QUANTIFYING HEAD-UP DISPLAY (HUD) PEDESTRIAN DETECTION BENEFITS FOR OLDER DRIVERS

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ABSTRACT

The current research was aimed at quantifying the potential *head-up display* (*HUD*) pedestrian detection benefits for older drivers. In a parked vehicle on a closed-course, test participants were required in rapid succession to read a digital speedometer (positioned either head-up or head-down) and a distant speed limit sign. 24 drivers were tested ranging from 59 to 71 years old. Liquid-crystal glasses were used to limit the driver's view of the forward scene to the time period immediately surrounding display glances. In the second half of testing, subjects were told that during a few trials a pedestrian would appear. On these trials, subjects were to immediately press a button. During these pedestrian trials, results indicated a HUD detection time advantage and a trend toward fewer missed pedestrians with the HUD. Indeed, 7 of the 9 fastest mean pedestrian detection times across all 16 conditions tested occurred in HUD conditions. These results clearly suggest HUDs improve the driver's ability to see forward scene events (and hence, potentially traffic safety) surrounding display glances.

INTRODUCTION

Since 1988, passenger car manufacturers have introduced automobiles which can present visual information to the driver through the windshield by way of a HUD (Weihrauch, Meloeny, and Goesch, 1989). The HUD allows the driver the ability to access visually displayed information in closer proximity to forward scene events relative to a conventional HD, instrument panel display. In this first generation of production HUD vehicles, *head-up* (*HU*) information has included digital speed, turn signals, high beam indicator, and master and/or specific telltale warnings. Figure 1 illustrates an "all segments on" image from a GM production HUD. Under most driving conditions only the speedometer is shown on the HUD, which is translucent and either blue- or yellow-green (depending on manufacturer). In addition, the HU information has been redundantly displayed at conventional *head-down* (*HD*) locations, and the driver has been able to dim the HUD off. A detailed description of the first HUD introduced by GM can be found in Weihrauch et al. (1989).

The next generation of HUDs may include information which would not be redundantly displayed at traditional HD locations, provided technological advances

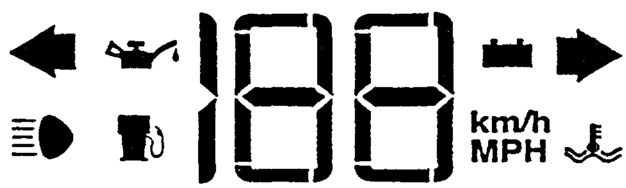

Figure 1. Production HUD graphics.

can be made to ensure HUD image visibility under a range of conditions comparable to HD displays. These advances involve increasing image source luminance and/or HUD optical system efficiency. Assuming this technological challenge can be overcome, automotive HUDs have increased potential to improve the driver-vehicle interface, present information which could not be effectively communicated via a HD display, and increase display space and interface design flexibility. In addition, future HUDs may include more advanced driver content, including navigation/route guidance, intelligent cruise control/forward collision warning, and infrared night vision displays (Grant, Kiefer, Wierwille, and Beyerlein, 1995). These relatively unexplored content areas may be better suited for yielding the greatest potential benefit of a HUD to the driver.

The primary focus of this study was to address the claim that current *automotive HUDs improve the driver's ability to see forward scene events (e.g., a crossing pedestrian) during the time period immediately surrounding when they are accessing displayed information.* This claim is subsequently referred to as the *improved forward visibility claim.* A secondary focus of this study was to address the claim that current *automotive HUDs reduce driver's re-focusing times from the display to the outside world,* subsequently referred to as the *reduced focusing time claim.* This latter claim provides more indirect evidence of a potential HUD safety benefit. A more extensive review of these two claims, as well as other positive and negative HUD claims, are provided in Kiefer (1996a).

The current research was also a follow-up to the Kiefer and Gellatly (1996b) field study. In this earlier study, subjects in a parked car were required in rapid succession to correctly read a speedometer and report forward scene targets under both expected and unexpected target conditions. Liquid-crystal glasses were used to limit the driver's view of the forward scene to the time period immediately surrounding display glances. Under the unexpected target conditions, drivers were not given any information as to what to expect with respect to these targets, but they did know when the target might occur. Under these conditions, results indicated a HUD advantage for a number of real-world targets, including standing and crossing pedestrians near parked vehicles, and approaching and crossing bicyclists.

It has been proposed that these results supporting the improved forward visibility claim can be interpreted in terms of a "*HUD benefit time window*" (Kiefer, in press). In order to clarify the time period during which the HUD is expected to support the improved forward visibility claim, consider a driver deciding to glance at his/her speedometer. Furthermore, consider the time-course of the ensuing speedometer eye movement with a HU versus HD digital speedometer. During this ensuing eye-movement, the HUD is expected to improve a driver's ability to see forward scene events (and hence, potentially traffic safety) during the time period which starts when the eyes would have arrived at the HD speedometer (i.e., the beginning of the HD speedometer fixation), and ends when the eyes would have returned to the roadway after fixating the HD speedometer. During this time period, defined as the *HUD benefit time window*, the driver's eyes are in closer proximity to forward scene events d in the HU relative to HD speedometer condition (approximately 15° closer to the driver's visual horizon with the GM HUD design).

This time window is shown below in Figure 2 for data gathered in an in-traffic study along with the roadway-display transition time, display fixation time, and display-road transition time for the HD and HU digital speedometer conditions (Kiefer, 1991; Kiefer, in press). For these data, the duration of the HUD benefit time window was 777 ms. This time window can be broken down into four different time periods, t_3 through t_6, which are preceded by time periods t_1 and t_2 (shown in Figure 2). During the first 71 ms (t_1), the driver's eyes are transitioning from the roadway to the speedometer in both display conditions. During the next 32 ms (t_2), the driver's eyes in the HD condition are completing a visual transition from the speedometer to the roadway, while the driver's eyes in the HU condition are fixating the speedometer. It is somewhat unclear whether the HUD benefit time window should include t_2, particularly the beginning of t_2. During this time, the driver's eyes in the HD condition may be transitioning just past the HU speedometer location, while the driver's eyes in the HU condition are just beginning to fixate and process the HU speedometer. Consequently, a more conservative estimate of the HUD benefit time window is assumed here which does not include any portion of t_2.

During the first 508 ms of the HUD benefit time window (t_3), the driver is fixating a HU versus HD speedometer, which puts the driver's eyes approximately 15° closer to the driver's visual horizon. During the following 102 ms of this time window (t_4), the driver's eyes in the HD condition are fixating the speedometer, while the driver's eyes in the HU condition are transitioning from the speedometer to the roadway. During the next 33 ms of this time window (t_5), the driver's eyes in the HD condition are beginning a visual transition from the speedometer to the roadway, while the driver's eyes in the HU condition have nearly completed the corresponding visual transition. Finally, during the last 134 ms of the HUD benefit time window (t_6), the driver's eyes in the HD condition are completing a visual transition from the speedometer to the roadway, while the driver's eyes in the HU condition are fixating on the roadway.

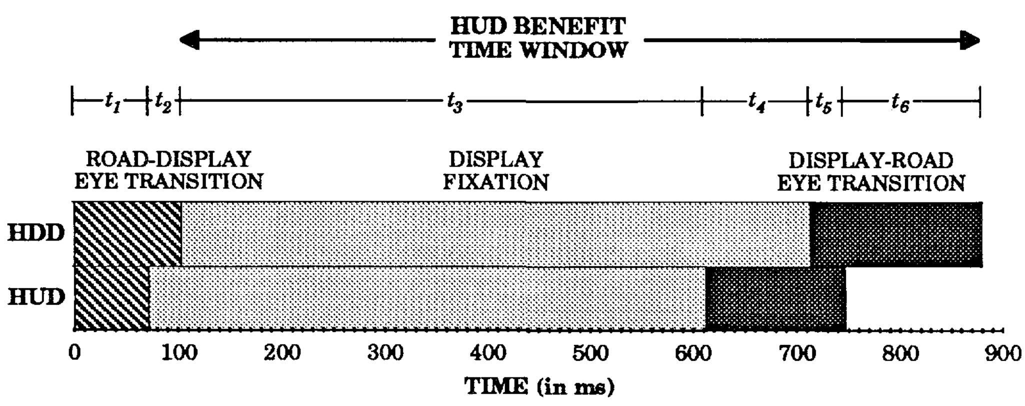

Figure 2. The HUD benefit time window and the roadway-display transition time, display fixation time, and display-road transition time for HD and HU digital speedometer conditions (from Kiefer, in press).

It should be stressed that t_6, which corresponds to the frequently cited HUD time savings for getting the driver's eyes back to the roadway, represents only 17% of the total time estimated for the HUD benefit time window. In contrast, 65% of the total time estimated for this time window corresponds to t_3, when the driver is fixating a HU versus HD speedometer.

In the current study, older drivers were asked to perform tasks with both a HU and HD digital speedometer in a parked vehicle on a closed test track. Liquid-crystal glasses were used to limit the driver's view of the forward scene. A speedometer and speed limit sign were modified to allow pre-selected values to be displayed. The first task involved reading a speedometer and then a distant speed limit sign in rapid succession. Results from this task were aimed at addressing the reduced focusing time claim, and were also used to set stimulus duration levels tailored for each subject during the second task. In the second task, drivers were again asked to perform the previous task; but they were told that during a few trials, a pedestrian would be positioned in the forward scene. On these pedestrian trials, subjects were instructed to immediately press a hand-held reaction time button as soon as they detected the pedestrian. The pedestrian targets were either at a 100 or 300 foot (30.5 or 91.4 m) distance, standing or crossing the road, and either near a parked vehicle or isolated. This second task was aimed at addressing both the improved forward visibility claim (with pedestrian detection performance) and the reduced focusing time claim.

There were several important differences between this study and the previous Kiefer and Gellatly (1996) study. First, this study was focused on testing older drivers, whereas the Kiefer and Gellatly study sampled a wider age range. Second, the methodology involving pedestrian targets was changed to allow gathering pedestrian detection times (Kiefer and Gellatly used percent correct performance measures), which allowed more precisely quantifying HUD benefits in terms of time and travel distance savings. Third, the probability of pedestrian target occurrence across trials was substantially lower in this study (13.5%) relative to the Kiefer and Gellatly study (80%). Fourth, stimulus durations were tailored individually for each subject (a constant duration was used across subjects in the Kiefer and Gellatly study) to increase sensitivity to detecting any performance differences across displays. Furthermore, in order to more closely mimic typical speedometer glance times (particularly for older drivers), substantially longer stimulus durations were used here (on average, about 700 ms) relative to the Kiefer and Gellatly study (250 ms). Fifth, in order to mimic real-world behavior as much as possible, subjects were instructed to stop performing the speedometer and sign reading tasks whenever a pedestrian was detected (Kiefer and Gellatly required correct performance on each task).

METHOD

All 13 male and 11 female test participants were licensed drivers and were tested to ensure they met the minimum standard of 20/40 far visual acuity. The subjects ranged between 59 and 71 years (M=65.2 years), and were tested individually in one 90-minute session and paid $75. None of the drivers had previously owned a HUD vehicle.

Data were collected on a straight, black asphalt test track which was closed to all other traffic during testing. The test vehicle remained parked in the center of the road throughout testing. All testing was conducted during daytime hours. Nearly all testing was conducted under dry weather and dry road conditions. During the few sessions when light rain was falling, the windshield was cleared prior to each trial.

The HU and HD digital speedometers of the test vehicle (a 1994 Buick Regal) were representative of current production speedometers, with one exception being that the latest production HUDs provide substantially higher maximum daytime luminance. The instrument panel cluster for the test vehicle was retrofitted with a 1993 Buick Regal digital instrument panel cluster. Subjects were instructed to set the HUD no brighter than necessary to clearly and comfortably see the speedometer. Overall, the mean HUD luminance setting was 887 cd/m^2, and the mean HUD:background contrast ratio during testing was 1.9:1. The nominal digit height for the HU and HD digital speedometers was 0.6° and 1.7°, respectively. The HU speedometer was positioned at front bumper depth (2.3 m) and centerline to the driver. At the start of testing, the top of the HU speedometer was set for each driver at 4.6° below the driver's visual horizon. For several drivers, such a setting prevented viewing the entire speedometer. As a result, the average look-down angle across all drivers was 4.5°, and the top of the HUD superimposed the roadway at an average of 22.6 meters. The HD speedometer was located at approximately 18.5° below the driver's visual horizon. It should be noted that, in practice, HUD look-down angle settings vary somewhat across drivers, depending on the driver's eye position and preference. Drivers of GM vehicles equipped with HUDs are advised in the owner's manual to adjust the HUD as low as possible in their field of view while the entire HUD image remains fully visible (i.e., so the HUD appears just above the driver's front hood).

The brief amount of time drivers had available to view the visual stimuli was controlled via *PLATO spectacles* (acronym refers to Portable Liquid-crystal

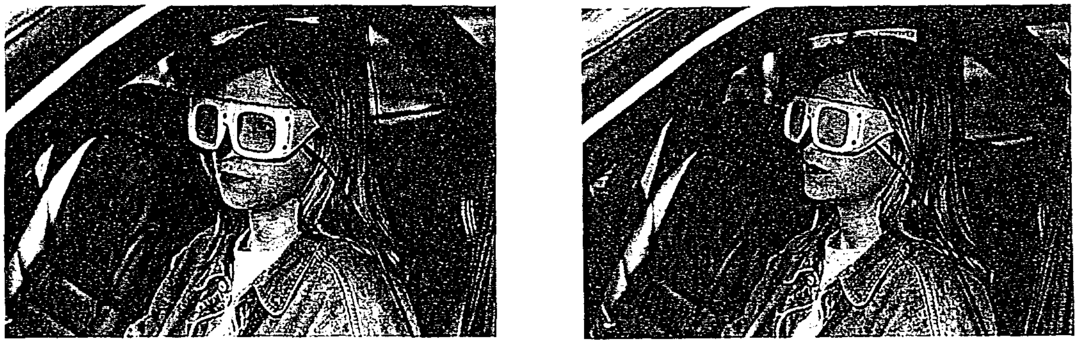

Figure 3. Open and closed states of "shutter type" liquid-crystal glasses.

Apparatus for Tachistoscopy via visual Occlusion) (Milgram, 1987). The open and closed states of these spectacles are illustrated in Figure 3. In the open state of these spectacles, the driver had a clear view. After receiving the open signal, the spectacles needed 8 ms to reach a 20% light transmission and an additional 62 ms to reach the peak transmission of 72%. In the closed state, the driver viewed a whitish, uniform, milky texture; and vision was effectively occluded. After receiving a close signal, the spectacles needed 32 ms to reach a 20% light transmission and an additional 68 ms to reach a 0% light transmission. Given these on/off switching characteristics, it is important to stress that the stimulus duration values reported in this paper refer to the difference in time between the open and closed signals, rather than the duration in which any given minimum light transmission value was exceeded. To put this in perspective, a 700 ms stimulus duration corresponds to either a 630 ms, 724 ms, or 800 ms stimulus duration, depending on if one assumes a 72%, 20%, or 0% light transmission criterion, respectively.

In the first task, referred to as the *Speedo + Sign task*, drivers were asked in rapid succession to read the speedometer (values ranging between 50 and 69) and then a distant speed limit sign (reading either 55 or 65 miles-per-hour). A small, color video camera allowed the experimenter the opportunity to ensure the driver was performing the tasks in the correct sequence. Immediately before the spectacles were briefly opened, subjects were given a 425 ms warning tone, followed by an 800 ms interval with no warning tone. This general trial sequence was used throughout the study, and is illustrated in Figure 4.

The speedometer and sign values were changed trial-to-trial by the back-seat experimenter and outside experimenter, respectively. The on-board and outside experimenters communicated via FM radios. An experimenter box positioned in the back seat allowed activation of one of the two speedometers and selection of the appropriate speedometer value. For the speed limit sign, a regulation rural road speed limit sign was created using Type II retroreflective Scotch-Lite material (The Michigan Department of State Highways, 1973). A 55 mile-per-hour (mph) and 65 mph speed limit sign were mounted back to back on a gray sleeve that fit over a post attached to a gray pedestal. The speed digits were 25.4 cm in height. The sign assembly was positioned 300 feet (or 91.4 m) in front of the vehicle, and 12 feet (or 3.7 m) from the right edge of the road.

For each display condition, a staircase threshold method (Cornsweet, 1962) was continued for 40 trials until a 50% identification threshold value (i.e., the stimulus duration at which drivers were able to read both the speedometer and sign with 50% accuracy) was obtained based on the last four reversals. For the first three trials, step changes of the stimulus duration were made in 200 ms increments, beginning at 1000 ms. Thereafter, step changes were made in 50 ms increments.

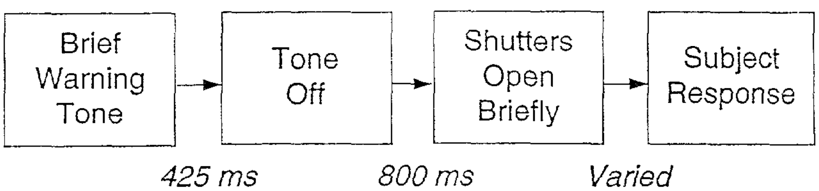

Figure 4. General trial sequence.

The back-seat experimenter recorded the driver's responses and set the appropriate stimulus duration values. The obtained 50% identification threshold value was the measure of driver performance analyzed. The within-subject variable analyzed for this task was display (HU and HD) and the between-subjects variable was display order. Display order was counterbalanced.

In the second task, referred to as the *Speedo + Sign/Pedestrian task*, drivers were again asked to perform the Speedo + Sign task, with two important differences. First, they were told that during a few trials a pedestrian would be positioned in the forward scene. On these trials, they were instructed to immediately stop performing the Speedo + Sign task and press a hand-held reaction time button as soon as they detected the pedestrian. Drivers were provided examples of each of the eight possible pedestrian target types (described below) prior to performing the task. Second, drivers were tested at two stimulus durations, calculated individually for each subject. The first stimulus duration was the higher of the two 50% identification threshold values found in the head-up versus head-down display condition in the previous Speedo + Sign task, referred to as the *maximum threshold* (*MT*). The second stimulus duration added 200 ms to the MT value (*MT + 200*). The rationale for tailoring stimulus durations was to attempt to create an equally demanding Speedo + Sign task for each driver, and to equally limit each driver's ability to focus attention on anticipating and detecting pedestrians. The stimulus duration, speedometer values, sign values, and pedestrian stimuli were varied on a trial-by-trial basis within each of the 4 blocks of trials. Four random block sequences were counterbalanced across display condition.

The forward scene consisted of a roadway with a white 1995 Chevrolet Sport van parked on the right side of the road just prior to the near (100 foot or 30.5 m) pedestrian target distance, and a blue 1995 Buick Skylark parked on the right side of the road just prior to the far (300 foot or 91.4 m) pedestrian target distance. The near and far "live" pedestrian targets wore matched denim shirts, denim jeans, and white canvas tennis shoes. The four pedestrian target types at both the near and far distance included a side-view of a pedestrian standing on the right side of the road, a side-view of a pedestrian crossing right to left on the right side of the road, a side-view of a pedestrian standing on the left side of the road, and a side-view of a pedestrian crossing left to right on the left side of the road. All pedestrian targets on the right side of the road occurred immediately to the left of and just forward of the parked vehicle. An illustration of the near and far right crossing pedestrian targets are shown in Figure 5. (Illustrations of the near and far right standing pedestrian target types can be found in Kiefer and Gellatly (1996b).) Each pedestrian target type was fully visible to the driver when the spectacles were in the open state.

The 100 and 300 foot (or alternatively 30.5 and 91.4 m) target distances employed were chosen to bound the upper and lower range of distances deemed critical in order for a driver to brake to a complete stop prior to reaching an obstacle in its path (assuming the driver would not have chosen or been able to avoid the obstacle by steering the vehicle). These distances were generated by combining a range of driver perception-reaction times (P-RTs), vehicle speeds, and vehicle braking distances at these speeds. In this case, driver P-RT refers to the time between when the forward obstacle first becomes visible to the driver and when the driver initiates a brake application (Olson and Sivak, 1986). The lower bound of the range of driver P-RT values considered, 0.7 sec, represents the mean value obtained under conditions in which an alerted driver encountered an obstacle in their driving lane after cresting a hill (Olson and Sivak, 1986). The upper bound of the range of driver P-RT values considered , 2.5 sec, was intended to be representative of a higher-percentile driver P-RT, and is based on design policy of the American Association of State Highway Transportation Officials (AASHTO) (Neuman, 1989). The range of speeds considered, 35-50 mph, account for the posted speed limits at the site of 57% of all non-occupant traffic fatalities (National Highway Traffic Safety Administration, 1986). The corresponding vehicle braking distances at these two speeds (67 and 144 feet, respectively) were again based on AASHTO design policy. The range of distances generated by combining the driver P-RT, speed, and braking distance variables varied from 103 feet (0.7 sec driver P-RT, 35 mph speed) to 328 feet (2.5 sec driver P-RT, 50 mph speed).

During each of 4 test blocks, subjects experienced 32 trials with no pedestrian present. Display condition was alternated between blocks, with half of the subjects experiencing the HD display condition first. During trial blocks 1, 2, 3, and 4, these 32 trials were interspersed with an additional 4, 6, 6, and 4 pedestrian trials, respectively. Overall, pedestrians occurred on 13.5% of all trials. Four of the 8 pedestrian targets were presented once during each of the four blocks, twice in each display condition. Each of these four targets occurred with 2.7% probability. These targets included the near right standing, near right crossing, far right standing, and far left crossing pedestrian targets, which were presented at the MT, MT, MT + 200, and MT + 200 durations, respectively. The remaining 4 of the 8 pedestrian targets were experienced exactly once by each subject (two targets in each display condition), and hence, these targets were examined separately with display as a between-subjects factor. Each of these four targets occurred with 0.7% probability. During block 2, the near left crossing and far left standing pedestrian targets were presented at the MT + 200 and MT durations, respectively. During block 3, the near left standing and far right crossing pedestrian targets were

Figure 5. Near and far right crossing pedestrian targets.

presented at the MT + 200 and MT durations, respectively. Overall, it should be noted that pedestrian targets occurred on the left side of the road (in isolation) and the right side of the road (near a parked vehicle) with 4.7% and 8.8% probability, respectively.

Two separate driver performance measures were analyzed for Speedo + Sign/Pedestrian task. The first measure analyzed was the percent of trials in which *both* the sign and the speedometer were correctly identified during trials in which a pedestrian *was not* presented. The within-subject variables analyzed for this measure were display (HU and HD), stimulus duration (MT, MT +200), and practice (first versus second half of testing). The second measure analyzed for this task was pedestrian detection times. For 4 of the pedestrian target types (near right standing, near right crossing, far right standing, and far left crossing), the within-subject variables analyzed for this measure were display (HU and HD) and pedestrian target type. For each of the remaining 4 pedestrian target types (near left crossing, far left standing, near left standing and far right crossing pedestrian) the between-subjects variable analyzed for this pedestrian detection time measure was display (HU and HD).

RESULTS AND DISCUSSION

A factorial Analysis of Variance (ANOVA) was performed on each driver performance measure, and the criterion set for statistical significance was $p < 0.05$. Results for the first task drivers performed, the Speedo + Sign task, indicated no significant effects ($p > 0.40$). For the second task, the Speedo + Sign/Pedestrian task, the average MT value employed across subjects was 734 ms. During trials in which no pedestrians were presented, results for the percent correct identification measure for the Speedo + Sign task indicated main effects of display ($F(1, 23) = 13.66$, $p < 0.005$) and stimulus duration ($F(1, 23) = 64.75$, $p < 0.0001$), and a Display x Stimulus Duration interaction ($F(1, 23) = 6.55$, $p < 0.05$). Follow-up simple main effect tests indicated display had a significant effect on percent correct identification rates at both stimulus durations (MT, ($F(1, 23) = 19.37$, $p < 0.0005$; MT + 200 ms, ($F(1, 23) = 5.79$, $p < 0.05$). At the MT stimulus duration, the mean percent correct identification rates for the HU and HD display conditions were 63.2% and 49.4%, respectively. At the MT + 200 ms duration, the corresponding mean percent correct identification rates were 84.0% and 76.5%, respectively. Overall, this absolute level of task performance suggests this task was challenging enough to deter drivers from focusing their attention on detecting pedestrians.

Unlike results from the first task, the second task (which added a pedestrian detection component) showed support for the HUD reduced focusing time claim. This discrepancy in findings could have several explanations. First, support for this claim may be contingent on practice with the HUD, which is consistent with earlier results (Kiefer and Gellatly, 1996b). Second, the technique used for measuring driver performance in the second task may have been more sensitive to detecting any differences across display conditions. Third, the driver's concern about the potential presence of a pedestrian target may have interfered more with speedometer and sign reading task performance in the HD relative HU condition.

Detection times and miss rates for each pedestrian target type are shown in Table 1. During trials in which pedestrians were presented in the Speedo + Sign/Pedestrian task, results indicated there was a trend toward higher pedestrian miss rates with the HD relative to HU speedometer. Overall, 21 of the 32 missed pedestrians occurred in the HD condition, and 4.4% and 2.3% of the pedestrian targets were missed in the HD and HU display conditions, respectively. These results also indicate that the relatively small differences in miss rates found for 5 of the 8 pedestrian target types all favor the HUD condition, suggesting a potential HUD advantage based on these limited data. In addition, a total of 12 and 8 false alarms occurred in the HD and HU display conditions, respectively. This suggests that the HUD pedestrian detection time benefits reported below are not due to subjects adapting a less stringent criterion for responding to a pedestrian target in the HU condition.

Results for the pedestrian detection time analysis in which pedestrian target type was treated as a within-subjects variable (near right standing, near right crossing, far right standing, and far left crossing pedestrian) indicated main effects of display ($F(1, 23) = 30.83$, $p < 0.0001$) and pedestrian target type ($F(3, 69) = 111.10$, $p < 0.0001$, and a Display x Pedestrian Target Type interaction ($F(3, 69) = 7.84$, $p < 0.0001$). Follow-up simple main effect tests indicated a HUD pedestrian detection time advantage for 3 of the 4 pedestrian targets in this analysis. These included the near right standing ($F(1, 23) = 27.59$, $p < 0.0001$), near right crossing ($F(1, 23) = 10.20$, $p < 0.005$), and far left crossing ($F(1, 23) = 18.38$, $p < 0.0005$) pedestrian target types. For the near right standing, near right crossing, and far left crossing pedestrian targets, the mean detection time advantage attributed to the HUD was 224, 87, and 281 ms, respectively. Results for the remaining 4 pedestrian target types in which display was a between-subjects variable (near left crossing, far left standing, near left standing and far right crossing pedestrian) indicated a HUD pedestrian detection time advantage for the near left standing pedestrian target type ($F(1, 19) = 4.79$, $p < 0.05$), and a marginally significant advantage for the far right crossing pedestrian target type ($F(1, 18) = 3.08$, $p < 0.10$). For the near left standing and far right crossing pedestrian targets, the mean detection time advantage attributed to the HUD was 302 and 325 ms, respectively. It is also worthwhile to

Table 1.
Mean Pedestrian Detection Times (in ms) and Number of Missed Pedestrians (indicated in parentheses) as a Function of Display, Pedestrian Distance, Lateral Location, and Movement

PEDESTRIAN TARGET DISTANCE = 100 FEET (30.5 METERS)

	Left-Side (Isolated)		Right-Side (Near Van)	
SPEEDOMETER	Standing	Crossing	Standing	Crossing
Head-Down	1062 (3/12)	751 (1/12)	1069 (3/48)	740 (0/48)
Head-Up	760 (1/12)	708 (1/12)	845 (1/48)	653 (0/48)
HUD Time Savings	*302 **	*43*	*224 **	*87 **

PEDESTRIAN TARGET DISTANCE = 300 FEET (91.4 METERS)

	Left-Side (Isolated)		Right-Side (Near Car)	
SPEEDOMETER	Standing	Crossing	Standing	Crossing
Head-Down	1248 (4/12)	1130 (2/48)	1303 (6/48)	1161 (2/12)
Head-Up	994 (1/12)	849 (1/48)	1300 (6/48)	836 (0/12)
HUD Time Savings	*254*	*281**	*3*	*325 ***

Note. *$p < .05$ (minimally). **$p < .10$.

Table 2.
Rank Ordering of Mean Pedestrian Detection Times (in ms) as a Function of Display, Pedestrian Distance, Lateral Location, and Movement

	Display	Movement	Distance (in feet)	Lateral Location	Mean Detection Time (Miss Rate Percentage)
		Pedestrian Target Type			
1.	Head-up	Crossing	100	Right	653 (0%)
2.	Head-up	Crossing	100	Left	708 (8.3%)
3.	Head-down	Crossing	100	Right	740 (0%)
4.	Head-down	Crossing	100	Left	751 (8.3%)
5.	Head-up	Standing	100	Left	760 (8.3%)
6.	Head-up	Crossing	300	Right	836 (0%)
7.	Head-up	Standing	100	Right	845 (2.1%)
8.	Head-up	Crossing	300	Left	849 (2.1%)
9.	Head-up	Standing	300	Left	994 (8.3%)
10.	Head-down	Standing	100	Left	1062 (25.0%)
11.	Head-down	Standing	100	Right	1069 (6.3%)
12.	Head-down	Crossing	300	Left	1130 (4.2%)
13.	Head-down	Crossing	300	Right	1161 (16.7%)
14.	Head-down	Standing	300	Left	1248 (33.3%)
15.	Head-up	Standing	300	Right	1300 (12.5%)
16.	Head-down	Standing	300	Right	1303 (12.5%)

note that for the far left standing pedestrian target, overall, 4 (of 12 possible) pedestrian targets were missed in the HD condition, whereas only 1 target was missed in the HU condition.

It is also interesting to note, that across all trials (i.e., without weighting pedestrian target type frequency), near pedestrian targets were detected on average 306 ms faster than far targets, crossing pedestrian targets were detected on average 260 ms faster than standing targets, and left-side (isolated) pedestrian targets were detected on average 303 ms faster than right-side targets (near parked vehicles). Similarly, across all trials, pedestrian miss rates for targets at the near and far distances were 4.2% and 9.2%, respectively. Pedestrian miss rates for standing and moving targets were 10.4% and 2.9%, respectively. Pedestrian miss rates for left- and right-side targets were 8.3% and 5.8%, respectively. In addition, miss rates were particularly high for left-side standing pedestrian targets in the HD condition. Averaging across both pedestrian distances, 29% of these pedestrian targets were missed. This pattern of results may be due to the reduced overall probability of targets on the left versus right side of the road (4.7% versus 8.8%), the lack of pedestrian movement cues, and/or that the speedometer and sign reading task oriented driver's attention to the right side of the road.

CONCLUSIONS

Overall, these pedestrian detection results found with older drivers are consistent with and extend previous research supporting the improved forward visibility claim attributed to HUDs (Flannagan and Harrison; 1994; Kiefer and Gellatly, 1996b; Okabayashi, Sakata, Furukawa, and Hatada, 1990; Sakata, Okabayashi, Fukano, Hirose, and Ozone, 1987; Sojourner and Antin, 1990; Weihrauch et al., 1989). Furthermore, there was a HUD pedestrian detection time advantage ranging from 87-325 ms for 5 of the 8 pedestrian target types (near right standing, near right crossing, near left standing, far right crossing, and far left crossing). At 35 MPH, these HUD time savings range from 4.5-16.7 feet (or 1.4-5.1 m) travel distance. At 55 MPH, these HUD time savings range from 7.0-26.2 feet (or 2.1-8.0 m) travel distance. It should also be stressed that there was a trend toward fewer missed pedestrians with the HUD. Overall, 11 pedestrians were missed in the HUD condition, whereas 21 pedestrians were missed in the head-down condition.

Overall, this pattern of pedestrian detection time results favoring the HUD can also be seen in Table 2 which ranks all 8 pedestrian target type conditions for each display as a function of mean pedestrian detection time. These data indicate that 7 of the 9 lowest mean pedestrian detection times occurred in the HUD condition. More generally, it should also be noted that these results were found under conditions in which the HUD did not superimpose the forward scene event, which is argued to be representative of the vast majority of driving (Kiefer and Gellatly, 1996b).

The failure to find a HUD advantage for the relatively inconspicuous far standing pedestrian targets may have been caused by the stimulus duration, since a HUD advantage for these targets was previously observed in a similar task with a shorter stimulus duration (250 ms) (Kiefer and Gellatly, 1996b). In addition, both the current study and Kiefer and Gellatly study found no difference in pedestrian detection performance across displays with the near left (isolated) crossing target, the most conspicuous pedestrian target.

A few points should be made with respect to the practical implications of the observed pedestrian detection results. First, even though these experimental conditions do not fully replicate a driver encountering an unexpected pedestrian, it should be stressed these HUD pedestrian detection time benefits occurred under conditions with relatively low pedestrian probability and high pedestrian location uncertainty (such that targets were somewhat unexpected when they did occur). Perhaps most importantly, these HUD pedestrian detection time benefits occurred for 3 of the 4 pedestrian targets (including both crossing pedestrian targets) near parked vehicles. Second, it should be noted that the pedestrian target distances employed (100 and 300 feet, or equivalently, 30.5 and 91.4 m) were chosen to bound the range of distances deemed relatively critical in order for a driver to brake to a complete stop prior to reaching an obstacle in its path (assuming the driver would not have chosen or been able to avoid the obstacle by steering the vehicle) These distances were generated by combining a range of driver P-RTs, vehicle speeds, and vehicle braking distances. Third, to the extent that accidents are caused by allocating visual attention to displays, these results suggest HUDs will improve traffic safety. Although accident data are generally not recorded or categorized in a manner which allows one to reliably estimate the number of such accidents, a keyword analysis of approximately 190,000 police report narratives from the 1989 North Carolina accident database suggested that for 0.82% of these accidents, driver vision was directed into the vehicle and this was the primary cause of the accident (Wierwille and Tijerina, 1993). Of this small portion of accidents, driver vision was directed into the vehicle at information which could be potentially shown on a HUD in about 13% of the cases. Unfortunately, police reports are not an entirely reliable source of accident causation, for a variety of reasons (e.g., driver/officer insensitivity to or misrepresentation of accident cause).

In conclusion, this research has come much closer than previous research toward the goal of understanding both the nature and magnitude of the real-world implications of the claimed eyes-on-road benefit of

HUDs. These results clearly suggest HUDs improve the older driver's ability to see forward scene events (and hence, potentially traffic safety) surrounding display glances. On a closing note, it should be stressed that the conclusions drawn in this paper cannot be readily generalized to other automotive HUDs which differ on fundamental HUD design parameters (e.g., HUD location).

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