of display location.

Without a more complete assessment of driver performance in which the confounding effects of HUD format are controlled (i.e., digital versus analog format), it is not possible to conclude that the HUD speedometer is better than the HDD speedometer. Because of this, Kiefer suggests that driver behavior with digital HUD speedometers should be characterized through measures of glance frequency to the speedometer, total glance time to the speedometer, speed control, lanekeeping, and roadway event detection.

Kiefer (1991) mentions requirements that must be met in order for the results of a HUD speedometer study to be generalizable. One is that all laboratory results need to be validated under on-the-road driving conditions, using a variety of road types and incorporating unobtrusive observations of driver behavior. Another requirement is that tradeoffs in driver behavior should be considered when determining the relative composite benefit of HUD speedometers over HDD speedometers. This could be done by looking at multiple performance measures, such as mean speedometer fixation time and mean speed maintained. By determining the relative contribution of each of these behaviors to overall safety, the best display type could be selected.

In order to better assess the relative benefits of HUD and HDD speedometers, Kiefer (1991) measured spontaneous driver visual sampling behavior under realistic driving conditions. He assessed drivers' visual sampling behavior by measuring these factors: glance frequency, average visual sampling time to speedometer, and total visual sampling time to the speedometer over a set time interval. This was the first on-the-road study to measure both visual sampling behavior and speed control performance, and to assess concomitantly the effects of practice and driver age on performance with HUD and HDD speedometers.

Kiefer tested two groups of participants, one of which was an older group (mean age of 67.0 years), and one of which was a younger group (mean age of 20.8 years). Each participant was tested individually over the course of four 90-minute sessions during which he or she performed an actual driving task. The HUD speedometer image was positioned 2.4 m from the driver's eyes, 6° below the driver's normal line of sight. The HUD image was a simple digital readout of vehicle speed, and the numerals in this readout were 1° of visual angle high. The equipment used to monitor the driver's eyes incorporated two cameras and three VCRs. These were used to produce three videotapes of the events occurring during the experiment. The tapes recorded the driver's visual eye movements, the roadway, and a split image of both the driver and the roadway. The VCRs used to make the videotapes were equipped with synchronized timers and each videotape had a day/time indication that allowed for a frame-by-frame synchronization of the three recordings.

The experiment was conducted at Stony Creek Metropark (Detroit) during the low-traffic hours for that facility. Before driving, participants were familiarized with the test vehicle, including its display and control locations. They were allowed to adjust the seat and steering wheel positions in accordance with their preferences as part of their vehicle acclimation. The test route that they drove was 6 miles long and included both straight and curved sections. Participants were instructed to drive at a speed between 30 mph and 35 mph, so that they would not violate the posted speed limit of 35 mph for the course. Participants were not to converse with the experimenters during the time they were driving unless necessitated by an emergency or mandated by the instructions.

During each of the four different experimental sessions that participants were to complete, they drove around the Metropark course six times. On four of the six circuits, they were instructed to say the word "speed" whenever they glanced at the speedometer, and for the other two circuits they were not required to do this. This instruction was included to add an auditory indication of the visual behavior of participants.

The design for each experimental session was fairly simple. For the first three circuits, participants used one type of speedometer display (HUD or conventional HDD), and were instructed to say "speed" on the first and third circuits. After a short break, a similar set of three circuits was completed with the other speedometer display type. The order of display types was counterbalanced across sessions.

After the four experimental sessions were completed, participants in the study were asked to fill out a questionnaire regarding their speedometer usage and speed-keeping behavior based on past driving experience, and their overall opinions of and reactions to the HUD speedometer.

The design of the study allowed Kiefer (1991) to test the effects of speedometer location (HUD or HDD), practice, verbal condition (saying "speed" or maintaining silence), and age. Speedometer location, practice, and verbal condition were within-subjects factors, and age was a between-subjects factor. The primary dependent variable was the percentage of time spent in the speedometer scanning cycle (SSC). The SSC was defined as the sum of visual scanning time from the roadway to the speedometer, speedometer fixation time, and visual scanning from the speedometer to the roadway. Percentage of time in the SSC was simply defined as time in the SSC divided by total driving time. Because traffic was extremely light during the experiment, the few time intervals during which the drivers altered their behavior in response to another vehicle or a pedestrian were simply omitted from the analysis.

Kiefer (1991) found that several characteristics of the SSC were influenced by the independent variables he tested. First of all, he found that there was a strong effect of speedometer location on the mean time spent in the SSC. The mean time spent in the SSC was 925 ms for the conventional HDD speedometer, versus 781 ms for the HUD speedometer. There was also a significant practice effect on the number of glances to the speedometer independent of display type, with participants glancing at the speedometer an average of 6.6 times per minute during the first of the four sessions, and 3.9 times per minute during the last of the four sessions.

There were significant interactions between speedometer location and practice. Although the average time spent in the SSC was less for the HUD, people made, on average, more frequent glances at the HUD speedometer than at the HDD speedometer. This difference in glance frequency was especially evident in earlier trials, in which the novelty of the HUD seems to have caused people to pay a greater amount of attention to it. The relative difference between the glance frequencies to the HUD and HDD decreased as a function of practice. Thus, the percentages of time spent in the SSC while people were using either the HUD speedometer or the HDD speedometer approached comparable levels as a function of practice, with the percentage of time spent in the SSC being higher for the HUD speedometer conditions in the earlier sessions of the experiment.

Although older participants spent significantly longer on average than younger drivers in the SSC with both the HUD and HDD, there were no observed interaction effects between speedometer location and age. Since there was no such interaction, it was concluded that there was no extra benefit of a HUD speedometer to older drivers. This finding is somewhat contrary to what we might expect, as it is reasonable to believe that HUDs might benefit older drivers more than younger drivers because HUDs do not require the large accommodative shifts with which older drivers have difficulty.

The subjective questionnaire data showed that people had fairly favorable opinions toward the HUD speedometer after a reasonable amount of experience with it. Eighty-eight percent of the participants preferred the HUD speedometer to the HDD speedometer in general, everyone preferred the HUD speedometer over the HDD speedometer for monitoring vehicle speed, and seventy-five percent in each age group preferred the HUD over the HDD speedometer for simultaneous monitoring of vehicle speed and roadway events.

The results of Kiefer's study are interesting, but they do not lead to any simple conclusions about the efficacy of HUD speedometers. The study suggests that people have quicker access to speed information displayed head-up, but they do not save any time on the speed monitoring task by using a HUD, because a speedometer displayed head-up will cause them to monitor their speed more frequently. There might be some benefit to having more frequent access to speed information when it is displayed head-up. While drivers in this study did not save any time monitoring their speed, they might have been more aware of their speed with the HUD than with the HDD speedometer, which could render a safety benefit in certain situations.

A safety benefit was not evident in the measurement of speeding behavior conducted in this study, though, as drivers using the HUD speedometer drove over the speed limit about as much as those using the HDD speedometer. This is consistent with the findings of Briziarelli & Allan (1989), who also did not find an effect of HUDs on speeding behavior. Because of this, it seems that it may be more appropriate to focus research on displaying other types of information with HUDs. Although Kiefer's research did not produce strong evidence for the efficacy of HUD speedometers, it indicates that HUDs allow more frequent access to displayed information. That access might be more beneficial for other types of information than for speed.

It is also interesting to consider the implications of the fairly strong practice effects Kiefer (1991) found for the HUD. People seemed to be affected by the novelty of the HUD for the first few sessions of this study. Thus, differences between performance with HUDs and HDDs may not be properly assessed by single-session experimentation.

Sojourner & Antin (1990)

Sojourner and Antin (1990) studied the effects of HUD and HDD speedometers on three perceptual tasks associated with driving an automobile. They tested performance on speed monitoring, navigation, and salient-cue detection. They believed that using the HUD speedometer would not cause decrements in the performance of the navigation or the salient-cue detection tasks because it would not be so complex as to capture drivers' attention and distract them.

Sojourner and Antin designed a laboratory study in which they used videotaped scenes of a route through the northern portion of Durham, North Carolina, an environment with which none of the participants in their study had significant experience. The participants viewed two videotapes of the same route, a practice tape that allowed participants to memorize the specified route and a test tape. In addition to viewing the practice tape, participants were also allowed to look at a map of the route through which they would be navigating during the experiment.

The driving scenes were displayed on a 1.8 m (diagonal) Sony projection television that was located approximately 3 m from the participants. For the HUD, the digital speedometer was displayed in dark blue characters superimposed over the driving scenes displayed on the projection television, whereas the HDD digital speedometer was displayed on an Amiga monitor slightly below dashboard level.

The participants in this study were divided into two groups, those who were to use HUDs, and those who were to use HDDs. The differences between these groups were tested by assessing performance in a variety of tasks. These assessments included recording the number of times that participants failed to notice that the value displayed on the speedometer exceeded the speed limit by more than 5 mph, the number of navigation errors in the test tape that the participants failed to notice, and the number of salient cues (a child's green ball) to which they reacted too slowly. These salient cues appeared in one of three locations: on the right of the road, at the center of the road, or on the left side of the road.

Several results suggested that a HUD speedometer might aid performance of the driving task. Participants using the HUD speedometer noticed more speed violations than participants using the HDD. Navigation performance of both groups of participants was nearly flawless, so relevant comparisons between the displays with respect to navigation could not be made. Although the difference in salient cue detection was not statistically significant, there was a slight indication that the HUD provided some benefit. Participants using the HUD speedometer only missed 3 of the 90 salient cues that they were to detect, whereas participants using the HDD speedometer missed 9 of the 90. Participants using the HUD speedometer had significantly shorter reaction times to the salient cues than the participants using the HDD speedometer. There was also a significant effect of the location of the salient cue upon reaction time. All participants were quicker to react to the salient cue when it was presented in the center of the display, rather than on the left or right side. In addition to these differences, the participants using the HUD speedometer performed much better than the participants using the HDD speedometer in the speed monitoring task. No one using the HUD failed to detect a speed violation, whereas those people using the HDD failed to detect 7 out of 90 possible speed violations.

The largest effect that the simulated HUD digital speedometer had was a savings in reaction time to salient cues. An estimate of the average time saved by the HUD over the HDD was 440 ms. This difference can be attributed to the fact that the participants using the HUD did not have to spend time shifting their gaze or accommodating. This time savings translates to 9.2 meters at a speed of 75 km/hr or 12.2 meters at a speed of 100 km/hr.

The fact that the HUD resulted in improved reaction times to the salient cues suggests that the HUD speedometer did not cause drivers to be distracted from monitoring the roadway. This suggests that HUD speedometers may not cause what Weintraub and Ensing (1992) call, "cognitive capture." Cognitive capture, the inability to shift visual attention from the HUD to the roadway, might result because both of these sources of information are available within a relatively small and homogeneous portion of the visual field. Weintraub and Ensing hypothesized that HUD information could be quite distracting, and that it could cause people to neglect roadway hazards, thus compromising their safety. While HUD speedometers do not seem to compromise driver safety, HUDs that display more complex types of information will have to be tested in order to determine whether they result in cognitive capture effects.

Table 4 summarizes the relative merits and findings of the HUD speedometer performance studies just reviewed.

Table 4 - HUD Speedometer Studies

Study	Speedometer types compared	Methods employed	Authors' Recommendations and Conclusions	Possible Improvements / Future Research
Armour (1984)	HDD analog, HDD digital (character sizes of 6.4mm and 25mm), HUD analog, HUD digital.	Observed the time participants spent monitoring each of the speedometer types.	The average effect of display format (analog versus digital) was that digital displays reduced monitoring time by 0.5 s. Display type (HUD versus HDD) also had a significant effect, as the HUD reduced monitoring time by an average of 0.1 s.	This study only assessed speedometer monitoring. HUD benefits might not be manifested in speedometer monitoring, though. HUDs are more likely to benefit environmental monitoring performance.
Briziarelli and Allan (1989)	HDD versus HUD, both analog format.	Tested forty drivers with conventional and HUD speedometers under both speed-adapted and nonspeed-adapted conditions. Participants' speeding behavior was measured in a residential area.	All groups sped equal amounts, they drove 35 mph in a 25 mph zone. Lack of a speedometer location effect could be attributable to HUD analog format, or because the HUD was annoying or aversive. People could have sped intentionally because the posted limit was low and they were referencing their speed to traffic flow.	The same experiment could be repeated in a zone with higher posted speed limits. A digital format for the displays could be used rather than an analog format in order to assess whether the analog format of the HUD was too annoying.
Kiefer (1991)	HUD and HDD, both digital in format.	Videotapes of the driver's visual behavior and the roadway were made while the participants drove around a course. The tapes were used to determine the average speedometer scanning time and the percent of driving time spent scanning the speedometer.	HUD required 144 ms less scanning time per reading. Glances to the HUD were made more frequently, though, such that the same percentage of driving time was spent scanning the HUD speedometer. Age by display interactions were assessed but none were found. Percentage of driving time spent scanning the speedometer was initially higher for the HUD, but was equal with the HDD after multiple practice sessions.	Future research should address whether there are types of information that could be displayed by a HUD for which more frequent access might be desired. In such cases, HUDs might allow quicker information retrieval that HDDs. Otherwise it might be useful for future work to focus on how HUDs could allow quicker reactions to roadway events.
Sojourner and Antin (1990)	Simulated digital HDDs and HUDs.	Laboratory assessment. Participants viewed videotapes of a previously memorized test route and were told to monitor their speedometer (HDD or HUD), their navigation through the test route, and whether or not a salient cue (green ball) appeared in the roadway.	Participants using the HUD missed fewer speed violations and demonstrated quicker response times to the salient cues. Overall, the HUD saved participants 440 ms of reaction time to salient cues.	Future work should focus on replicating the performance benefits for HUDs found in this study, as well as determining whether HUDs could cause cognitive capture or other performance decrements.

The information in the preceding table allows us to draw some general conclusions about human performance with HUD speedometers. The foremost of these is that using a HUD rather than a HDD to display speedometer information will not lead to any decrements in speedometer reading performance, and can actually be expected to reduce the time necessary to read one's speed by about 100-150 ms (Armour, 1984; Kiefer, 1991). Although this is an appreciable benefit, it is unlikely that a HUD speedometer will actually reduce the proportion of driving time allocated to reading speed information (Kiefer, 1991). Therefore, it is reasonable to consider whether increased awareness of speed results in significant safety benefits for users of automotive HUDs, and whether there may be other justifications for using HUD technology.

Such a justification for automotive HUDs has been found with respect to environmental monitoring performance by Sojourner and Antin (1990). They found that participants in a laboratory simulation of driving with HUD and HDD speedometers had significantly faster reaction times to roadway obstacles (440 ms faster). The quicker reaction times demonstrated by participants in Sojourner and Antin's study serve as evidence that HUDs allow improved roadway monitoring, which would presumably lead to fewer accidents.

Future research should address the effects of displaying different types of information with a HUD, and whether displaying more complex information with a HUD (such as navigation information) would adversely affect environmental monitoring performance. Some of the pioneering work on complex HUD displays will be covered in the following section.

Navigation HUDs and other possible future directions for HUD research

The following section discusses how HUDs can be used to display information other than vehicle speed or simple warning signals. There has been relatively little work done in this area, but a few studies of navigation HUDs are reviewed herein, and other suggestions for information that could be displayed with a HUD are made.

Balke & Ullman (1992)

While there has been a good deal of research dedicated to navigation systems for automobiles in the past few years, the notion of displaying navigation information with a HUD is still relatively new. Balke and Ullman (1992), in a review of automated information systems for automobiles, characterized people's performance with dashboard-mounted navigation systems. Because the dashboard-mounted navigation systems required long glances away from the roadway, they suggested that HUDs might be an appropriate means for displaying navigation information.

The navigation systems that they examined were displayed at the same location as conventional HDDs. These systems made navigation information more readily accessible than it would be if drivers had to refer to common road maps, they allowed for the constant and continuous flow of information to drivers that would be difficult to achieve with conventional maps, and they allowed navigation information to be displayed in a flexible format. While dashboard-mounted navigation systems offered these notable advantages over common road maps, they were fairly expensive and were found to capture drivers' attention because the information that they displayed was rather complex.

Balke and Ullman measured the display glance times associated with different types of information extractions from conventional dashboard displays and navigation system displays. They found that some navigation information extractions required longer display glance times than have ever been necessary with conventional dashboard displays. The average amounts of time people took to extract information from different types of displays are listed in table 5.

Table 5

Display Glance Times for
Conventional and Navigation Information Extractions
Conventional information extractions are written in plain text.
Navigation activities are written in *italics*.

Display Glance Time (T_d, s)	**Information extractions performed**
$0.0 \leq T_d \leq 1.0$	Check following speed
$1.0 < T_d \leq 2.5$	Check remaining fuel, information about headlamps, tone controls, stereo balance, fan, vent, time *Check destination distance, check destination direction*
$2.5 < T_d \leq 4.0$	Check fuel range, fuel economy, defrost, temperature, cassette tape *Check heading, check zoom level, determine whether traveling in the appropriate direction, given the desired destination.*
$4.0 < T_d \leq 8.0$	Check power mirror, tune radio, set cruise control *Check name of the road upon which one is driving, check distance to a roadway immediately available on map display, check distance to next cross street*
$T_d > 8.0$	*Check the name of a roadway that is not immediately available (n.i.a.) on the display, check roadway distance (n.i.a.), check cross street (n.i.a.)*

Table 5 indicates that all but the simplest of navigation information extractions (and many information extractions associated with the more complex conventional devices) require long display glance times. This implies that using navigation systems in automobiles could cause even greater levels of distraction from the events occurring on the roadway than are already caused by many conventional displays. Thus, navigation systems could represent significant safety problems if they are displayed head-down.

Displaying navigation information with a HUD would allow people to monitor the roadway for significant events while they were extracting necessary information from navigation displays. There are a variety of issues associated with displaying navigation information with a HUD that will need to be addressed in future research. There should be assessments of the appropriate complexity of navigation HUDs, the degree of control that drivers should have over the information displayed, the format of the navigation information (e.g., verbal or pictorial), and the degree to which navigation information could result in drivers being distracted from events occurring on the roadway.

Shekhar, Coyle, Shargal, Kozak, & Hancock (1991)

Shekhar, Coyle, Shargal, Kozak, & Hancock (1991) have investigated some of the appropriate display parameters of a simple navigation HUD. They attempted to determine how to make such a display as safe as possible by considering issues such as how to display navigation information so that it is easy to read and understand, and the hazards associated with displaying complex information with a HUD.

In order to evaluate navigation HUDs in a controlled environment, Shekhar et al. conducted their two experiments in a fixed-base simulation facility. They simulated a HUD-assisted driving task in these experiments in order to determine the appropriate format in which to display HUD navigation information. Their first experiment evaluated the differences in driver responses to verbal (alphanumeric) versus iconic presentations of navigation information. The second experiment involved the assessment of the effects of compatibility between the direction of travel required of drivers and the map representations of the environment provided to these drivers.

Ten people of a mean age of 29.5 years participated in the first experiment. They were divided into two groups of five; one group used alphanumeric HUD maps and the other used iconic HUD maps. The task for both of these groups was to make either a left or a right turn based on the navigation information presented. Before the experiment began, participants were given five minutes to memorize a conventional road map of the region through which they would be navigating. The task of the participants was to navigate between the same origin and destination points for each of a series of trials, with the only difference between trials being the location of a blockage that they were to avoid. Each participant completed 28 trials, consisting of seven different blockage locations that were repeated four times.

Participants using the iconic information navigated between the origin and destination points in as little as 1/3 as much time as participants using the alphanumeric information. Those who used the iconic map also made significantly fewer errors in avoiding blockages than the group using the alphanumeric map. This was taken as evidence of the superiority of iconic maps over alphanumeric maps.

This second experiment focused on people's ability to make routing decisions using iconic maps. As in the first experiment, participants were to navigate between origin and destination points using a map which gave a north-up representation of the environment. In this study, the independent variable was the required direction of travel between the origin and destination points. Drivers were to travel from either north-to-south, south-to-north, east-to-west, or west-to-east.

Ten people participated in this study, and their mean age was 28.8 years. Each participant navigated using each of the four directions of travel. The difficulty of navigation varied with the degree of compatibility between the direction of travel and the north-up representation of the environment provided by the map. It was expected that it would be easiest for drivers to navigate from south-to-north because the map provided a north-up representation of the environment, and that it would be most difficult for drivers to navigate from north-to-south because such navigation was incompatible with the north-up representation of the environment provided.

As in the first experiment, the amount of time it took drivers to make either a left or right turn in order to get from their point of origin to their destination was measured. For each of the four directions of travel, and the results were as expected; the more compatible the direction of travel was with the north-up mapping, the faster people's response times were. Drivers' response times were about 1.2 s on average for the trials in which they were to travel south-to-north, about 2.0 s on average for the trials in which they had to travel east-to-west and west-to-east, and about 2.7 s on average for the trials in which they had to travel from north-to-south.

Based on these data, Shekhar et al. concluded that it was easiest for drivers to navigate when their direction of travel was consistent with the mapping of the environment with which they are provided. Because of this, the investigators recommended that navigation HUDs provide drivers a representation of the environment compatible with their direction of travel at any given time. So, for example, if a driver were traveling from east-to-west, it would be best to provide that driver with a map of the environment in which westward travel was represented by upward movement in the map. This map would change in accordance with the driver's direction of travel, so if the driver changed his or her direction of travel from east-to-west to south-to-north, the map displayed would be rotated from a west-up to a north-up orientation. This type of representation of the driver in the map was called ego-centered by the investigators, because the driver would always be provided with a map in which their immediate direction of travel would be represented by upward movement in the map.

In summary, Shekhar et al. (1991) recommended that it would be best to use iconic, ego-centered maps in order to represent navigation information if this information is to be displayed with a HUD. This seems like a well-advised recommendation for the present time, and it should be further tested with more naturalistic studies as navigation HUD technology becomes available.

Recommendations

While the idea of using HUDs to display navigation information to drivers is appealing, very little work has been conducted in order to determine whether it would be feasible to do so. While Shekhar et al. argue that navigation systems might be more safely displayed head-up and Balke and Ullman discuss how navigation information should be formatted if it is going to be displayed to drivers, there has not been any research conducted on how well people would drive while using navigation HUDs. Since navigation information is more complex than standard speedometer information, human performance with navigation HUDs will need to be addressed in future work.

In addition to displaying navigation information, HUDs might also be designed to display the readouts of complex conventional instruments. Balke and Ullman suggested that the status of car stereos, cruise controls, and cellular phones could be displayed with HUDs. There are a number or reasons why it would be reasonable to investigate how the displays of complex conventional features could be presented at a head-up location: these features are already available in most automobiles, they are devices with which most drivers are familiar, and they require long glance times away from the roadway. Such investigation might also serve to inform us on the human performance issues associated with head-up displays of complex information.

GENERAL DISCUSSION AND CONCLUSIONS

This review has covered a variety of issues pertaining to automotive head-up displays. While much progress has been made in applying HUD technology to automobiles, some of the major issues pertaining to automotive HUDs have yet to be resolved. The current state of the literature on automotive HUDs suggests that while we may now have an acceptable understanding of how to display information in a head-up location, we have not fully characterized the benefits that might be achieved by displaying information with HUDs.

Although the optimal display parameters of a HUD have not been strictly established, it is possible to determine the design of an acceptable HUD. An acceptable HUD would consist of an image projected at a location upon which drivers frequently fixate, at a distance of about 2.5 m from drivers' eyes. This image would be green (dominant wavelength = 540 nm), and would have adjustable brightness. The HUD image would be between 15% and 50% as bright as the roadway against which it will be viewed under daylight conditions, and about 300% as bright as the roadway under nighttime conditions. This image would probably cover about 2 to 3 degrees of a driver's visual field, and the characters displayed in the image should subtend about 0.8 degrees of visual angle.

The HUD parameter most in need of further research is location. Locating a HUD nearer to the driver's average line of sight makes it easier for the driver to monitor the HUD without looking away from the roadway, but at some point there may be conflict as the HUD becomes too close to roadway objects. This issue will be not be resolved until people's ability to monitor simultaneous roadway and HUD stimuli with HUDs located at varying degrees of eccentricity is more fully assessed.

Although the literature on HUD display parameters offers fairly well-established recommendations, the literature on human performance with HUDs has not covered as much ground. The majority of human performance assessments of head-up displays have investigated the effects of displaying speedometer information with a HUD. Research on displaying other types of information has been minimal. Nonetheless, there are several things we do know about human performance with HUDs. It has been shown that people can monitor and extract information from a HUD speedometer more rapidly than they can from a conventional HDD speedometer, but that they still spend the same amount of time monitoring their speed with a HUD because they glance at the HUD more frequently than the HDD. It is also known that although HUDs afford quicker access to speedometer information than HDDs, they do not have a significant effect on speeding behavior.

People using HUD speedometers have been found to fail to detect as many speed violations as people using HDD speedometers.

The most significant benefit that HUDs have demonstrated is that they keep drivers' attention directed towards the roadway ahead of them so that they make quicker reactions and fewer errors in detecting obstacles. This benefit could be applied towards improving driver safety, and HUDs could be used to display information that would normally require long glance times away from the roadway. Rather than simply displaying speedometer information, HUDs could be used to display more complex sources of information that drivers normally access while driving, such as navigation information, cellular phone status, or cassette deck status. By displaying these sources of information at a head-up location, some of the long glance times away from the roadway that drivers would normally make could be eliminated.

Future work should address how to display more complex information with HUDs and whether doing so will result in a safety benefit to drivers. This work will require an assessment of the effects of HUD complexity on environmental monitoring performance, because locating complex HUDs close to roadway objects might cause drivers to be distracted from monitoring those roadway objects.

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APPENDIX

The following technical reports related to HUDs are currently under review by the sponsor of the research (U.S. Federal Highway Administration). As of the publication date of this review they have not yet been released, but they are cited here for completeness.

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