Which is a Better In-Vehicle Information Display? A Comparison of Google Glass and Smartphones

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***Abstract*—In-vehicle information display is critical for driving safety and has been the focus of transportation and display technology research. Cellphone use, while driving is popular, leads to distraction and impairs driving performance. A new head-mounted display (HMD), Google Glass, has been developed in hope of reducing the visual distractions caused by a head-down display (HDD), such as a smartphone. Alternatively, HMD could induce greater distraction by giving drivers the false impression that they are simultaneously paying attention to both the HMD and the road. We compared driving performance in a simulated tactical lane-changing task while drivers read from either an HMD (e.g., Google Glass) or an HDD (e.g., smartphone). Although both HMD and HDD use impaired driving performance, drivers produced smaller lane variation, had fewer lane excursions, and lower subjective workload when using an HMD than when using an HDD. Wearable display technologies like Google Glass might reduce the impairment caused by looking down at a smartphone.**

***Index Terms*—Adaptive safety behaviors, head-down display (HDD), Head mounted display (HMD), in-vehicle display, Google Glass, Tactical vehicle control, smartphone.**

I. Introduction

IN-VEHICLE information displays and mobile devices, such as iPods, mobile media players, smartphones, wearable head-mounted displays (HMD, for example Google Glass) and smart watches, are increasingly prevalent [1]–[4]. The rapid increase of these in-vehicle displays is accompanied by increasing driving risk [3], [5]–[7]. A multiple regression analysis estimated that as many as 16,141 additional distracted driving fatalities were caused by the increases in texting volume for the years 2002 to 2007 [8].

The recent development of wearable display technologies brings many new gadgets into vehicles, such as Google Glass. Google Glass is a monocular optical HMD in the shape of glasses. Google Glass is essentially an Android device, which allows almost all functions of a smartphone, such as cell phone conversation, texting, Internet browsing and E-Mail composition. Google Glass mainly uses voice recognition technology for inputs and shows information in an optical HMD near the top of the right eye. HMDs and head-up displays (HUDs) share many similarities; both displays allow users to look at or through the displayed image and view the world beyond [9]. As HMD like Google Glass is entering the vehicle, many people, including driving researchers, auto-manufacturers, insurance companies, legislators, software developers and drivers, hope to know whether it is safe to drive while using an HMD and how distracting an HMD is compared to other alternate display technologies, such as smartphones and head-down displays (HDDs).

HMD like Google Glass may be potentially less risky than a smartphone, or other HDDs. Like other HMDs or HUDs, HMD can show task-critical information in the perceptual neighborhood [10], thus reducing eye scanning compared to HDDs, such as a dashboard or a smartphone display [11]–[13]. HMDs make information easily accessible and minimize mental workload [12]–[16]. Thus, several driving studies have shown that drivers using HUD produced better lane-keeping, better speed maintenance and quicker response time for speed limit sign changes and urgent events [17]–[20].

Despite the benefits of HMDs, the type of display may also pose many risks to driving performance. HMDs may incur binocular rivalry, a known problem for HMDs because of content instability and visual occlusions [21]–[23]. HMDs can also cause eyestrain, which is a common issue associated with HMD use [24], [25]. In addition, HMD can potentially increase visual clutter, which increases perceptual workload [26] and causes a fixation tunnel effect [13]. HMD can potentially incur inattentional blindness, a common phenomenon which users fail to detect salient unexpected events in the outside world [27]–[29]. In a flight simulator, pilots wearing a HUD or a HMD are more likely to miss a runway incursion than when using a HDD, even when the runway incursion is clearly visible in their field of view [28], [30]. Moreover, HMD such as Google Glass brings potential distractors closer to eyes, which may increase drivers' exposure to distractions. Users of Google Glass can initiate a distracting task, such as sending text messages, by simply nodding their head to light up the Google Glass display. The easy accessibility of HMD to distractions may expose its users more frequently to distracting tasks unrelated to driving than a smartphone.

It is important to understand how HMDs (such as Google Glass) and cell phones (including smartphone) influence driving performance, as driver distraction is one of the major causes of traffic crashes. While we know little about how an HMD/Google Glass influences driving, the influence of cell phone use on driving performance has attracted the attention of legislators and researchers.

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Cell phone use, including cell phone conversation, texting and E-Mail composition, impairs driving performance in various ways. For example, cell phone use increases braking response time [31]–[34], causes larger variations of lane position [35]–[41], incurs higher mental workload [41], [42], increases gaze-off-road durations [38], [39], [42], [43], causes more collisions [32], [35], and raises the risks of traffic accident as many as 23 times for truck drivers [44]. Thus, many governments have banned the use of cell phones, either or both handheld and hands-free cell phones while driving.

Compared to the attention paid to cell phone use while driving, studies of HMDs, such as Google Glass, on driving performance are scarce. However, HMDs are widely used and investigated in the aviation and medical domains [23], [45]–[47]. The aviation literature often suggests that pilots produce better performance when using HMDs than HDDs [45], [48]. Only a few studies have compared the driving performance costs of HUD and HDDs [20], [49], finding relatively reduced performance decrement with a HUD. However, HMD differs from HUD in several aspects, such as stability of the display information and binocular rivalry. Will an HMD incur the same performance costs as an HDD, or will it be more comparable to an HUD? Safety researchers have only recently begun exploring how HMD influences driving performance [3], [7], [22], [50]. However, these studies all used a car-following task and did not assess other aspects of driving performance, such as tactical lane changes. Additionally, these studies mainly focused on the speech-recognition feature of Google Glass [3], [7], [50]. None of the studies examines the performance costs of using the visual HMD of Google Glass. In the current study, we investigated how reading using the transparent HMD of Google Glass influences driving performance. Driving performance was gauged using a tactical lane change task, in which drivers drove in a straight three-lane road with intermittent traffic and changed lanes when necessary to maintain a safety margin [51]. The tactical lane change task mimics highway driving in rush hours.

II. Methods

A. Subjects

Thirty members of the Wichita State University community (17 males and 13 females, mean age $= 21.47$ years, $SD = 4.89$ years) received course credit for participating. All had held a driver's license for at least three years prior to the experiment ($M = 6.26$ years, $SD = 4.31$ years), and their self-reported annual mileage averaged 10 976 miles ($SD = 8330$ miles). All subjects reported having normal or corrected-to-normal visual acuity. One subject was excluded from analysis after the subject reported motion sickness during the experiment.

B. Apparatus and Stimuli

Data were collected at the Human Automation Interaction Laboratory at Wichita State University. The driving scenarios were created using HyperDrive Authoring Suite Version 1.6.1 and controlled by Drive Safety's Vection Simulation Software$^{\mathrm{TM}}$ Version 1.6.1. The driving simulator consisted of three 26-inch ASUS monitors (1920×1080 pixels). Drivers sat approximately one meter away from the front monitor, at a visual angle of 76°. Road information was visible both through the windows and through rear-view and side mirrors, and vehicle dynamics were sampled at 60 Hz.

Fig. 1. Android smartphone and Google Glass used in this driving study. (a). Android smartphone. (b). Google glass.

A smartphone and a Google Glass were used to display the secondary reading task. The smartphone was a 4.0" Samsung touch-screen smartphone running Android 4.04 displayed. The smartphone had a 1.2 GHz dual core processor. The resolution of the Super AMOLED$^{\mathrm{TM}}$ display is 800×480 WVGA. Google Glass had monocular optical HMD, which was equivalent to a 25-inch high definition screen viewed from a distance of eight feet. Google Glass was worn like a regular pair of glasses. The Google Glass had a 1.2 GHz dual core processor and 640×360 resolution display. Please see Fig. 1 for an example of the devices.

C. Driving and Reading Tasks

Lane-change task. The driving task consisted of an unconstrained drive on a straight, six-lane divided freeway, with three lanes in either direction (see [51]). The vehicle started on a freeway entry ramp, and drivers then merged onto the freeway. The posted speed limit was 65 mph. Drivers were told to obey all traffic rules, but were free to change lanes and pass vehicles when appropriate.

Other vehicles (all four-door sedans) drove in the same direction as the driver's vehicle. The initial gaps between vehicles were randomly selected from a uniform distribution ranging from 140 to 180 m, and each vehicle's speed was randomly selected from a uniform distribution between 64 and 122 kph. Faster vehicles spontaneously passed slower ones by changing lanes while maintaining safe headway distances. The variability of vehicle speed and spontaneous passing led to naturalistic patterns of traffic congestion, with some dense traffic regions and other regions with little traffic.

Secondary reading task. In the distracted driving conditions, drivers performed a reading task designed to simulate reading while driving, which was roughly comparable to reading web pages, E-Mails, and text messages while driving. The reading materials were excerpted from chapter one to six of *Alice's*

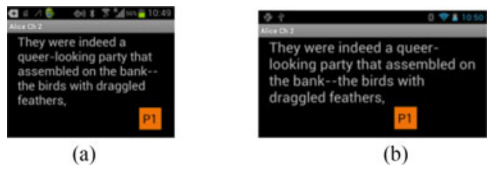

Fig. 2. Reading materials shown in Android and Google Glass. (a). Android smartphone (b) Google glass.

Adventures in Wonderland [52]. Drivers read aloud as they drove. Subjects wore the Google Glass or held the smartphone in their hand when reading the materials. Subjects were instructed to put the smartphone back in the same location of the simulator deck. Fig. 2 depicts the secondary reading task shown in either a smartphone or a Google Glass.

For the reading task, drivers pressed a 'start' button to start showing the reading materials. For the Android phone, drivers touched anywhere on the touch screen to show the next page. For Google Glass, drivers touched anywhere on the arm of Google Glass to show the next page. The time stamp for each page -forward event was saved by the application showing the secondary reading task.

The same Android application controlled the display of reading materials for the smartphone and Google Glass. The text content, number of words, font size, and text-alignment (left-aligned) were the same across the two devices. For Google Glass, text appeared in a transparent display positioned at the upper corner of the right eye's field of view when the subject looked straight ahead. The text appeared to be overlaid on the simulated world. Fig. 2 depicts the secondary reading task shown in either a smartphone or a Google Glass.

D. Procedure

After granting informed consent to participate, subjects filled in a survey about their driving experience and demographic information. The experiment then measured subjects visual acuity. Only drivers who had normal visual acuity and at least three years driving experience were allowed to participate.

After receiving a brief description of the driving and reading tasks, subjects completed a practice drive to familiarize themselves with the simulator and the driving environment. The practice drive included all three task conditions, in the following order: drive - only, drive + smartphone, drive + glass, each lasting about three minutes. The experimental blocks began after subjects reported that they fully understood the instructions and were comfortable driving in the simulator. All subjects completed three drives, one in each task condition, with the order of conditions counterbalanced across subjects. The readings materials were shown in a fixed order from chapter one to six. The order of the experimental conditions was counter-balanced using Latin-Square design. An experimenter pressed buttons to log when drivers started reading and when they paused for more than one second. These time-stamped key presses were logged into the vehicle dynamics data files so that we could determine when drivers were performing the reading task. Each drive lasted exactly fifteen minutes, and subjects were given a chance to rest between blocks. At the end of each trial, subjects self-reported their mental workload using the NASA-TLX workload scale [53], [54].

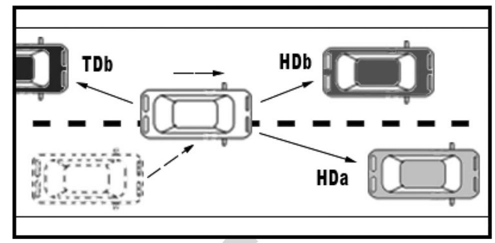

Fig. 3. Safety margin measures during tactical lane changes.
(Note: The white subject vehicle moves from the lower lane into the upper lane. HDa, headway distance to the lead vehicle in the original lane; HDb, headway distance to the lead vehicle in the new lane; TDb, tailway distance to the trailing vehicle in the new lane.)

E. Dependent Variables

Three aspects of driving performance were assessed: car following, lane keeping, and the safety margins during tactical lane change.

The measures of lane-keeping performance included the mean and standard deviation of lane position, the duration of lane excursions, the number of purposeful lane changes, and the standard deviation of steering wheel position. The zero reference point of lane position was the center of the right lane. A larger standard deviation of lane position and a longer duration of lane excursions indicate poorer lane-keeping performance, with higher risks of lane departure and collisions with vehicles in the neighboring lanes. A positive value of lane position indicates a deviation to the left of the center of the right lane. Increased standard deviation of steering wheel position indicates decreased vehicular control and suggests increased workload [55], [56]. We operationally defined a lane excursion as a shift to a new lane for less than three seconds followed by a return to the previous lane. If drivers entered a new lane and stayed in the new lane for longer than three seconds, this was defined as a purposeful lane change.

The measurements for car-following performance included the mean and standard deviation of speed and headway distance.

Measures of safety margins when passing included headway distance to the lead vehicle in the original lane (HDa) and in the new lane (HDb), and tailway distance to the vehicle in the new lane (TDb). Headway distance is the distance between the driver's car and the closest leading car in the passing lane. Tailway distance is the distance between the driver's car and the passed vehicle when the driver enters the new lane. Fig. 3 depicts the definition of the three safety margin variables.

Secondary reading task performance was measured using the number of words per minute subjects read.

III. Results

A. Lane-Keeping Performance

For the standard deviation of lane position, analysis of variances revealed a significant effect of condition, F (2, 58) = 5.53,

$p = .006$, $\eta_p^2 = .16$. Pairwise comparisons indicated that standard deviation of lane position in the drive - only condition ($M =$ 0.50 m, $SD =$ 0.08 m) and the drive + glass condition ($M = 0.50$ m, $SD = 0.09$ m) were significantly smaller than that in the drive + smartphone condition ($M =$ 0.53 m, $SD =$ 0.09 m), $t\,(29) =$ 3.00, $p = .005$ and $t\,(29) =$ 3.10, $p = .004$ respectively. The standard deviation of lane position did not differ significantly between the drive + glass and drive – only conditions, $t\,(29) =$ .05, $p = .96$. Analysis of the rooted mean square error of lane position produced similar results.

The total duration of lane excursions for the 15-minute drive also varied across conditions, F (2, 58) = 3.96, $p = .03$, $\eta_p^2 = .12$. Drivers produced significantly briefer lane excursions in the drive - only condition ($M = 17.05$ s, $SD =$ 4.45 s) than in the drive + smartphone condition ($M =$ 21.87 s, $SD =$ 12.74 s), t (29) = 2.26, $p = .03$. The total duration of lane excursions did not differ between drive – only condition and drive + glass condition ($M =$ 18.82 s, $SD =$ 7.62 s), t (29) = 1.53, $p = .14$, nor between the drive + glass condition and the drive + smartphone condition, $t\,(29) = 1.73$, $p = .09$.

The combination of more variable lane position and longer duration of lane excursions in the drive + smartphone condition than the drive – only condition suggest that smartphone use impaired lane-keeping performance. Although these factors were numerically larger in the drive + glass condition, they did not differ significantly from the drive - only condition.

The standard deviation of steering wheel position also generated a significant main effect of driving conditions, F (2, 58) = 40.31, $p < .001$, $\eta_p^2 =$ .58. The standard deviation of steering wheel position in the drive – only condition ($M = 2.97°$, $SD = 0.63°$) was significantly smaller than that of the drive + glass condition ($M = 3.94°$, $SD = 0.80°$) and the drive + smartphone condition ($M = 3.95°$, $SD = 0.79°$), t (29) = 8.12, $p <$ .001 and t (29) = 6.86, $p <$ .001 respectively. The standard deviation of steering wheel position was similar for the drive + glass and drive + smartphone condition, t (29) = 0.15, $p = .88$. Higher standard deviation of steering wheel position in the distracted driving conditions indicates higher workload of drivers when they drive while reading from the HMD or the smartphone [55], [56].

The total number of purposeful lane change maneuvers in the fifteen-minute drive also showed a significant effect of task condition, F (2, 58) = 7.98, $p = .001$, $\eta_p^2 = .22$. Drivers changed lanes less often in the drive + smartphone condition ($M = 22.66$, $SD = 8.59$) and the drive + glass condition ($M = 25.64$, $SD = 10.63$) than in the drive - only condition ($M = 30.21$, $SD = 13.28$), t (29) = 11.66, $p = .001$ and $t\,(29) = 2.16$, $p = .04$ respectively. The number of lane changes in the drive + smartphone condition was also smaller than in the drive + glass condition, $t\,(29) = 2.08$, $p = .05$. To ensure these effects were not an artifact of the automated algorithm used to classify lane changes, two research assistants working independently coded the data manually, counting lane changes in every experimental drive. The data based on the manual coding of the research assistants produced the same pattern of results as the data generated by the automated algorithm for the number of purposeful lane change maneuvers.

TABLE I
SAFETY MARGINS DURING TACTICAL LANE CHANGE, *M (SD)*

	Distance (m)		
	Mean HD_a	Mean HD_b	Mean TD_b
Drive - only	43.57 (17.69)	89.81 (20.01)	133.64 (56.77)
Drive + glass	45.73 (17.86)	89.33 (20.30)	136.40 (61.45)
Drive + smartphone	46.63 (21.62)	92.27 (20.31)	141.89 (71.45)
F (2, 58)	.44	.17	.07
p value	.65	.84	.94

Note. HD_a = closest headway distance to the vehicle being passed; HD_b = initial headway distance to a vehicle in the target lane; TD_b = initial tailway distance to a trailing vehicle in the target lane.

B. Speed

Analysis of speed showed a significant main effect of condition (F (2, 58) = 8.48, $p = .001$, $\eta_p^2 = .23$), with significantly higher speed in drive - only condition ($M = 62.75$ mph, $SD = 3.21$ mph) than in the drive + glass condition ($M =$ 60.81 mph, $SD = 4.12$ mph) or the drive + smartphone condition ($M = 57.34$ mph, $SD = 8.37$ mph), $t\,(29) = 3.57$, $p =$ .001 and $t\,(29) =$ 3.41, $p = .002$ respectively. The speed in the drive + glass condition was also higher than that in the drive + smartphone condition, t (29) = 2.10, $p = .04$. The standard deviation of speed did not vary significantly across conditions, F (2, 58) = .51, $p = .61$, $\eta_p^2 = .02$.

C. Tactical Vehicle Control Performance

The literature suggests that distracted drivers may drive more slowly [57], [58] or increase their headway distance [59], [60] to offset increased risks. To explore whether drivers using Google Glass or a smartphone exhibit such adaptive behaviors, we measured drivers' safety margins during tactical lane change. We used three measures to gauge safety margins, including headway distance to the lead vehicle in the original lane (HDa) and in the new lane (HDb), and tailway distance to the vehicle in the new lane (TDb). Headway time was also explored and generated similar results to headway distance. Thus, only the results based on headway distance and tailway distance were reported here. We found no significant effect of condition for any of the three measures of safety margin, suggesting that drivers did not adaptively adjust their driving behaviors when distracted (a finding that mimics evidence from [51]. See Table I for details.

Drivers may adaptively choose to read only when they had a safe headway distance and stop reading when they had a risky headway distance. Thus, we further compared the headway and tailway distances when drivers were reading and not reading. Two-way analyses of variances were used with devices (HDD versus HMD) and reading status (reading versus not reading) as within-subject factors. Both headway distances to the vehicle in the original lane (HDa) to the vehicle in the new lane (HDb) did not produce any significant effects, all ps $>.10$.

However, tailway distance to vehicle in the new lane (TDb) did generate a significant main effect of reading, F (1, 20) = 5.43, $p = .03$, $\eta_p^2 = .21$. Tailway distance was longer when reading ($M = 155.30$ m, $SD = 106.26$ m) than not reading ($M = 120.99$ m, $SD = 83.61$ m) during tactical lane changes.

Distracted drivers sometimes maintain a longer headway distance [61]. For example, Greenberg *et al.* reported that drivers engaging in a visual secondary task increased their headway distance. Drivers may not increase their headway distance or headway time during tactical lane change or approaching a vehicle, but still be able to increase their safety margins in steady car following. To explore possible adaptive behaviors in steady car following, we calculated the headway distance in a steady-state period too. We defined a steady-state period as the time period when the change rate of headway distance fell below 1.5 m/s for at least five seconds [51]. The mean headway distance during steady-state periods did not differ across task conditions, F (2, 58) = 1.16, $p = .32$, $\eta_p^2 = .04$. Similarly, the mean headway distance calculated across the whole trials (including headway distance in the steady-state and tactical lane change periods) did not differ across task conditions too, F (2, 58) = .06, $p = .95$, $\eta_p^2 = .002$. The headway distance result suggested that drivers did not adaptively increase their headway distance when reading from a smartphone or Google Glass in either tactical lane change or steady car following periods.

D. Reading Performance

For lane-keeping performance, we found that the increase of variability of lane position and the total duration of lane excursions was smaller when drivers reading from an HMD than from an HDD, which suggest less impairment of lane-keeping performance for HMD users than HDD users. The reduction of task interference for the HMD could benefit from the potential advantage of an HMD (Google Glass) over an HDD (smartphone) or a strategy change. It is possible that drivers performed better in the drive + glass condition than the drive + smartphone condition by reading slower in the drive + glass condition. To explore this possibility, we also measured drivers' reading speed.

Contrary to the later explanation of a strategy change, participants read significantly more words when using the HMD ($M = 91.28$ words per minute, $SD = 34.89$) than the HDD ($M = 80.47$ words per minute, $SD = 36.91$), t (26) = 2.05, $p = .05$. The data thus suggested that the performance advantage of HMD was not because subjects deprioritized the reading task when using HMD.

E. Subjective Workload

We measured drivers' workload at the end of each trial using the NASA-TLX scale [53], [54]. Three subjects did not finish the NATA-TLX scale and were excluded from the analysis, leaving 27 valid participants. Participants' overall total workload was significantly different across driving conditions, F (2, 52) = 62.91, $p < .001$, $\eta_p^2 = .71$. Drivers in the drive – only condition ($M = 26.51$, $SD = 16.85$) reported significantly lower workload than the drive + glass condition ($M = 55.09$, $SD = 19.57$) and drive + smartphone condition ($M = 62.86$, $SD = 17.22$), t (26) = 9.67, $p < .001$ and t (26) = 10.74, $p < .001$. The self-reported workload in the drive + glass condition was significantly lower than the drive + smartphone condition too, t (26) = 2.04, $p = .05$. The finding of higher self-reported workload in the distracted driving conditions resonates the result of larger standard deviation of steering wheel position. Reading from both the HDD and the HMD while driving significantly increased drivers' workload.

F. User Preference of HDD Versus HMD

We also asked drivers to report their preference of an HDD versus an HMD while driving at the end of an experiment. Four subjects did not complete the surveys, leaving 26 survey respondents. Binomial Sign Tests were used to compare subjects' preference of the HMD and the HDD. Seven subjects considered the HMD to be more distracting compared to nineteen who considered the HDD to be more distracting, $p = .36$. Twenty subjects said they drove better with the HMD while six favored the smartphone, $p = .12$. Finally, seventeen subjects preferred driving with the HMD and nine favored the HDD, $p = .36$. The data tends to suggest that more people preferred the HMD over the HDD, but the difference did not reach a statistical significance level. This may because of the relatively small sample size for a user preference survey and relatively lack of using experience of the HMD.

IV. Discussions

This study compared driving performance when drivers read materials shown in two display technologies: an HDD (such as a smartphone) versus an HMD (such as Google Glass). Results showed that, compared to the drive – only condition, drivers using a smartphone produced larger standard deviation of lane position, and longer duration of lane excursions, which indicated higher risks of lane departures or collisions with vehicles in the side lanes. Distracted drivers also reported higher subjective workload and produced higher standard deviation of steering wheel position. The performance of drivers reading materials shown in the HMD sits in-between the drive – only condition and drive + smartphone condition. The finding suggests a potential benefit of HMD over HDD as an in-vehicle display. Nevertheless, both reading from the HMD and the HDD impaired driving performance.

We observed that the HMD impaired driving less than the HDD when reading while driving. This reduction of task interference may partially result from the reduction of visual distraction for drivers using the HMD. HMDs can reduce visual distractions and help wearers focus on their primary tasks, as reported in the aviation and health care fields. When drivers move their eyes to look at the smartphone (an HDD), they cannot process detailed visual information during saccadic eye movement, which we called *saccadic suppression*. Google Glass (an HMD) is positioned significantly nearer to the drivers' gaze points than the smartphone (an HDD), thus the duration of saccadic suppression is shorter for an HMD than an HDD. In addition, the smartphone can be placed at several places when not in use, such as in the pocket, a cup-holder or the passenger seat, while HMD is always worn on the head. Thus, drivers can take less time to look for and reach the HMD than the HDD, which thereby reduces the amount of visual distraction. For example, HUDs can reduce the number of visual distractions that HDDs causes and let operators focus on the forward view [17], [19], [62], [63]. Anesthesiologists wearing an HMD spent more time looking at their patients and less time toward the anesthesia machine than when using a standard monitoring alone. They also reported they were less busy and performed better in detecting abnormal changes [64].

This study demonstrated that an HMD allowed drivers to read more and caused less driving performance decrement than an HDD. An HMD may be a better option to show visual information than an HDD for display-intensive in-vehicle tasks, such as map reading, GPS navigation, dashboard display, Eco-Driving feedback, etc. The location of the information display is an important factor in the detection performance of in-vehicle display tasks. Researchers at the University of Michigan Transportation Research Institute did a couple of studies examining the optimal location for an HUD. They found that the most preferable location for an HUD was five degrees right or left of the center [65], [66]. Horrey & Wickens (2004) reported drivers using an HDD (approximately 38° offset from the center of the horizon line; 34 cm below and 37 cm to the right) produced longer response times to critical events and larger variability of lane position than the adjacent display (seven degrees below horizon point)[67]. Similarly, an HMD, such as Google Glass, which shows important information near drivers' field of view and within the preferred five-degree boundary for an HUD, may be better than an HDD to show task-critical information.

Drivers engaging in a secondary task may adapt to the increase in driving risks by reducing speed [57], [58], increasing headway distance [59], [60] or changing lanes less often. Some of these adaptive behaviors were observed in this study, such as reduction of speed. Drivers using an HMD or an HDD both reduced the speed and changed lanes less often, and the behavioral change was more pronounced when drivers used an HDD compared to an HMD. However, such adaptive behaviors may depend on the driving scenario. No increase in safety margins was observed during the tactical lane change behaviors in this study or in the study of Horrey and Simons (2007).

In-vehicle display technology, such as HDD and HMD, can be a double-edge sword. If used properly, smartphones and Google Glass can improve driving safety. For example, we can use mobile devices as a GPS navigation device [68], a collision warning system [69], a drowsiness detection system [70], or a driver-training device. If mobile devices are improperly used to distract drivers, for example with texting, cell phone conversation, or writing E-Mails while driving, mobile devices will harm driving performance [43], [71]. More efforts should be aimed at educating drivers to use these in-vehicle technologies properly and develop new technologies to improve driving safety.

Drivers need to have a better understanding of how their driving performance is impacted by various in-vehicle technologies. This study found that HMD was less distracting than an Android smartphone when reading stories displayed on the mobile devices. It does not suggest that the HMD is mind-free and risk-free. Contrary to the intuitive belief that it is safe to drive while using an HMD e.g. Google Glass, it still impaired driving performance. The false belief that an HMD is risk-free may increase drivers' exposure to distraction while driving. Considering that the HMD makes distractions more accessible to drivers than a smartphone, it is likely that the HMD can be more distracting than the HDD if drivers engage in distracting tasks using the HMD significantly longer than the HDD. Future studies should investigate whether drivers are more likely to engage in distracting tasks when using HMDs versus other displays types. In addition, future research can consider advanced deep learning [72] and signal processing algorithm [73] to extract rich information from driving data and detect driver distraction in the dynamic driving environment.

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Which is a Better In-Vehicle Information Display? A Comparison of Google Glass and Smartphones

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***Abstract*—In-vehicle information display is critical for driving safety and has been the focus of transportation and display technology research. Cellphone use, while driving is popular, leads to distraction and impairs driving performance. A new head-mounted display (HMD), Google Glass, has been developed in hope of reducing the visual distractions caused by a head-down display (HDD), such as a smartphone. Alternatively, HMD could induce greater distraction by giving drivers the false impression that they are simultaneously paying attention to both the HMD and the road. We compared driving performance in a simulated tactical lane-changing task while drivers read from either an HMD (e.g., Google Glass) or an HDD (e.g., smartphone). Although both HMD and HDD use impaired driving performance, drivers produced smaller lane variation, had fewer lane excursions, and lower subjective workload when using an HMD than when using an HDD. Wearable display technologies like Google Glass might reduce the impairment caused by looking down at a smartphone.**

***Index Terms*—Adaptive safety behaviors, head-down display (HDD), Head mounted display (HMD), in-vehicle display, Google Glass, Tactical vehicle control, smartphone.**

I. Introduction

IN-VEHICLE information displays and mobile devices, such as iPods, mobile media players, smartphones, wearable head-mounted displays (HMD, for example Google Glass) and smart watches, are increasingly prevalent [1]–[4]. The rapid increase of these in-vehicle displays is accompanied by increasing driving risk [3], [5]–[7]. A multiple regression analysis estimated that as many as 16,141 additional distracted driving fatalities were caused by the increases in texting volume for the years 2002 to 2007 [8].

The recent development of wearable display technologies brings many new gadgets into vehicles, such as Google Glass. Google Glass is a monocular optical HMD in the shape of glasses. Google Glass is essentially an Android device, which allows almost all functions of a smartphone, such as cell phone conversation, texting, Internet browsing and E-Mail composition. Google Glass mainly uses voice recognition technology for inputs and shows information in an optical HMD near the top of the right eye. HMDs and head-up displays (HUDs) share many similarities; both displays allow users to look at or through the displayed image and view the world beyond [9]. As HMD like Google Glass is entering the vehicle, many people, including driving researchers, auto-manufacturers, insurance companies, legislators, software developers and drivers, hope to know whether it is safe to drive while using an HMD and how distracting an HMD is compared to other alternate display technologies, such as smartphones and head-down displays (HDDs).

HMD like Google Glass may be potentially less risky than a smartphone, or other HDDs. Like other HMDs or HUDs, HMD can show task-critical information in the perceptual neighborhood [10], thus reducing eye scanning compared to HDDs, such as a dashboard or a smartphone display [11]–[13]. HMDs make information easily accessible and minimize mental workload [12]–[16]. Thus, several driving studies have shown that drivers using HUD produced better lane-keeping, better speed maintenance and quicker response time for speed limit sign changes and urgent events [17]–[20].

Despite the benefits of HMDs, the type of display may also pose many risks to driving performance. HMDs may incur binocular rivalry, a known problem for HMDs because of content instability and visual occlusions [21]–[23]. HMDs can also cause eyestrain, which is a common issue associated with HMD use [24], [25]. In addition, HMD can potentially increase visual clutter, which increases perceptual workload [26] and causes a fixation tunnel effect [13]. HMD can potentially incur inattentional blindness, a common phenomenon which users fail to detect salient unexpected events in the outside world [27]–[29]. In a flight simulator, pilots wearing a HUD or a HMD are more likely to miss a runway incursion than when using a HDD, even when the runway incursion is clearly visible in their field of view [28], [30]. Moreover, HMD such as Google Glass brings potential distractors closer to eyes, which may increase drivers' exposure to distractions. Users of Google Glass can initiate a distracting task, such as sending text messages, by simply nodding their head to light up the Google Glass display. The easy accessibility of HMD to distractions may expose its users more frequently to distracting tasks unrelated to driving than a smartphone.

It is important to understand how HMDs (such as Google Glass) and cell phones (including smartphone) influence driving performance, as driver distraction is one of the major causes of traffic crashes. While we know little about how an HMD/Google Glass influences driving, the influence of cell phone use on driving performance has attracted the attention of legislators and researchers.

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Cell phone use, including cell phone conversation, texting and E-Mail composition, impairs driving performance in various ways. For example, cell phone use increases braking response time [31]–[34], causes larger variations of lane position [35]–[41], incurs higher mental workload [41], [42], increases gaze-off-road durations [38], [39], [42], [43], causes more collisions [32], [35], and raises the risks of traffic accident as many as 23 times for truck drivers [44]. Thus, many governments have banned the use of cell phones, either or both handheld and hands-free cell phones while driving.

Compared to the attention paid to cell phone use while driving, studies of HMDs, such as Google Glass, on driving performance are scarce. However, HMDs are widely used and investigated in the aviation and medical domains [23], [45]–[47]. The aviation literature often suggests that pilots produce better performance when using HMDs than HDDs [45], [48]. Only a few studies have compared the driving performance costs of HUD and HDDs [20], [49], finding relatively reduced performance decrement with a HUD. However, HMD differs from HUD in several aspects, such as stability of the display information and binocular rivalry. Will an HMD incur the same performance costs as an HDD, or will it be more comparable to an HUD? Safety researchers have only recently begun exploring how HMD influences driving performance [3], [7], [22], [50]. However, these studies all used a car-following task and did not assess other aspects of driving performance, such as tactical lane changes. Additionally, these studies mainly focused on the speech-recognition feature of Google Glass [3], [7], [50]. None of the studies examines the performance costs of using the visual HMD of Google Glass. In the current study, we investigated how reading using the transparent HMD of Google Glass influences driving performance. Driving performance was gauged using a tactical lane change task, in which drivers drove in a straight three-lane road with intermittent traffic and changed lanes when necessary to maintain a safety margin [51]. The tactical lane change task mimics highway driving in rush hours.

II. Methods

A. Subjects

Thirty members of the Wichita State University community (17 males and 13 females, mean age = 21.47 years, $SD = 4.89$ years) received course credit for participating. All had held a driver's license for at least three years prior to the experiment ($M = 6.26$ years, $SD = 4.31$ years), and their self-reported annual mileage averaged 10 976 miles ($SD = 8330$ miles). All subjects reported having normal or corrected-to-normal visual acuity. One subject was excluded from analysis after the subject reported motion sickness during the experiment.

B. Apparatus and Stimuli

Data were collected at the Human Automation Interaction Laboratory at Wichita State University. The driving scenarios were created using HyperDrive Authoring Suite Version 1.6.1 and controlled by Drive Safety's Vection Simulation Software^{TM} Version 1.6.1. The driving simulator consisted of three 26-inch ASUS monitors (1920 × 1080 pixels). Drivers sat approximately one meter away from the front monitor, at a visual angle of 76°. Road information was visible both through the windows and through rear-view and side mirrors, and vehicle dynamics were sampled at 60 Hz.

(a) (b)

Fig. 1. Android smartphone and Google Glass used in this driving study. (a). Android smartphone. (b). Google glass.

A smartphone and a Google Glass were used to display the secondary reading task. The smartphone was a 4.0" Samsung touch-screen smartphone running Android 4.04 displayed. The smartphone had a 1.2 GHz dual core processor. The resolution of the Super AMOLED^{TM} display is 800 × 480 WVGA. Google Glass had monocular optical HMD, which was equivalent to a 25-inch high definition screen viewed from a distance of eight feet. Google Glass was worn like a regular pair of glasses. The Google Glass had a 1.2 GHz dual core processor and 640 × 360 resolution display. Please see Fig. 1 for an example of the devices.

C. Driving and Reading Tasks

Lane-change task. The driving task consisted of an unconstrained drive on a straight, six-lane divided freeway, with three lanes in either direction (see [51]). The vehicle started on a freeway entry ramp, and drivers then merged onto the freeway. The posted speed limit was 65 mph. Drivers were told to obey all traffic rules, but were free to change lanes and pass vehicles when appropriate.

Other vehicles (all four-door sedans) drove in the same direction as the driver's vehicle. The initial gaps between vehicles were randomly selected from a uniform distribution ranging from 140 to 180 m, and each vehicle's speed was randomly selected from a uniform distribution between 64 and 122 kph. Faster vehicles spontaneously passed slower ones by changing lanes while maintaining safe headway distances. The variability of vehicle speed and spontaneous passing led to naturalistic patterns of traffic congestion, with some dense traffic regions and other regions with little traffic.

Secondary reading task. In the distracted driving conditions, drivers performed a reading task designed to simulate reading while driving, which was roughly comparable to reading web pages, E-Mails, and text messages while driving. The reading materials were excerpted from chapter one to six of *Alice's*

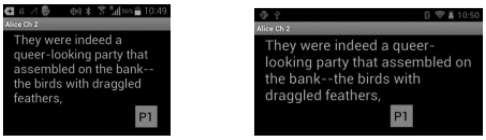

Fig. 2. Reading materials shown in Android and Google Glass. (a). Android smartphone (b) Google glass.

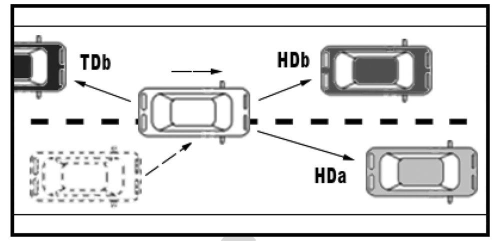

Fig. 3. Safety margin measures during tactical lane changes. (Note: The white subject vehicle moves from the lower lane into the upper lane. HDa, headway distance to the lead vehicle in the original lane; HDb, headway distance to the lead vehicle in the new lane; TDb, tailway distance to the trailing vehicle in the new lane.)

Adventures in Wonderland [52]. Drivers read aloud as they drove. Subjects wore the Google Glass or held the smartphone in their hand when reading the materials. Subjects were instructed to put the smartphone back in the same location of the simulator deck. Fig. 2 depicts the secondary reading task shown in either a smartphone or a Google Glass.

For the reading task, drivers pressed a ‘start’ button to start showing the reading materials. For the Android phone, drivers touched anywhere on the touch screen to show the next page. For Google Glass, drivers touched anywhere on the arm of Google Glass to show the next page. The time stamp for each page -forward event was saved by the application showing the secondary reading task.

The same Android application controlled the display of reading materials for the smartphone and Google Glass. The text content, number of words, font size, and text-alignment (left-aligned) were the same across the two devices. For Google Glass, text appeared in a transparent display positioned at the upper corner of the right eye’s field of view when the subject looked straight ahead. The text appeared to be overlaid on the simulated world. Fig. 2 depicts the secondary reading task shown in either a smartphone or a Google Glass.

D. Procedure

After granting informed consent to participate, subjects filled in a survey about their driving experience and demographic information. The experiment then measured subjects visual acuity. Only drivers who had normal visual acuity and at least three years driving experience were allowed to participate.

After receiving a brief description of the driving and reading tasks, subjects completed a practice drive to familiarize themselves with the simulator and the driving environment. The practice drive included all three task conditions, in the following order: drive - only, drive + smartphone, drive + glass, each lasting about three minutes. The experimental blocks began after subjects reported that they fully understood the instructions and were comfortable driving in the simulator. All subjects completed three drives, one in each task condition, with the order of conditions counterbalanced across subjects. The readings materials were shown in a fixed order from chapter one to six. The order of the experimental conditions was counter-balanced using Latin-Square design. An experimenter pressed buttons to log when drivers started reading and when they paused for more than one second. These time-stamped key presses were logged into the vehicle dynamics data files so that we could determine when drivers were performing the reading task. Each drive lasted exactly fifteen minutes, and subjects were given a chance to rest between blocks. At the end of each trial, subjects self-reported their mental workload using the NASA-TLX workload scale [53], [54].

E. Dependent Variables

Three aspects of driving performance were assessed: car following, lane keeping, and the safety margins during tactical lane change.

The measures of lane-keeping performance included the mean and standard deviation of lane position, the duration of lane excursions, the number of purposeful lane changes, and the standard deviation of steering wheel position. The zero reference point of lane position was the center of the right lane. A larger standard deviation of lane position and a longer duration of lane excursions indicate poorer lane-keeping performance, with higher risks of lane departure and collisions with vehicles in the neighboring lanes. A positive value of lane position indicates a deviation to the left of the center of the right lane. Increased standard deviation of steering wheel position indicates decreased vehicular control and suggests increased workload [55], [56]. We operationally defined a lane excursion as a shift to a new lane for less than three seconds followed by a return to the previous lane. If drivers entered a new lane and stayed in the new lane for longer than three seconds, this was defined as a purposeful lane change.

The measurements for car-following performance included the mean and standard deviation of speed and headway distance.

Measures of safety margins when passing included headway distance to the lead vehicle in the original lane (HDa) and in the new lane (HDb), and tailway distance to the vehicle in the new lane (TDb). Headway distance is the distance between the driver’s car and the closest leading car in the passing lane. Tailway distance is the distance between the driver’s car and the passed vehicle when the driver enters the new lane. Fig. 3 depicts the definition of the three safety margin variables.

Secondary reading task performance was measured using the number of words per minute subjects read.

III. Results

A. Lane-Keeping Performance

For the standard deviation of lane position, analysis of variances revealed a significant effect of condition, F (2, 58) = 5.53,

$p = .006$, $\eta_p^2 = .16$. Pairwise comparisons indicated that standard deviation of lane position in the drive - only condition ($M = 0.50$ m, $SD = 0.08$ m) and the drive + glass condition ($M = 0.50$ m, $SD = 0.09$ m) were significantly smaller than that in the drive + smartphone condition ($M = 0.53$ m, $SD = 0.09$ m), $t\,(29) = 3.00$, $p = .005$ and $t\,(29) = 3.10$, $p = .004$ respectively. The standard deviation of lane position did not differ significantly between the drive + glass and drive – only conditions, $t\,(29) = .05$, $p = .96$. Analysis of the rooted mean square error of lane position produced similar results.

The total duration of lane excursions for the 15-minute drive also varied across conditions, $F\,(2, 58) = 3.96$, $p = .03$, $\eta_p^2 = .12$. Drivers produced significantly briefer lane excursions in the drive - only condition ($M = 17.05$ s, $SD = 4.45$ s) than in the drive + smartphone condition ($M = 21.87$ s, $SD = 12.74$ s), $t\,(29) = 2.26$, $p = .03$. The total duration of lane excursions did not differ between drive – only condition and drive + glass condition ($M = 18.82$ s, $SD = 7.62$ s), $t\,(29) = 1.53$, $p = .14$, nor between the drive + glass condition and the drive + smartphone condition, $t\,(29) = 1.73$, $p = .09$.

The combination of more variable lane position and longer duration of lane excursions in the drive + smartphone condition than the drive – only condition suggest that smartphone use impaired lane-keeping performance. Although these factors were numerically larger in the drive + glass condition, they did not differ significantly from the drive - only condition.

The standard deviation of steering wheel position also generated a significant main effect of driving conditions, $F\,(2, 58) = 40.31$, $p < .001$, $\eta_p^2 = .58$. The standard deviation of steering wheel position in the drive – only condition ($M = 2.97°$, $SD = 0.63°$) was significantly smaller than that of the drive + glass condition ($M = 3.94°$, $SD = 0.80°$) and the drive + smartphone condition ($M = 3.95°$, $SD = 0.79°$), $t\,(29) = 8.12$, $p < .001$ and $t\,(29) = 6.86$, $p < .001$ respectively. The standard deviation of steering wheel position was similar for the drive + glass and drive + smartphone condition, $t\,(29) = 0.15$, $p = .88$. Higher standard deviation of steering wheel position in the distracted driving conditions indicates higher workload of drivers when they drive while reading from the HMD or the smartphone [55], [56].

The total number of purposeful lane change maneuvers in the fifteen-minute drive also showed a significant effect of task condition, $F\,(2, 58) = 7.98$, $p = .001$, $\eta_p^2 = .22$. Drivers changed lanes less often in the drive + smartphone condition ($M = 22.66$, $SD = 8.59$) and the drive + glass condition ($M = 25.64$, $SD = 10.63$) than in the drive - only condition ($M = 30.21$, $SD = 13.28$), $t\,(29) = 11.66$, $p = .001$ and $t\,(29) = 2.16$, $p = .04$ respectively. The number of lane changes in the drive + smartphone condition was also smaller than in the drive + glass condition, $t\,(29) = 2.08$, $p = .05$. To ensure these effects were not an artifact of the automated algorithm used to classify lane changes, two research assistants working independently coded the data manually, counting lane changes in every experimental drive. The data based on the manual coding of the research assistants produced the same pattern of results as the data generated by the automated algorithm for the number of purposeful lane change maneuvers.

TABLE I
SAFETY MARGINS DURING TACTICAL LANE CHANGE, *M (SD)*

	Distance (m)		
	Mean HD_a	Mean HD_b	Mean TD_b
Drive - only	43.57 (17.69)	89.81 (20.01)	133.64 (56.77)
Drive + glass	45.73 (17.86)	89.33 (20.30)	136.40 (61.45)
Drive + smartphone	46.63 (21.62)	92.27 (20.31)	141.89 (71.45)
F (2, 58)	.44	.17	.07
p value	.65	.84	.94

Note. HD_a = closest headway distance to the vehicle being passed; HD_b = initial headway distance to a vehicle in the target lane; TD_b = initial tailway distance to a trailing vehicle in the target lane.

B. Speed

Analysis of speed showed a significant main effect of condition ($F\,(2, 58) = 8.48$, $p = .001$, $\eta_p^2 = .23$), with significantly higher speed in drive - only condition ($M = 62.75$ mph, $SD = 3.21$ mph) than in the drive + glass condition ($M = 60.81$ mph, $SD = 4.12$ mph) or the drive + smartphone condition ($M = 57.34$ mph, $SD = 8.37$ mph), $t\,(29) = 3.57$, $p = .001$ and $t\,(29) = 3.41$, $p = .002$ respectively. The speed in the drive + glass condition was also higher than that in the drive + smartphone condition, $t\,(29) = 2.10$, $p = .04$. The standard deviation of speed did not vary significantly across conditions, $F\,(2, 58) = .51$, $p = .61$, $\eta_p^2 = .02$.

C. Tactical Vehicle Control Performance

The literature suggests that distracted drivers may drive more slowly [57], [58] or increase their headway distance [59], [60] to offset increased risks. To explore whether drivers using Google Glass or a smartphone exhibit such adaptive behaviors, we measured drivers' safety margins during tactical lane change. We used three measures to gauge safety margins, including headway distance to the lead vehicle in the original lane (HDa) and in the new lane (HDb), and tailway distance to the vehicle in the new lane (TDb). Headway time was also explored and generated similar results to headway distance. Thus, only the results based on headway distance and tailway distance were reported here. We found no significant effect of condition for any of the three measures of safety margin, suggesting that drivers did not adaptively adjust their driving behaviors when distracted (a finding that mimics evidence from [51]. See Table I for details.

Drivers may adaptively choose to read only when they had a safe headway distance and stop reading when they had a risky headway distance. Thus, we further compared the headway and tailway distances when drivers were reading and not reading. Two-way analyses of variances were used with devices (HDD versus HMD) and reading status (reading versus not reading) as within-subject factors. Both headway distances to the vehicle in the original lane (HDa) to the vehicle in the new lane (HDb) did not produce any significant effects, all *p*s >.10.

However, tailway distance to vehicle in the new lane (TDb) did generate a significant main effect of reading, F (1, 20) = 5.43, p = .03, $\eta_p^2 = .21$. Tailway distance was longer when reading ($M = 155.30$ m, $SD = 106.26$ m) than not reading ($M = 120.99$ m, $SD = 83.61$ m) during tactical lane changes.

Distracted drivers sometimes maintain a longer headway distance [61]. For example, Greenberg *et al.* reported that drivers engaging in a visual secondary task increased their headway distance. Drivers may not increase their headway distance or headway time during tactical lane change or approaching a vehicle, but still be able to increase their safety margins in steady car following. To explore possible adaptive behaviors in steady car following, we calculated the headway distance in a steady-state period too. We defined a steady-state period as the time period when the change rate of headway distance fell below 1.5 m/s for at least five seconds [51]. The mean headway distance during steady-state periods did not differ across task conditions, F (2, 58) = 1.16, $p = .32, \eta_p^2 = .04$. Similarly, the mean headway distance calculated across the whole trials (including headway distance in the steady-state and tactical lane change periods) did not differ across task conditions too, F (2, 58) = .06, $p = .95, \eta_p^2 = .002$. The headway distance result suggested that drivers did not adaptively increase their headway distance when reading from a smartphone or Google Glass in either tactical lane change or steady car following periods.

D. Reading Performance

For lane-keeping performance, we found that the increase of variability of lane position and the total duration of lane excursions was smaller when drivers reading from an HMD than from an HDD, which suggest less impairment of lane-keeping performance for HMD users than HDD users. The reduction of task interference for the HMD could benefit from the potential advantage of an HMD (Google Glass) over an HDD (smartphone) or a strategy change. It is possible that drivers performed better in the drive + glass condition than the drive + smartphone condition by reading slower in the drive + glass condition. To explore this possibility, we also measured drivers' reading speed.

Contrary to the later explanation of a strategy change, participants read significantly more words when using the HMD ($M = 91.28$ words per minute, $SD = 34.89$) than the HDD ($M = 80.47$ words per minute, $SD = 36.91$), t (26) = 2.05, $p = .05$. The data thus suggested that the performance advantage of HMD was not because subjects deprioritized the reading task when using HMD.

E. Subjective Workload

We measured drivers' workload at the end of each trial using the NASA-TLX scale [53], [54]. Three subjects did not finish the NATA-TLX scale and were excluded from the analysis, leaving 27 valid participants. Participants' overall total workload was significantly different across driving conditions, F (2, 52) = 62.91, $p < .001$, $\eta_p^2 = .71$. Drivers in the drive – only condition ($M = 26.51$, $SD = 16.85$) reported significantly lower workload than the drive + glass condition ($M = 55.09$, $SD = 19.57$) and drive + smartphone condition ($M = 62.86$, $SD = 17.22$), t (26) = 9.67, $p < .001$ and t (26) = 10.74, $p < .001$. The self-reported workload in the drive + glass condition was significantly lower than the drive + smartphone condition too, t (26) = 2.04, $p = .05$. The finding of higher self-reported workload in the distracted driving conditions resonates the result of larger standard deviation of steering wheel position. Reading from both the HDD and the HMD while driving significantly increased drivers' workload.

F. User Preference of HDD Versus HMD

We also asked drivers to report their preference of an HDD versus an HMD while driving at the end of an experiment. Four subjects did not complete the surveys, leaving 26 survey respondents. Binomial Sign Tests were used to compare subjects' preference of the HMD and the HDD. Seven subjects considered the HMD to be more distracting compared to nineteen who considered the HDD to be more distracting, $p = .36$. Twenty subjects said they drove better with the HMD while six favored the smartphone, $p = .12$. Finally, seventeen subjects preferred driving with the HMD and nine favored the HDD, $p = .36$. The data tends to suggest that more people preferred the HMD over the HDD, but the difference did not reach a statistical significance level. This may because of the relatively small sample size for a user preference survey and relatively lack of using experience of the HMD.

IV. Discussions

This study compared driving performance when drivers read materials shown in two display technologies: an HDD (such as a smartphone) versus an HMD (such as Google Glass). Results showed that, compared to the drive – only condition, drivers using a smartphone produced larger standard deviation of lane position, and longer duration of lane excursions, which indicated higher risks of lane departures or collisions with vehicles in the side lanes. Distracted drivers also reported higher subjective workload and produced higher standard deviation of steering wheel position. The performance of drivers reading materials shown in the HMD sits in-between the drive – only condition and drive + smartphone condition. The finding suggests a potential benefit of HMD over HDD as an in-vehicle display. Nevertheless, both reading from the HMD and the HDD impaired driving performance.

We observed that the HMD impaired driving less than the HDD when reading while driving. This reduction of task interference may partially result from the reduction of visual distraction for drivers using the HMD. HMDs can reduce visual distractions and help wearers focus on their primary tasks, as reported in the aviation and health care fields. When drivers move their eyes to look at the smartphone (an HDD), they cannot process detailed visual information during saccadic eye movement, which we called *saccadic suppression*. Google Glass (an HMD) is positioned significantly nearer to the drivers' gaze points than the smartphone (an HDD), thus the duration of saccadic suppression is shorter for an HMD than an HDD. In addition, the smartphone can be placed at several places when not in use, such as in the pocket, a cup-holder or the passenger seat, while HMD is always worn on the head. Thus, drivers can take less time to look for and reach the HMD than the HDD, which thereby reduces the amount of visual distraction. For example, HUDs can reduce the number of visual distractions that HDDs causes and let operators focus on the forward view [17], [19], [62], [63]. Anesthesiologists wearing an HMD spent more time looking at their patients and less time toward the anesthesia machine than when using a standard monitoring alone. They also reported they were less busy and performed better in detecting abnormal changes [64].

This study demonstrated that an HMD allowed drivers to read more and caused less driving performance decrement than an HDD. An HMD may be a better option to show visual information than an HDD for display-intensive in-vehicle tasks, such as map reading, GPS navigation, dashboard display, Eco-Driving feedback, etc. The location of the information display is an important factor in the detection performance of in-vehicle display tasks. Researchers at the University of Michigan Transportation Research Institute did a couple of studies examining the optimal location for an HUD. They found that the most preferable location for an HUD was five degrees right or left of the center [65], [66]. Horrey & Wickens (2004) reported drivers using an HDD (approximately 38° offset from the center of the horizon line; 34 cm below and 37 cm to the right) produced longer response times to critical events and larger variability of lane position than the adjacent display (seven degrees below horizon point)[67]. Similarly, an HMD, such as Google Glass, which shows important information near drivers' field of view and within the preferred five-degree boundary for an HUD, may be better than an HDD to show task-critical information.

Drivers engaging in a secondary task may adapt to the increase in driving risks by reducing speed [57], [58], increasing headway distance [59], [60] or changing lanes less often. Some of these adaptive behaviors were observed in this study, such as reduction of speed. Drivers using an HMD or an HDD both reduced the speed and changed lanes less often, and the behavioral change was more pronounced when drivers used an HDD compared to an HMD. However, such adaptive behaviors may depend on the driving scenario. No increase in safety margins was observed during the tactical lane change behaviors in this study or in the study of Horrey and Simons (2007).

In-vehicle display technology, such as HDD and HMD, can be a double-edge sword. If used properly, smartphones and Google Glass can improve driving safety. For example, we can use mobile devices as a GPS navigation device [68], a collision warning system [69], a drowsiness detection system [70], or a driver-training device. If mobile devices are improperly used to distract drivers, for example with texting, cell phone conversation, or writing E-Mails while driving, mobile devices will harm driving performance [43], [71]. More efforts should be aimed at educating drivers to use these in-vehicle technologies properly and develop new technologies to improve driving safety.

Drivers need to have a better understanding of how their driving performance is impacted by various in-vehicle technologies. This study found that HMD was less distracting than an Android smartphone when reading stories displayed on the mobile devices. It does not suggest that the HMD is mind-free and risk-free. Contrary to the intuitive belief that it is safe to drive while using an HMD e.g. Google Glass, it still impaired driving performance. The false belief that an HMD is risk-free may increase drivers' exposure to distraction while driving. Considering that the HMD makes distractions more accessible to drivers than a smartphone, it is likely that the HMD can be more distracting than the HDD if drivers engage in distracting tasks using the HMD significantly longer than the HDD. Future studies should investigate whether drivers are more likely to engage in distracting tasks when using HMDs versus other displays types. In addition, future research can consider advanced deep learning [72] and signal processing algorithm [73] to extract rich information from driving data and detect driver distraction in the dynamic driving environment.

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Authors' photographs and biographies not available at the time of publication.