RESEARCH & DEVELOPMENT

Designing In-Vehicle Message Delivery with Manual and Highly Automated Driving

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16. Abstract

With the rapid development of sensor and computing technologies, personal vehicles are now capable of collecting voluminous information on vehicle status and the road environment, as well as making proximity estimates and predicting potential driving events. Recent advances in vehicle automation have envisioned future driving without the need for drivers to attend to the road. With these trends in vehicle technology for the driving task, a shift in information communication is taking place from driver-roadway interaction to driver and in-vehicle display interaction. This project examined the influence of in-vehicle dynamic message displays of trip-related but non-safety critical information on driver visual behavior and driving performance, as compared with conventional on-road guide or logo sign use, during manual and highly automated driving. To achieve this goal, we first conducted a literature review on relevant topics. Two experiments were then conducted using the NCSU advanced driving simulator examining how drivers respond to messages posing various information loads during manual driving and automated driving. Our findings support the use of in-vehicle displays, especially in combination with on-road signage.

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Executive Summary

With the rapid development of sensor and computing technologies, personal vehicles are now capable of collecting voluminous information on vehicle status and the road environment, as well as making proximity estimates and predicting potential driving events. Recent advances in vehicle automation have envisioned future driving without the need for drivers to attend to the road. With these trends in vehicle technology for the driving task, a shift in information communication is taking place from driver-roadway interaction to driver and in-vehicle display interaction.

Despite decades of research on in-vehicle notification display designs, the majority of studies have concentrated on presenting information related to the driving task, such as display of collision warnings and navigation information. There is little knowledge on how to effectively present information that is secondary to driving but important for a trip, such as notifications of a rest area and local businesses. This information is conventionally presented on a guide or logo sign. Furthermore, existing research on in-vehicle information presentation during highly automated driving has only focused on safety critical messages such collision warnings. These studies do not necessarily generalize to notifications that are trip-related but non-safety critical information, as driver attentional processing could differ depending on the degree of relevance of the notification to the driving task and under various levels of automation.

This project examined the influence of in-vehicle dynamic message displays of trip-related but non-safety critical information on driver visual behavior and driving performance, as compared with conventional on-road guide or logo sign use, during manual and highly automated driving. To achieve this goal, we first conducted a literature review on the following topics: (1) advances in content and update rates of in-vehicle trip-related messaging, (2) driver interaction with autonomous vehicle technology, (3) driver alertness and information processing, and (4) human factors issues in design of driver notification systems. The research team also performed two empirical studies using the NCSU advanced driving simulator, with the first experiment (E1) examining how drivers respond to messages posing various information loads during manual driving and the second (E2) investigating driver responses to messages when driving with high-level automation.

Our findings support the use of in-vehicle displays, especially in combination with on-road signage.

Under manual driving:

- Driver reactions to road hazards were slower when logos were present but the number of collisions did not increase.
- The use of in-vehicle displays produced better vehicle control with comparable workload and visual distraction, as compared to on-road signage.
- Simultaneous in-vehicle and on-road displays showed a benefit on hazard negotiation (fewer collisions).
- Some age differences were observed in driving and visual behaviors, but the evidence does not suggest any particular age-related safety concerns.

When driving with partial automation (level 2):

- Simultaneous in-vehicle and on-road displays led to the highest logo identification accuracy and little impairment of hazard negotiation when logos were present.
- Simultaneous in-vehicle and on-road displays led to shorter single off-road glance durations and mitigated the effect of information load on driver visual processing. Drivers made fewer but longer glances to on-road signage, as compared to in-vehicle displays.
- Older drivers were less accurate in logo identification than young and middle-aged drivers. However, all three age groups showed comparable driving performance, glance durations, and number of glances.

When driving with conditional automation (level 3):

- Compared to (SAE) Level 2, drivers under Level 3 automation were less accurate in logo identification, likely due to a reduced number of glances to on-road signs.

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1. Background

Conventional road signage communicates traffic laws and route information to drivers via visual signs in or near the right-of-way. This form of communication is one-way communication and some research has identified limited effectiveness in terms of information transfer (Castro, Horberry, & Tornay, 2004; Tiffin & Kissling, 2005). For example, driver awareness of a road sign can be easily affected by weather (e.g., fog vs. clear), lighting conditions (e.g., night vs. day), vegetation growth (e.g., tree branches covering a sign), and sign legibility (e.g., font size of a street name being too small to see). In addition, even when a driver is aware of the presence of a road sign, because they may not perceive an associated action as necessary, driver compliance with some road signs has been found to be surprisingly low. For example, a driver may ignore the need to stop at a stop sign when there is no traffic at an intersection. A comparison across studies conducted from 1931 to 1999 on driver compliance with conventional stop signs using traffic counts revealed a sharp decline in the percentage of drivers who made a full stop at stop signs (Noble, Dingus, & Doerzaph, 2016; p. 2775, Table XIV; full stop from 47% in 1931 to 1% in 1996, full violation from 42% in 1931 to 97% in 1996).

With the development of highly advanced automobile technologies, such as connected vehicles, in-vehicle information systems have been proposed as a potential alternative, or supplement, to road signage (e.g., Creaser & Manser, 2013; Lee, Gore, & Campbell, 1999; Toffin & Kissling, 2005; Zalacain, 2013). Compared to conventional signs, in-vehicle information has many advantages, such as being less susceptible to poor weather conditions and presenting messages that are tailored to traffic conditions (current and anticipatory) as well as driver information needs (e.g., more frequent display of lodging information in the evening). However, very little research has been conducted to guide the presentation of in-vehicle information. Lee et al. (1999) found that in-vehicle messages, such as warnings about "icy roadway" and "accident in lane", were much more effective when presented as redundant information, in addition to road signs, than when presented alone. Caird et al. (2008) found that in-vehicle display of traffic light notifications 8 to 12 s before arriving at an intersection reduced the frequency of drivers running yellow lights. In Creaser and Manser (2013), drivers were provided with in-vehicle speed limit information. Although the displays did not lead to significant improvements in driving performance, drivers rated the in-vehicle information as favorable and helpful when following an unfamiliar route. It is important to note that this limited body of research has focused on in-vehicle display of safety-critical messages. Delivery of non-safety-critical, but trip-related, information (e.g., available local services) remains unexplored. Because our attention varies according to the relevance of a message to concurrent tasks (e.g., safely maneuvering a vehicle; Biehl et al., 2013; Egner & Hirsch, 2005), the findings on in-vehicle messages of safety-critical information may not generalize to messages of non-safety-critical information, such as that presented on guide and logo signs.

With high levels of automation becoming a reality in personal vehicles, the "driving" task for human drivers is being redefined in the context of this new technology. When driving with "full automation", the driver is essentially a "passenger" in the vehicle. Although their responsibilities to vehicle safety may remain unchanged relative to manual control, the extent to which they are involved in vehicle state monitoring, action planning and execution vary according to the "level of automation". A range of changes in driver attention and behavior are expected with increasing automation in vehicles. For example, higher levels of vehicle automation may lead to reduced vigilance of a driver to the road (Saxby et al., 2013), increased driver boredom and drowsiness (Miller et al., 2015; Schömig et al., 2015), more driver engagement in non-driving-related activities (Carsten et al., 2012; Merat et al., 2012), and overreliance on automation (Lee & See, 2004; Saffarian et al., 2012). Given lower levels of vigilance are associated with impaired perceptual, attentional, decision making and motor functions (Oken, Salinsky, & Elsas, 2006), how to deliver in-vehicle messages when a driver is potentially in a low vigilance state remains unclear. In addition, how characteristics of in-vehicle messages (e.g., the amount of information, update rate, and number of messages/graphics for simultaneous presentation) impact overall driver vigilance and, thus influence the effectiveness of driver interaction with a highly automated vehicle, is yet another issue that needs to be examined.

2. Research Questions

The specific research questions addressed by this project include the following:

- When using in-vehicle messaging, can we effectively deliver more information about a business than is typically displayed on a road sign (**Information load**);
- Does in-vehicle messaging enhance or detract from information on roadside signs (when presented simultaneously) (**Information Source**);
- Are the effects of information load and source similar or different among younger, middle-aged and older drivers (**Age**);
- Are any effects of information load and source, as well as driver age, different under different levels of automation (**Level of Automation**).

3. Overview of Project Tasks

The first objective of the proposed work was to develop a protocol for examining in-vehicle message delivery of trip-related information that has been conventionally presented on roadside signs (e.g., guide and logo signs). The protocol and associated apparatus were used for the two planned experiments but can also be used in future research on advanced strategies for in-vehicle message delivery. A second objective of the research was to identify the characteristics of effective message delivery (e.g., the amount of information, update rate, and number of logos for simultaneous presentation) during manual driving. A third objective of the work was to extend our understanding of effective message delivery of trip-related information in a vehicle utilizing high-level automation. The supporting literature review and empirical research activities comprised nine tasks, as illustrated in Figure 1 and described below:
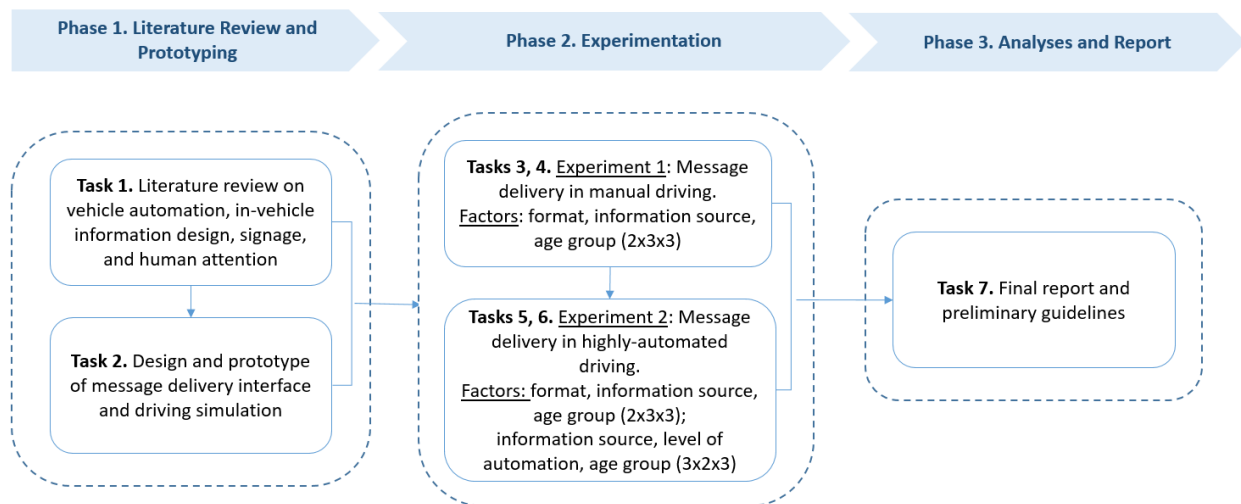

Figure 1. Phases of research and task sequence.

4. Literature Review

We reviewed relevant research findings on advances in messaging content and update rates, driver interaction with high-level vehicle automation, driver alertness and information processing, and human factors issues in design of driver notification systems. Below is an abbreviated summary of and our full literature review manuscript. The manuscript is also attached as Appendix A.

4.1 Review summary

This literature review was motivated by the need to identify critical considerations in effective design and development of in-vehicle road signage presentation. The intent was to provide a detailed review and analysis of knowledge gaps to drive future research on the topic and development of in-vehicle interface designs for highly automated driving.

As automated vehicles become more prevalent on roadways, it is necessary to research driver behavior during interaction with these systems. With higher levels of vehicle automation, drivers can become less engaged with the road environment. For example, how to effectively deliver information that has been traditionally shown on roadside signage is a challenge for state departments of transportation.

In this review, we summarize current knowledge on three existing domains of research: (1) the effectiveness of traditional road signage, (2) vehicle automation and human factors considerations, and (3) current design guidelines of in-vehicle information presentation. Based on a review of existing empirical studies, we identify critical research gaps in the literature to guide the design of effective communication of road signage information in automated vehicles. We also propose a framework (see Figure 2) highlighting various factors that could determine the effectiveness of in-vehicle messaging. These factors include trait-based and state-based characteristics of the driver (e.g., attentional capability, experience with technology), characteristics of the driving environment (e.g., visibility) and vehicle automation (e.g., level of automation), as well as design parameters of the in-vehicle display (e.g., information content and display format).
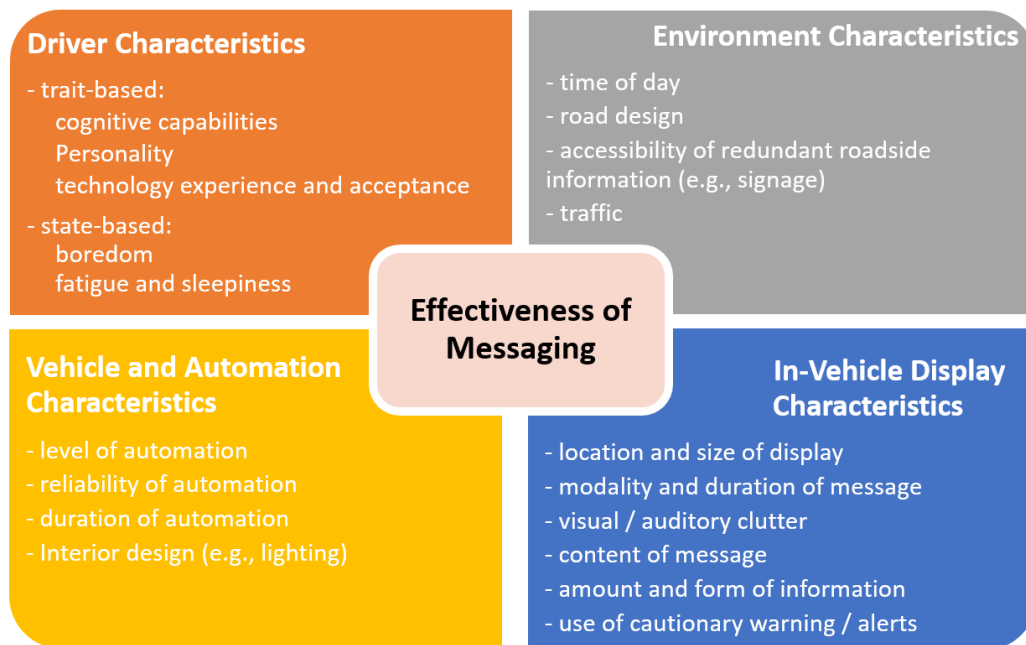
4.2 Proposed conceptual framework of factors

Figure 2. A conceptual framework of factors that could influence the effectiveness of in-vehicle message delivery.

5. Study 1

5.1 Summary

   This study investigated the effects of information source and load on driver signage logo identification, glance behavior, and vehicle control among younger, middle-aged and older drivers. Logos were presented on: (1) an on-road

sign panel, (2) an in-vehicle display, or (3) a combination of both, with half of the drives showing logos only, and the other half showing logos plus additional text.

The general findings support the use of in-vehicle displays, especially when it is presented simultaneously with on-road signs. In-vehicle displays did not lead to higher workload or more visual distraction than the on-road signage only, and simultaneous in-vehicle and on-road displays resulted in slightly better speed control. Findings also revealed minimal negative impacts from increased information load. Significant age group differences were found, including older drivers performing less well in sign identification and vehicle control. Older drivers also exhibited longer glances to logo information, suggesting design considerations should be made to accommodate specific driver characteristics.

The research team collected two sets of data: a first set with 36 participants and a second set of 18 participants (see Table 1). The two datasets differed slightly in terms of the data collection procedure. The first data set did not included observations on driver use of signage when exposed to roadway hazards. The second data set did include such observations. Findings from both datasets have been reported in a published HFES (Human Factors & Ergonomics Society) paper/presentation (Deng et al., 2019), a TRB (Transportation Research Board) abstract/poster (Deng et al., 2020), and an ICHMS (International Conference on Human-Machine Systems) paper (Deng et al., 2020). In addition, a journal manuscript has been prepared. All documents are attached in the appendix. Here, we focus on results from the second dataset.

Table 1. Participant demographic data for Datasets 1 and 2.

Participant Set 1 (n=36):

Characteristics	Participants (n = 36)	Age Groups		
		Younger	Middle	Older
Age Range		18-23	24-64	65-85
Mean Age		20.92[a] (1.51)	34.48 (13.76)	73.67 (5.52)
Gender: Male | Female	18|18	6|6	6|6	6|6
Years Licensed		4.45 (2.21)	10.08 (13.34)	47.36 (23.04)

[a.] Note: the numbers in parentheses are SD for each mean

Participant set 2 (n=18):

Table 1. Age and driving experience of participants.

Age Group	Age Statistics (yrs.)	Driving Experience (yrs.)
Younger	M = 21.17, SD = 1.17	M = 4.00, SD = 1.79
Middle-aged	M = 46.83, SD = 11.99	M = 29.33, SD = 13.26
Older	M = 73.33, SD = 5.28	M = 52.17, SD = 16.17

5.2 Methods

5.2.1 Participants

Eighteen participants (9 males, 9 females; dataset 2) were recruited from three age groups, including: (1) younger drivers (19-22 years of age), middle-aged drivers (23-64 years of age) and older drivers (65 years of age or older).

5.2.2 Apparatus

Driving simulator. The experiment took place in a lab that was used exclusively for driving simulator research. The simulator is a high-fidelity, full motion system. The vehicle cab is a full-size model of a Hyundai vehicle cockpit. Participants interacted with the simulator through a full sized steering wheel and modular accelerator and brake pedal unit. The simulator includes eight surrounding monitors that provide a 365 degree field of view. The virtual driving environment was simulated using the Forum8 UC/WinRoad software (Tokyo, Japan). The simulator allowed for synchronized motion with the virtual vehicle (Figure 3a).

In-vehicle display. Based on a market survey done by the research team showing trends of in-vehicle display sizes (Figure 3c), a 10.5-inch tablet computer was used as an in-vehicle display (Figure 3b). The size of the display was determined based on a survey of commercial vehicles as well as the assumption that the size of in-vehicle displays will continue to increase in the future. The tablet was integrated with the driving simulation system. It incorporated basic

features of common in-vehicle display systems and presented logo panel signs that matched the layout and format of on-road logo signs (see Figure 4).
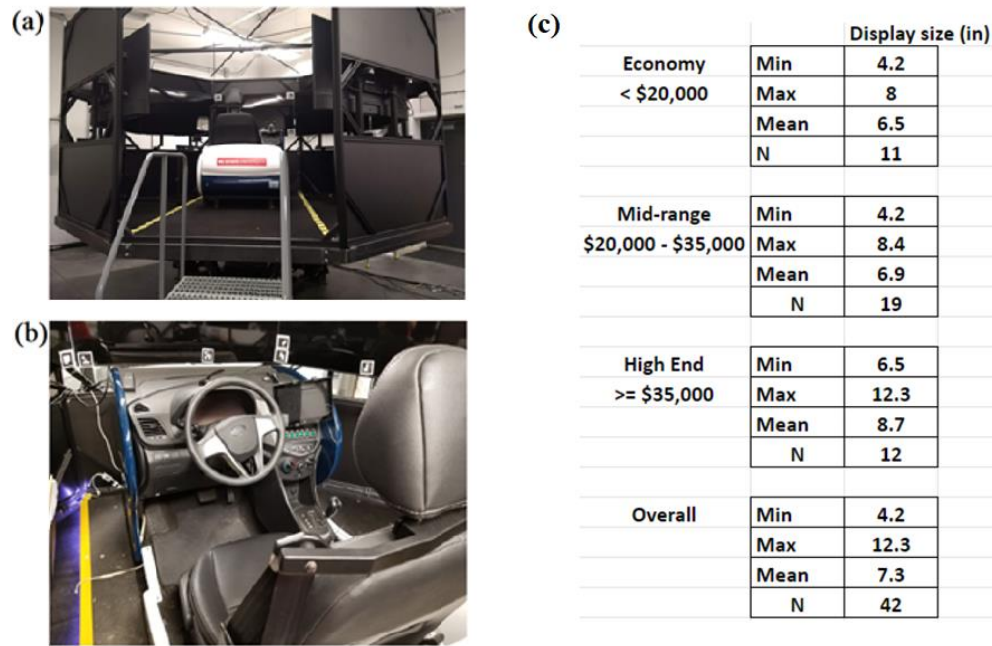

			Display size (in)
Economy	Min		4.2
< $20,000	Max		8
	Mean		6.5
	N		11
Mid-range	Min		4.2
$20,000 - $35,000	Max		8.4
	Mean		6.9
	N		19
High End	Min		6.5
>= $35,000	Max		12.3
	Mean		8.7
	N		12
Overall	Min		4.2
	Max		12.3
	Mean		7.3
	N		42

Figure 3. (a) the overall simulator setup; (b) setup of the in-vehicle display; (c) summary of 2018 market survey on in-vehicle display sizes.
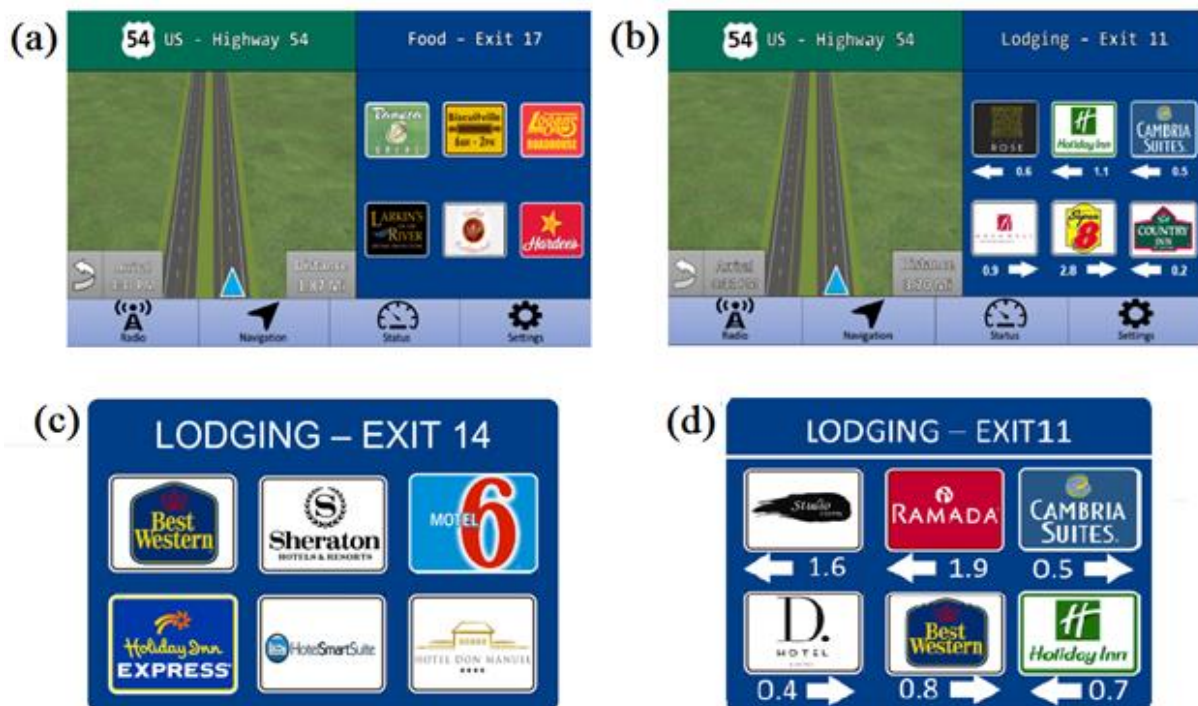

Figure 4: (a) IVD (in-vehicle display) with logos; (b) IVD with logos and text; (c) on-road signage with logos; (d) on-road signage with logos and text.

Eye tracker and NASA TLX. A Pupil Labs Pupil Core eye tracker was used for this experiment. This device is a head-mounted eye tracker with two eye cameras and one world camera. The eye cameras have a sampling frequency of 200 Hz while the world camera has a maximum sampling frequency of 120 Hz. The camera scene field of vision is 100 degrees. The NASA Task Load Index (TLX; Hart and Staveland, 1988), including pre-trial and post-trial questionnaires, was delivered using paper and pencil/pen.

5.2.3 Performance measures

Logo identification measures. In addition to the driving task, participants were instructed to look for target logos while driving. Before each simulated drive, participants were presented with two logo targets (e.g., Wendy's and Motel 6). They were instructed to verbally indicate the presence of logo targets ("yes" or "no") when a logo panel was visible. At each interchange, there were three logo panels, with one for food, one for lodging, and the other for gas stations. Target logos were selected from the food and lodging panels; thus, in each trial, there were six relevant logo panels (i.e., food or lodging). Three logos were randomly selected as targets (no more than one target occurred at each panel). Therefore, the target prevalence rate was 50%. Driver verbal responses were recorded by an experimenter. Measures of driver logo identification included hit and false alarm rates coded following the signal detection method (see Figure 5).

Logo

	Present	Absent
Yes	Hit	False Alarm
No	Miss	Correct Rejection

Response

Figure 5. Signal detection coding.

Driving measures. Each participant completed a total of 6 simulated drives. Each drive presented a four-lane freeway (two-lanes in each direction) with 3 interchanges (and 1.5 miles of straight road section in between) followed by a 2-mile straight road. The route of simulated driving with locations of various signs is illustrated in Figure 6. All road and sign configurations were consistent with regulations set by the North Carolina Department of Transportation and MUTCD (Federal Highway Administration, 2009). Participants were instructed to follow the speed limit while maintaining a safe following distance with a lead vehicle (time to collision of ~2.5 seconds), including situations when the lead vehicle braked suddenly.
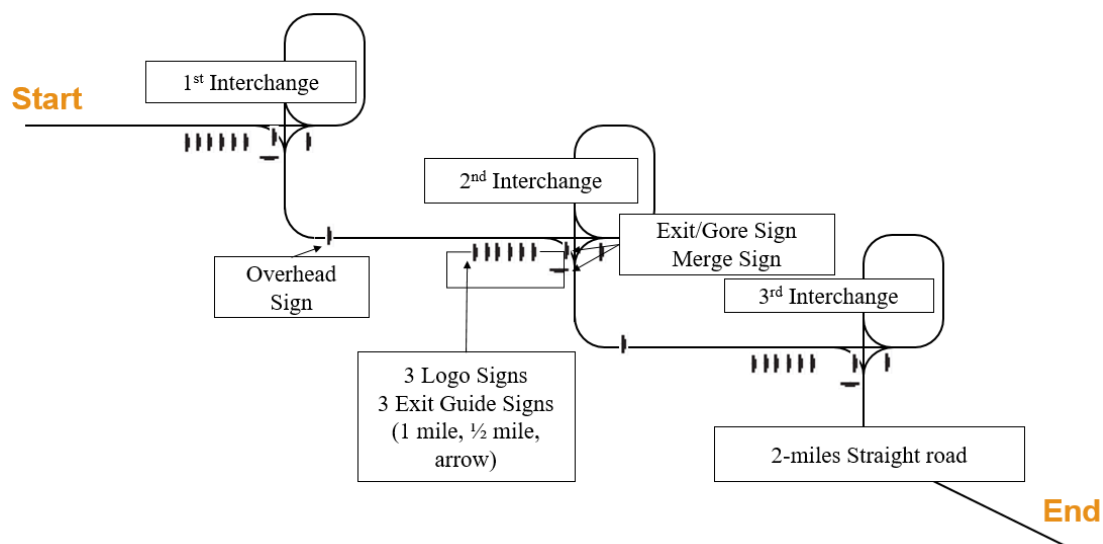

Figure 6. Route map of a driving scenario.

Glance behavior measures. Two areas of visual interest (AOIs) were specified for the study, including: the in-vehicle display and the on-road signage panel. Glance duration was defined as the time between one entry of gaze point to the following exit of gaze point from a specific AOI during an observation period (the period when a logo signs were visible to drivers). The longest single glance duration was computed for each observation period within each drive for every participant. The longest single glance duration was used to assess visual demands when drivers processed signage information.

Workload measure. The NASA TLX (Hart & Staveland, 1988) was used to measure driver workload. Participants rated perceived workload on a 100-point scale for six different demand components, including: mental demand, physical demand, temporal demand, performance, effort, and frustration. At the beginning of the experiment participants completed pairwise comparisons of these demand components to obtain rankings. Participants completed ratings after each trial. The TLX composite score was computed as a rank-weighted sum of all ratings.

5.2.4 Procedure

Participants were given sufficient practice allowing them to become familiar with the simulator and were instructed to drive safely by maintaining a proper lane position, adhering to the posted speed limit (65 mph), as well as being vigilant at all times and responding properly whenever a road hazard occurred. To increase task fidelity, drivers were presented a scenario in which they were travelling to a particular destination. Prior to each simulated drive, a target destination was identified and drivers were required to take the exit for the target destination. Their responses (through action) were recorded by experimenters. Driving measures included vehicle control performance such as speed and lane deviations and driver hazard negotiation performance, including crash rate and brake reaction time. A diagram of the procedure is provided in Figure 7.
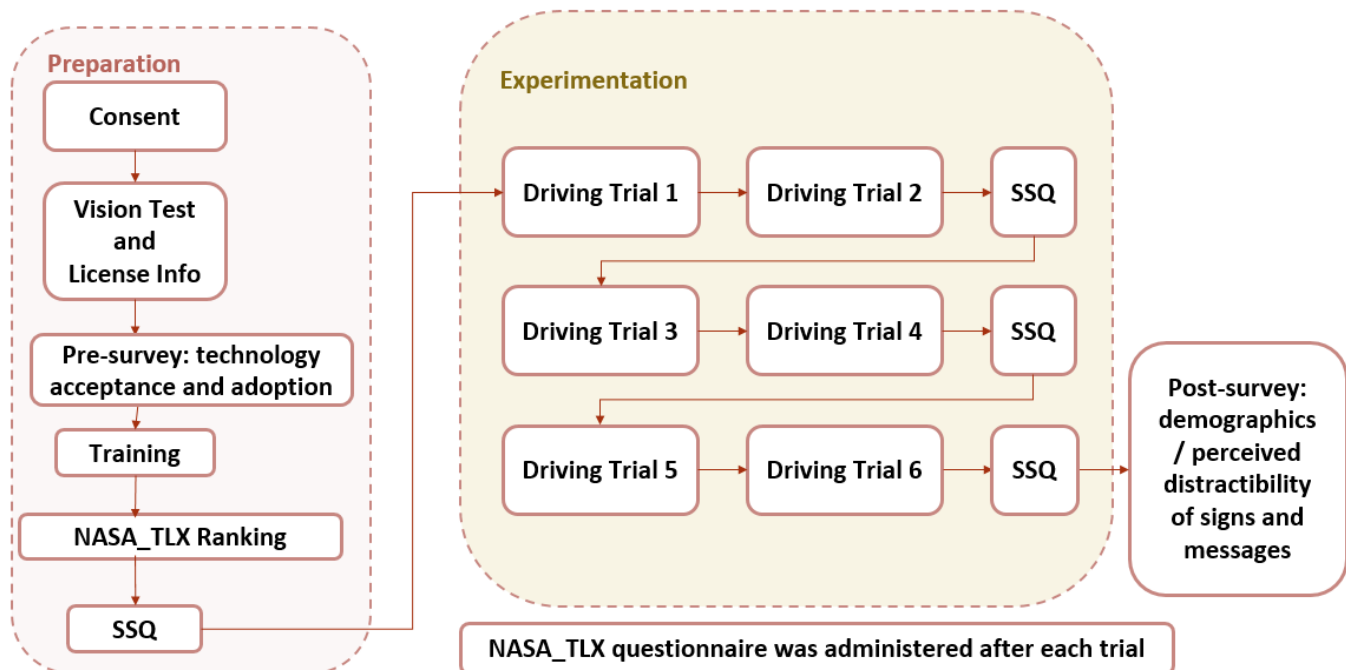

Figure 7. Procedure of Study 1.

5.3 Results

5.3.1 Logo identification

Hits

A Chi-square analysis was conducted to assess driver target response accuracy based on "hit" responses. A significant age effect was identified (Pearson Chi-square=9.855, p=0.0072), which indicated that older drivers produced fewer hits than younger and middle-aged groups: younger - 95.83%, middle-aged - 97.22%, older - 84.72%. There were no significant differences among information sources (Pearson Chi-square=0.945, p=0.6234): in-vehicle - 90.28%, on-road - 94.44%, both - 93.06%. There was also no significant effect of information load (Pearson Chi-square=0.443, p=0.5450): logo only - 89.91%, logo plus text - 93.37%.

*	Younger	Middle Aged	Older
Hit	95.83%	97.22%	84.72%
False Alarm	0%	2.86%	9.09%

*	In-Vehicle	On-Road	Both
Hit	90.28%	94.44%	93.06%
False Alarm	8.7%	0%	2.94%

	Logo only	Logo+text
Hit	89.91%	93.37%
False Alarm	4.76%	2.97%

* Marks significance

False alarms

A Chi-square analysis was also performed on false alarm rates. Driver age was found to be significant (Pearson Chi-square=7.821, p=0.02). Older drivers (9.09%) produced more false alarms than younger (0%) and middle-aged (2.86%) groups. In-vehicle displays

Figure 8. Significant effects of age and information source on logo identification.

were found to produce more false alarms than on road signs or the combination of on-road and in-vehicle displays (Pearson Chi-square=7.23, p=0.0269): in-vehicle - 8.7%, on-road - 0%, both - 2.94%. There was no significant effect of information load (Pearson Chi-square=2.43, p=0.119): logo - 4.76%, logo plus text - 2.97%.

5.3.2 Visual behavior

Max single glance durations

To compare the visual demands of various message formats (in-vehicle vs. on-road vs. both) and information load (logo vs. logo plus text) across the three age groups, the longest single glance duration was captured for each combination of conditions for every participant. Therefore, in drives with only the in-vehicle display presentation or the on-road signage presentation, the longest glance duration was determined for either area of interest (AOI). In drives with simultaneous in-vehicle and on-road displays, the longest glance duration was identified among all durations for both AOIs. An ANOVA procedure was performed to examine the effects of information source, information load, age, and their interactions. The data did not meet the ANOVA normality assumption; thus, a rank transformation was performed. Driver age was found to have significant effect on gaze duration ($F_{(2,339)}$ = 5.2540, p = 0.00057, 1-β = 0.8314). Old drivers exhibited a significantly longer gaze duration than young drivers (see Figure 9).

The information source was not significant but its interaction with age ($F_{(2,339)}$ = 2.8138, p = 0.0256, 1-β = 0.7658) was significant. It appeared that older drivers exhibited longer glances when using on-road signage, as compared with in-vehicle display or simultaneous presentations. Middle-aged drivers exhibited the shortest gaze durations while using on road signage. Younger drivers' gaze duration was not significantly affected by information source. Information load was also found to be significant ($F_{(1,339)}$ = 5.7316, p = 0.0173, 1-β = 0.6652). Signage with logo and text information produced longer glance durations than logo only (see Figure 9).
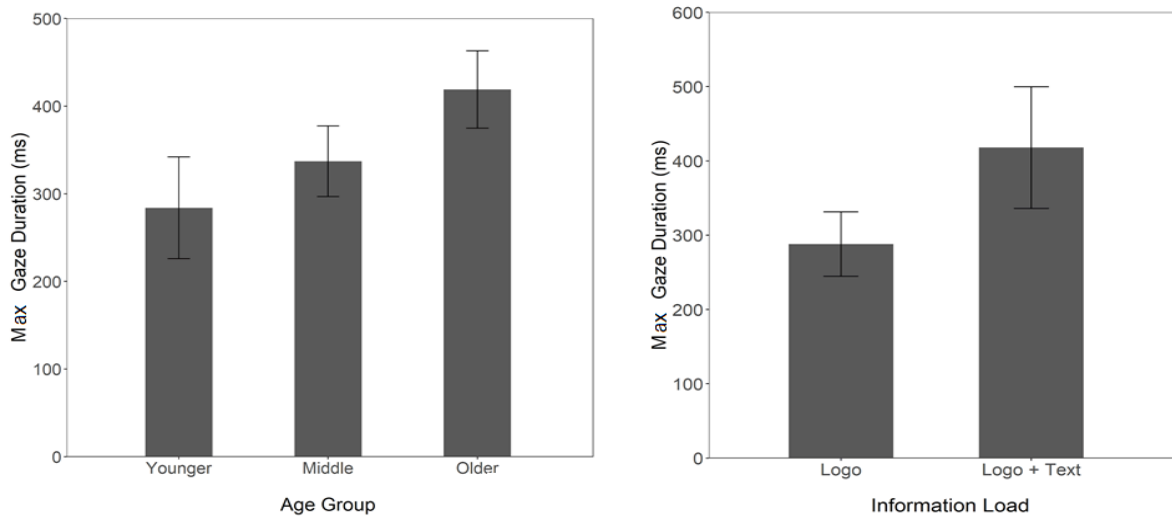
Figure 9. The three age groups differed significantly on max single glance durations. A higher information load also led to longer max gaze durations.

The second analysis investigated driver visual engagement with either information source (in-vehicle or on-road signage) when both are available. This analysis only included drives in which both in-vehicle and on-road signage were displayed simultaneously. An ANOVA procedure was performed to examine the effects of information source (in-vehicle vs. on-road), information load (logo vs. logo plus text), age group (younger vs. mid-aged vs. older), and their interactions. The data again did not meet the ANOVA normality assumption; thus, a rank transformation was performed. There was a significant effect of information source ($F_{(1,240)}$= 24.5519, p <0.0001, 1-β = 0.9985). Drivers had longer single glance durations to the on-road signage AOI than the in-vehicle display AOI. The interaction of age group and information source was also significant ($F_{(2,240)}$= 7.0354, p =0.0011, 1-β = 0.9257). Glances durations for the in-vehicle display AOI and on-road signage panels were comparable for younger drivers and older drivers, while middle-aged drivers had longer glance durations to the on-road signage AOI than the in-vehicle display AOI.
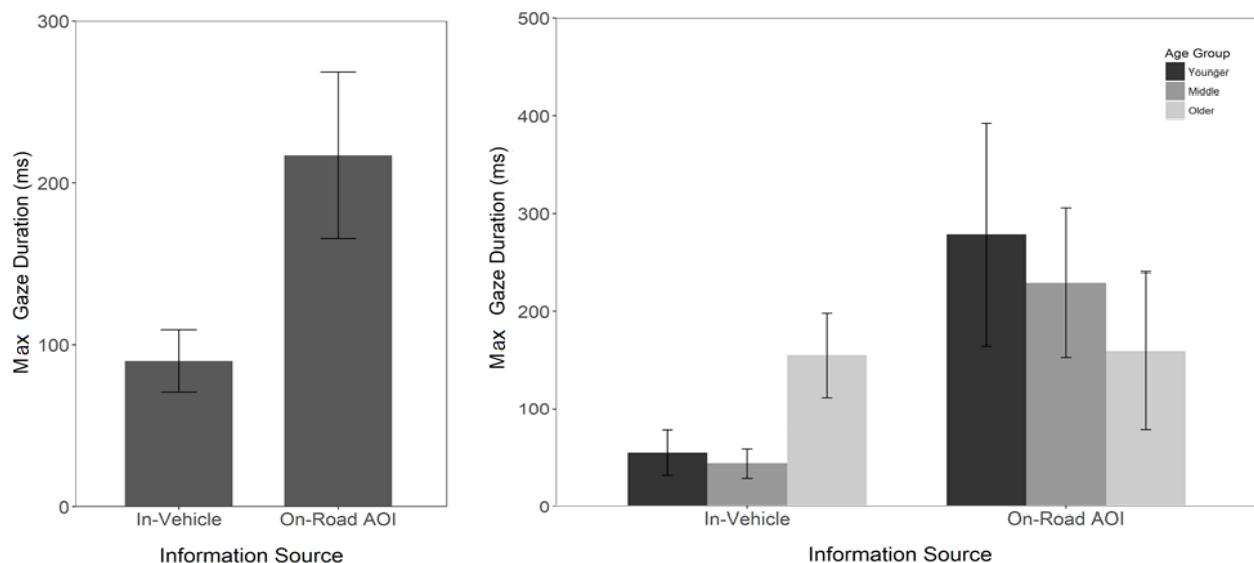

Figure 10. With simultaneous in-vehicle and on-road displays, maximum single glance durations were longer for on-road signage. Older drivers showed more balanced maximum glance durations to both sources.

5.3.3 Vehicle control

Vehicle control performance was examined in terms of speed and lane deviation. First, driving performance during hazard-free sign observation periods was inspected with a total of 480 observations. As previously stated, participants were instructed to drive in the same lane during sign observation and to maintain 65 mph throughout the experiment, aside from hazard encounters. Performance deviations from instructions were considered as indicators of performance degradation or hazard mitigation techniques. There was a total of 205 observations on hazard responses. However, effect sizes suggested insufficient numbers of participants and observations for analysis of the hazard response measures; thus, only vehicle control performance measures are reported here.

Speed Deviation

Speed deviation was defined as the absolute value of vehicle speed deviations from the posted 65 mph limit. A log transformation was applied to the data set to meet the ANOVA test assumptions. Both main effects of age group ($F_{(1,458)} = 18.67$, $p < 0.0001$, $1-\beta = 0.9999$) and information source ($F_{(1,458)} = 3.44$, $p = 0.0329$, $1-\beta = 0.6444$) were found to be significant. Further application of Tukey's HSD post-hoc test on age group effect revealed that older drivers exhibited greater speed deviations than younger and middle-aged counterparts. As for the information source effect, an application of Dunnett's test revealed the simultaneous presentation of road signs to produce lower speed deviations than the in-vehicle display or on-road signs, alone. The remaining main effect of presentation format was not significant; however, its interaction with information source was found to be significant in the statistical model. In particular, Tukey's post-hoc test revealed the logo plus text format to produce higher speed deviations with the in-vehicle display and the lowest speed deviation (greater vehicle control) was achieved by presenting logos plus text information with both road signs and in-vehicle displays.

Lane Deviation

Lane deviation was defined in this experiment as the absolute value of deviations from the lane center. The only significant factor found in this analysis was a main effect of age group ($F_{(1,458)} = 26.32$, $p < 0.0001$, $1-\beta = 1.0$) where elderly drivers were found to exhibit significantly higher lane deviations than other driver groups. All other factors in the model were found to be insignificant.
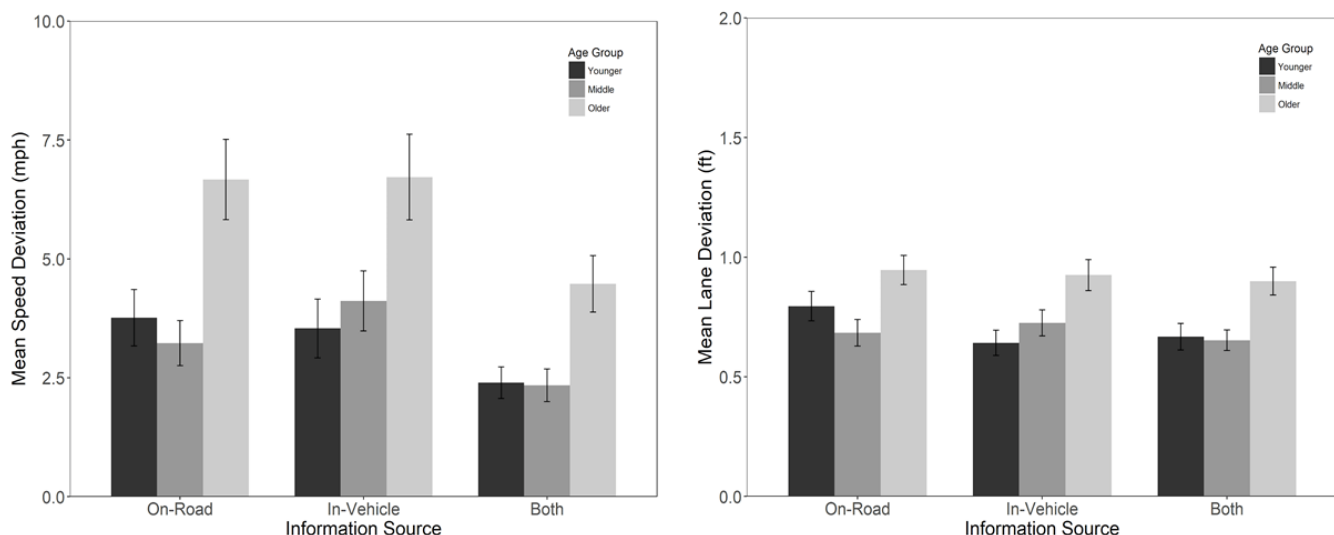

Figure 11. Simultaneous presentation of in-vehicle displays and on-road signs led to lower speed deviations. Older drivers exhibited greater speed and lane deviations than the other drivers.

5.3.4 Workload

For the NASA TLX composite score, a mixed-model ANOVA was significant (r^2=0.857, p < 0.0001). The untransformed response data satisfied parametric test assumptions. There was a main effect of age group (F[2, 37] = 11.249, p < 0.0001,1-β = 0.990): younger - 33.0, middle-aged - 41.2, and older - 40.9. There were significant individual differences within age group, F[15, 37] = 24.014, p < 0.001, 1-β = 1.00. and an effect of test trial (F[5, 37] = 3.820, p = 0.004,1-β = 0.921) was also present. Post-hoc tests (Student-Newman-Keuls) revealed the younger age group to perceive workload to be significantly less than the middle and older age groups. Post-hoc tests also revealed that the composite TLX score for Trial 1 was significantly higher than Trials 3-6, suggesting that driver time-on-task played a role in the workload rating.

6 Study 2

6.1 Summary

This study investigated the presentation of service logo information under partially automated driving. Drivers completed simulated drives with partial vehicle automation during which they had to detect target logo signs and react to hazards by taking over vehicle control when needed. Driver performance was measured in terms of sign detection rate, crash rate, and hazard response time. A number of factors, including sign information source, sign information load, and driver age group, were investigated. In general, our findings support the delivery of service logo information via in-vehicle displays under partially automated driving, especially when the in-vehicle display occurred simultaneously with on-road signage. Under this presentation condition, drivers were most accurate in detecting target logo signs, and showed little impairment from processing sign information as a secondary task when negotiating a hazard. Simultaneous presentation of in-vehicle displays and on-road signage also mitigated negative impacts of higher information load on total and single glance durations. On-road only presentation led to longer glance durations as well as a greater number of long (> 2s) glances.

6.2 Method

6.2.1 Participants

Thirty-six (36) participants were recruited from the area around a medium-sized southern city to participate in this study. The sample was balanced across age and gender. The three age groups were younger (18-23 years), middle-aged (24-64 years) and older (65 and above years) drivers. We recruited participants via online advertisements and visits to retirement communities. Each driver was compensated $20 per hour of participation. Every participant had a valid driver's license and normal or corrected-to-normal vision and was driving regularly at the time of participation.

6.2.2 Design

There were a total of eight simulated drives: six under (SAE) Level 2 automation and two under Level 3 automation. For the Level 2 automated driving scenarios, the experiment followed a 2×3×3 mixed factorial design (information source × load × age). The two Level 3 drives presented logos only via in-vehicle display or on-road sign, which were contrasted with two other matched drives under Level 2 automation, forming a 2x2x3 design (information source x level of automation x age).There were three age groups: younger, middle-aged, and older. Information source and load were within-subject manipulations. Information source had three levels (on-road vs. in-vehicle vs. both) and information load had two levels (logo vs. logo plus text), yielding a total of six combinations of conditions. There was one simulated drive for each combination of conditions. Every participant completed a total of six simulated drives for

the experiment. A Latin square method was used to randomize exposure to conditions and control for any carry-over effects among drives; thus, the order of drives was counterbalanced between participants within each age group.

6.2.3 Tasks, Measures and Procedures

The experiment setup and procedures were the same as in Study 1 except that several of the hazards were handled by automation. Here we did not design for all hazards to be handled by automation in order to mimic situations when an automation failure occurs and a driver has to takeover hazard negotiation (i.e., a brake response). The brake time was measured in response to hazards. Under Level 2 automation, drivers were instructed to remain vigilant about the driving environment. In contrast, under Level 3 automation, drivers were instructed to engage in an anagram task (i.e., complete as many word problems as possible) while the vehicle informed the driver if a takeover was necessary.

6.3 Level 2 Automation Results

6.3.1 Sign Detection

Driver responses to the sign detection task were coded as either a correct or incorrect response, which resulted in a dichotomous outcome variable. There were 1332 sign responses collected and of these, 47 responses could not be used due to technical or recording issues. Therefore, a total of 1285 responses were included in the present analysis. As such, a logistic regression model was applied with the predictors being information source (on-road, in-vehicle, or both), information load (logo, logo plus text), and age group (younger, middle-aged, and older). The overall model was significant (χ^2 = 32.55, p < .01). There were significant main effects for information load, source, and age. For information load, results showed that for the logo plus text condition, drivers were significantly less likely to provide a correct response (β = -1.42, p < .01; logo only – 94%, logo plus text – 98%). Results also showed that during on-road only presentations (β = -1.69, p < .01) and in-vehicle only presentations (β = -1.40, p < .01) drivers were significantly less likely to make a correct response, as compared to when logo information was presented both in-vehicle and on-road (on-road – 94%, in-vehicle – 95%, both – 99%). Driver age differences revealed that older drivers (β = -1.07, p < .01) were less likely to provide a correct response than middle-aged drivers (older – 94%, middle-aged – 98%), while younger drivers and middle-aged drivers were not statistically different (β = -.20, p > .05; younger – 97%).

6.3.2 Driving performance

Crash rate

Crash rate was computed as the frequency at which a driver's vehicle collided with a lead vehicle at hazard events during test drives. For this analysis, all hazards exposure observations were included for a total of 1257 data points. A logistic regression analysis of crash outcome (coded as a dichotomous variable; crash, non-crash) was conducted. The model predictors included sign presence (present or absent), information source (on road, in-vehicle display, or both), information load (logo or logo plus text), and age group (younger, middle-aged, or older). Results revealed that drivers were more likely to crash during a hazard events when a logo sign was present (β = -1.45, p < .05; sign present – 36, sign absent – 24), and when the logo information was delivered via on-road signage (β = .67, p < .05; on-road – 22, in-vehicle – 18, both – 20). There were no significant main effects for age group or information load for the crash rate response (younger – 27, middle-aged – 17, older – 16; logo only – 29, logo plus test – 31). Figure 12(a) presents the differences between the sign presentation conditions, present and absent. There were also no significant interactions.

Hazard Response Time

Driver braking response time, was computed as the difference in time between when a hazard event began and when the participant manually decelerated to a rate equal to or more than -3.048 m/s^2. This deceleration criterion has been used in prior studies involving braking response time (Institute of Transportation Engineers, 2016). For this analysis, only those hazards for which drivers exhibited a manual response were analyzed. Observations were categorized based on whether a crash had occurred or not. Cook's D was then used to identify outliers in the dataset. Two observations were removed based on the Cook's D criterion. This process resulted in a total 1208 observations where the automation failed during a hazard exposure.

A mixed factorial ANOVA was conducted to determine differences in braking response time for the sign presentation condition (present, absent), information source (on-road, in-vehicle, both), information load (logo, logo plus text), and age group (younger, middle-aged, older). Results revealed significant main effects for sign presence [F(1,1172) =25.17 p < .05] and information source [F(2,1126) = 3.03, p < .05]. The main effects for information load and age group were not significant (logo only – 2.30s, logo plus test – 2.27s; younger – 2.34s, middle-aged – 2.19, older – 2.31). A Tukey's HSD post-hoc test was conducted to explore the significant effects of sign presence and information source. Results revealed that drivers took longer to takeover control (i.e., a longer braking response time) when logo signs were present (M = 2.43 s) than when there was no sign (present – 2.43s, absent – 2.21s). For information source, driver hazard response time was slowest when logo information was presented only on the in-vehicle display. Drivers were slightly faster with on-road information presentation, and fastest when information was presented on both in-vehicle and on-road displays (on-road – 2.30s, in-vehicle – 2.45s, both – 2.13s).

Aside from the main effects, there was a significant two-way interaction between sign presence and information source [F(2, 1172) = 3.44, p < .05] such that when a logo sign was present, on-road and in-vehicle presentation resulted in the slowest response times (Figure 12(b)). When a logo sign was present and delivered via both the in-vehicle display and on-road signage, the braking response times were similar to when no-sign was present.
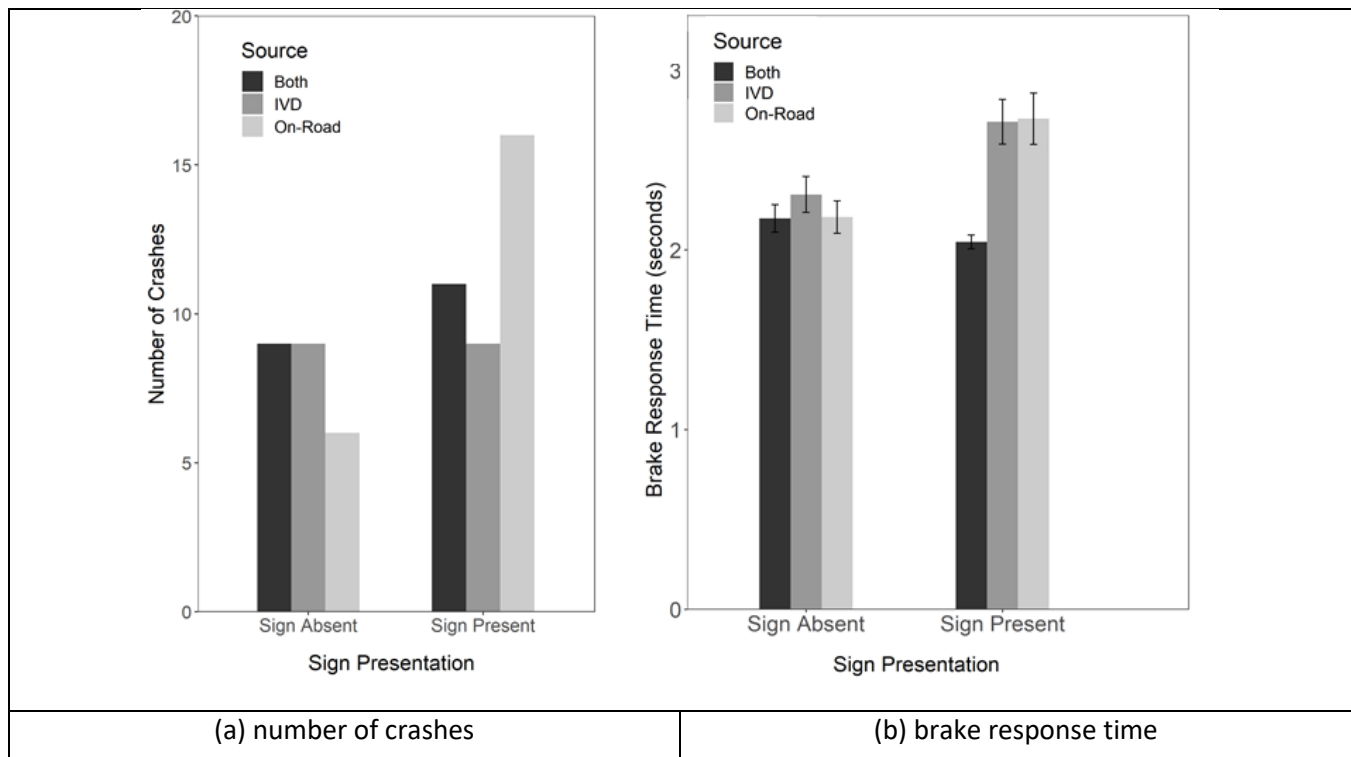

| (a) number of crashes | (b) brake response time |

Figure 12. Drivers crashed more when logos were present. Simultaneous presentation mitigated the effect of sign presence on the number of crashes and brake response time.

6.3.3 Driver Glance Behavior

As noted above, Areas of Interest (AOIs) were specified for the driving simulation environment, including: in-vehicle display, and on-road sign. Beginning and end times for glances to each AOI were manually coded through the analysis of Pupil Lab videos showing gaze fixations overlaid on the simulated driving scene. Observation periods began as soon as logo information was perceptible in foveal vision and ended when the information was no longer viewable. Two student researchers were responsible for coding all videos. Multiple training sessions were completed with both researchers before the coding task was completed.

A total of 1221 data points were included in the present analysis. Given that there was some loss of eye tracking data due to technical issues during the experiment with a number of participants, we analyzed glance data via Mixed Effect Models (SPSS MIXED procedure) instead of the conventional Repeated Measures ANOVA. Each outcome variable was modeled with the fixed effects of age group, information source, information load, and their 2-way and 3-way interactions (full factorial), as well as random slopes for participants.

Total Glance Duration

The analysis revealed no significant effect of information source/display location (in-vehicle – 1859ms, on-road – 2010ms, both – 2167ms), $F_{(2, 52.737)} = 1.180$, $p = .315$. However, the effect of information load approached significance, $F_{(1, 23.222)} = 3.559$, $p = .072$, with a tendency for participants to spend greater time viewing a sign when there was text accompanying logos (logo – 1867ms, logo plus text – 2158ms). There was a significant interaction between information load and source, $F_{(2, 435.709)} = 3.109$, $p = .046$, with the higher load (logo+text) more consistently led to greater viewing time of a sign.

The three age groups exhibited similar total glance duration (younger – 1969ms, mid-aged – 2103ms, older – 1964ms), $F_{(2, 85.291)} = .192$, $p = .826$. No interaction was found between age and other factors. There was a significant 3-way interaction, age x source x load, $F_{(4, 434.760)} = 3.468$, $p = .008$. As shown in Figure 13, increasing load generally led to greater view time except when mid-aged drivers used only the in-vehicle display and when older drivers used both the in-vehicle display and on-road signs.
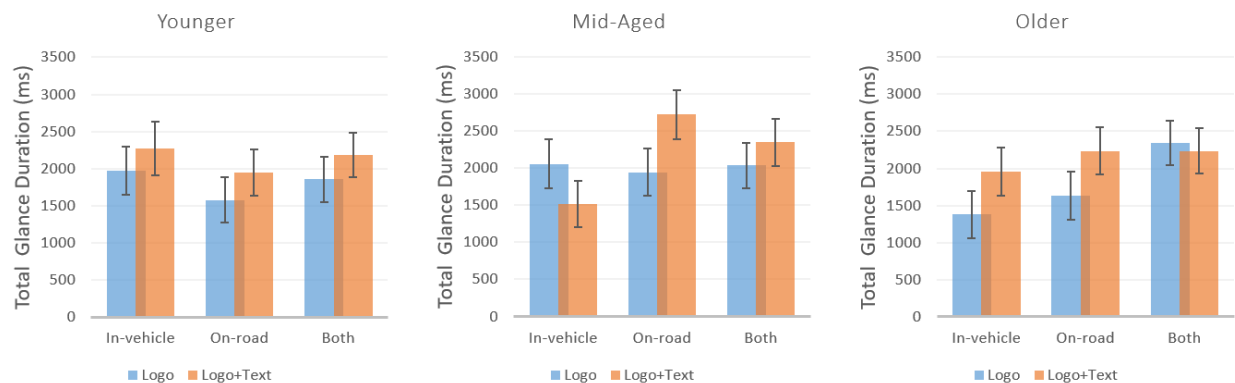

Figure 13. Trend of longer glance durations for logo plus text vs. logo only. Trend varied among sources with smaller differences when both displays were available. Simultaneous in-vehicle and on-road displays may mitigate negative impacts of higher information load (logo plus text), particularly for older drivers.

Median Glance Duration

In this study, median glance duration was used to estimate single glance duration. There was a significant effect of information source/display location (in-vehicle – 708ms, on-road – 1289ms, both – 715ms), $F_{(2, 60.803)} = 15.635$, $p <$

.001. There was no effect of information load (logo only – 856ms, logo plus text – 950ms), $F_{(1, 24.973)}$ = 1.782, p = .194. There was, however, a significant interaction between information source and load, $F_{(2, 477.716)}$ = 5.830, p = .003 (see Figure 14). Similar to the total glance duration response, the three age groups had similar median glance duration (younger – 840ms, mid-aged – 945ms, older – 927ms), $F_{(2, 98.392)}$ = .356, p = .701. No interaction was found between age and other factors.
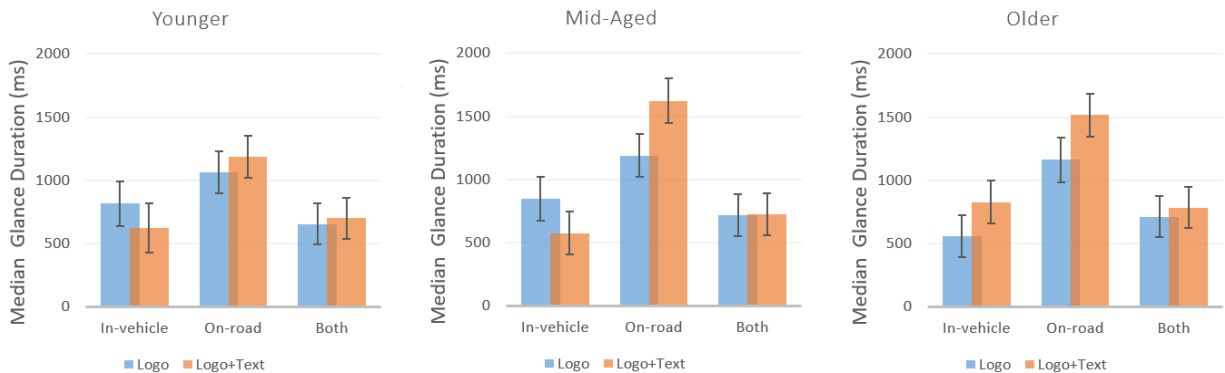

Figure 14. Single glance duration was longer for the on-road sign condition. The effect of information load (logo vs. logo+text) was most pronounced for the on-road sign condition. Older drivers did not spend a longer time viewing signage, even under conditions that required longer glance durations (i.e., on-road only).

Number of Glances per Sign

The number of glances to an AOI is count data, which typically follows a Poisson distribution. Consequently, Generalized Mixed Effect Models were used for this analysis with the distribution specified as Poisson and the link function as identity.

There was a significant effect of information source/display location (in-vehicle – 2.66, on-road – 1.79, both – 2.46), $F_{(2, 88.089)}$ = 12.047, p < .001 but no effect of information load (logo only – 2.26, logo plus text – 2.34), $F_{(1, 462.477)}$ = .846, p = .358, or interaction between load and source/location. The three age groups exhibited similar numbers of glances per scenario (younger – 2.23, mid-aged – 2.41, older – 2.27), $F_{(2, 88.737)}$ = .481, p = .620. There was a significant interaction between driver age and information load, $F_{(2, 462.351)}$ = 3.103, p = .046 (see Figure 15), indicating that younger drivers were more likely to make more glances with increasing information load while older drivers tended to exhibit the opposite visual behavior (Figure 15). No other interactions were significant.
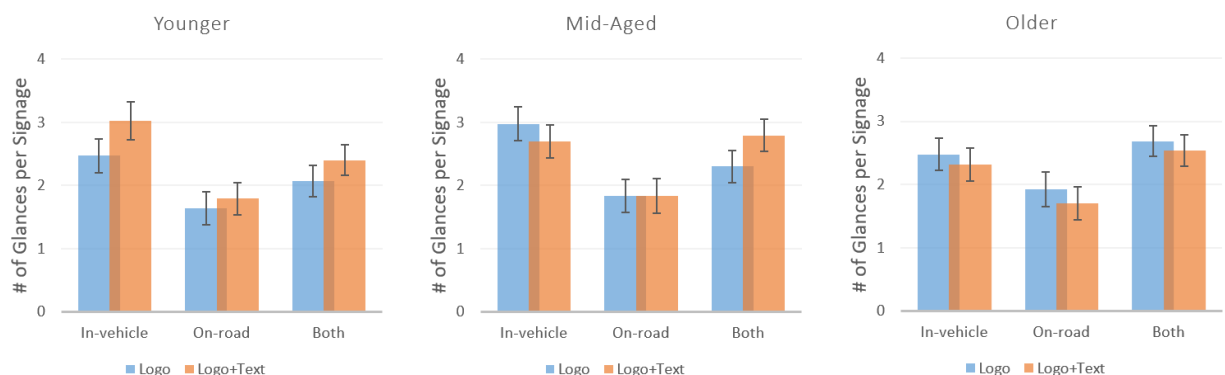

Figure 15. Drivers made fewer glances to signage in the on-road only condition (but longer individual glances as shown in Figure 14).

Number of Long Glances (>2s) per Sign

We also calculated the number of long glances (duration > 2s) for each AOI, as this type of glance is particularly threatening to driving safety (NHTSA, 2013). The effect of information source/location approached significance, $F_{(2, 44.317)} = 2.900$, $p = .065$, revealing in-vehicle displays to demand fewer long glances (.166) than on-road signage (2.89) or simultaneous presentation of both in-vehicle and on-road displays (.263). There was no effect of information load on the occurrence of long glances (logo – .212, logo plus text – .267), $F_{(1,18.896)} = 2.190$, $p = .155$, but there was a significant interaction between information source/display location and information load, $F_{(2, 506.456)} = 4.009$, $p = .019$.

The three age groups exhibited a similar overall frequency of long glances (younger – .222, mid-aged – .261, older – .234), $F_{(2, 89.330)} = .214$, $p = .808$, and there were no 2-way interactions between age group and other experimental factors. The 3-way interaction of age x load x source/location was, however, significant, $F_{(4, 505.455)} = 3.199$, $p = .019$ (see Figure 16).
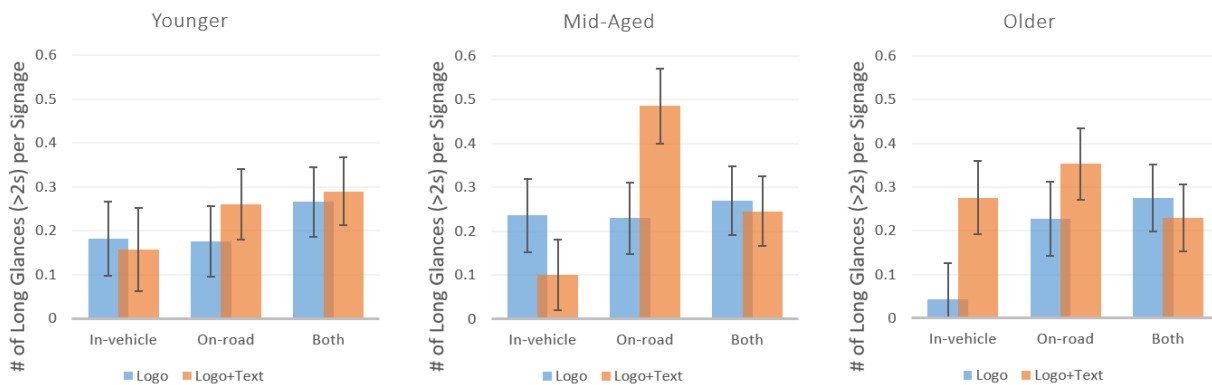

Figure 16. The number of glances was the lowest for the in-vehicle display condition and did not differ significantly among the age groups.

6.4 Results on Level 2 vs. Level 3 Automated Driving

In this section, we address comparison of the SAE Level 2 and Level 3 automated driving behaviors observed during the experiment. As in the previous analysis, driver target sign detection, vehicle control performance, and visual behavior were analyzed.

6.4.1 Sign Detection

Sign detection was defined as the driver's ability to correctly identify whether a target sign was present or absent during each presentation of blue sign as part of a simulated drive. For this analysis, Level 2 automation scenarios were compared to Level 3. In order to conduct a balanced comparison, data points from trials in which the information load was logo + text, or the information source was both on-road and in-vehicle, were omitted from the analysis. Consequently, we only made comparison of the use of automation when the information load was logo only and the information source was either in-vehicle or on-road. As such, there were 848 sign observations for analysis. A logistic regression model was applied to the dataset with the predictors being source (on-road or in-vehicle), age group (older, middle-aged, or younger), and level of automation (Level 2 or Level 3). The overall model was significant ($\chi2 = 19.57$, $p < .01$). There was a significant main effect for age group, such that older drivers were less likely to provide a correct sign responses than middle-aged drivers ($\beta = -.91$, $p < .01$; older = 84%, middle-aged = 93%). Younger drivers were not significantly different from middle-aged drivers ($\beta = -.38$, $p = .21$; younger = 90%).

There was also a main effect of level of automation where drivers were less likely to provide a correct response to a sign when using Level 3, as compared to Level 2 (β = -.62, $p < .01$; level 2 = 92%, level 3 = 86%). There were no significant differences between on-road or in-vehicle presentations. Figure 17 shows the differences between age groups and levels of automation.
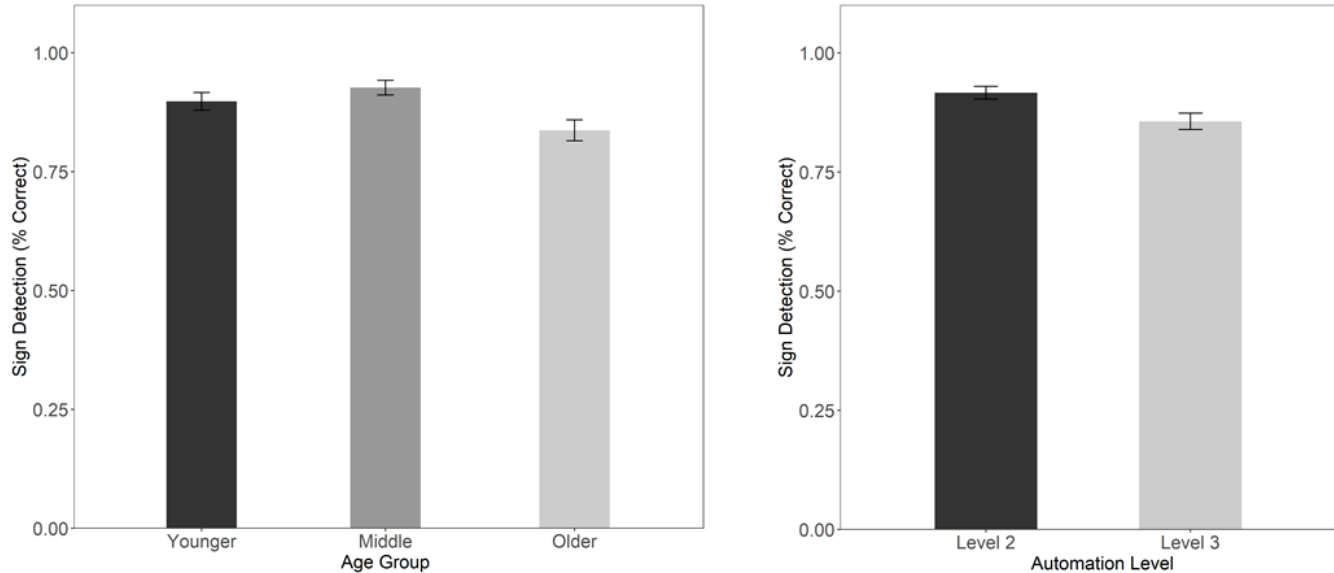

Figure 17. Older drivers performed worse on logo identification. Drivers in general performed worse under level 3 than level 2 automation.

6.4.2 Driving Performance

Crash Rate

Crash rate was determined by identifying the number of instances in which drivers collided with a lead vehicle during simulated drives. The same driving scenarios that were used for the sign detection analysis were also used for the crash rate analysis. This dataset provided 1027 observations for analysis. A logistic regression model was once again used to identify differences in crash outcomes among the experimental conditions. The predictors used for this analysis were information source (on road or in-vehicle), age group (younger, middle-aged, and older), sign presentation (present or absent), and level of vehicle automation (Level 2 or Level 3). Results of the analysis revealed no significant differences in crash rates for any of the predictors and the overall model was insignificant (χ^2 = 6.33, p = .28).

Brake Response Time

Driver braking response time was defined as the time between when a hazard event occurred and when a driver applied the brakes to the virtual vehicle to achieve a deceleration of -3.048 m/s^2. This level of deceleration has been used in previous studies, which have measured braking response time (Institute of Transportation Engineers, 2016). For this analysis, we only considered those hazards for which drivers exhibited a manual braking response. Observations were categorized based on whether a crash had occurred or not. Cook's D was then used to identify outliers in the dataset. This process resulted in a total of 920 crash observations being included in the analysis. A mixed factorial ANOVA was conducted to determine differences in braking response time. The factors used for this analysis were the same as were used for the crash rate analysis (information source, age group, sign present, and

automation level). The results of the analysis determined that there were no significant differences in braking response time between any of the factors included in the model.

6.4.3 Glance behavior

This analysis involved comparison of driver total and median glance durations as well as the number of glances and long glances (> 2s) to an AOI. A total of 691 data points were included in this analysis. The SPSS MIXED procedure was used to analyze these response measures with fixed effects including age group, information source/display location, information load, and all 2-way and 3-way interactions, as well as random slopes for participants.

There was a significant effect of level of automation on the number of glances, $F(1, 31.137) = 6.362$, $p = .017$. There was also some trend of total glance duration but it did not reach significance, $F(1, 39.672) = 2.169$, $p = .149$ (Figure 18). There was no effect of level of automation on median glance duration, $F(1, 32.020) = .060$, $p = .808$ or the number of long glances, $F(1, 47.480) = .146$, $p = .704$.
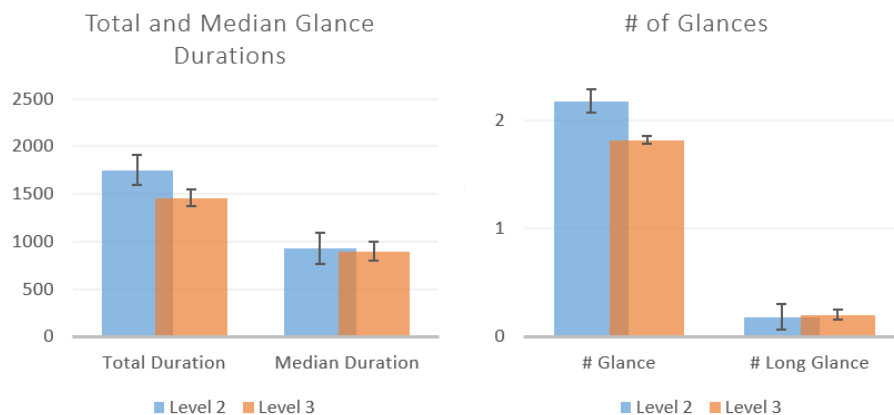

Figure 28. Drivers made fewer glances to signage information under level 3 automation.

7 Findings and Conclusions

The purpose of this study was to investigate the presentation of non-safety-related sign information, specifically service logo signs, on driver performance during manual and automated driving. Driver performance in sign detection and hazard responses were examined along with visual behaviors.

Findings suggest a dual-task cost on hazard response time when drivers were required to negotiate a hazard event in the presence of target sign detection. Inflated hazard response time appeared to occur as a result of general driver distraction in processing logo sign information. However, the in-vehicle display, as well as simultaneous presentation condition (both in-vehicle and on-road displays), seemed to mitigate the distraction effect. In contrast, on-road presentation conditions led to the most crashes, longer hazard response times, longer single glance durations, and more long glances (> 2s).

Participants self-reported acceptance of on-road signs and there may have been some bias in responses due to driver familiarity with this particular type of information source. Nonetheless, driver vehicle control performance suggested a benefit of in-vehicle displays especially when coupled with the on-road signs. Information load, including logos vs. logos plus text, had modest to no effects on various outcome measures, likely due to the small difference in the amount of information presented in each condition.

Older drivers did not demonstrate longer gaze durations to information displays when using Level 2 or Level 3 vehicle automation, possibly due to a lack of trust in the technology. Older drivers appeared to pay more attention to the road than the other two age groups. Consequently, few age-related differences were observed in driving performance. Older driver poor performance in logo identification also suggested that they may have prioritized the driving task over the sign detection, as compared to the other age groups.

8   Recommendations

Our general findings support the use of in-vehicle displays, especially when logo information was presented simultaneously via in-vehicle display and on-road signs. Simultaneous presentation, as compared to the other two conditions (i.e., in-vehicle only or on-road only), result in the safest driving outcomes and most effective signage communication. Future research can examine asynchronous presentations of a variety of sign types via in-vehicle displays and on-road signs under different levels of vehicle automation.

9   Implementation and Technology Transfer Plan

Products from this project, including the developed driving scenarios and task set up, will enable the research team to effectively deploy studies on signage, information delivery to drivers, and vehicle automation. The findings would support preliminary guideline to enable in-vehicle displays of service logos, and to use both on-road and in-vehicle presentations to promote sign recognition. Our research team would be very interested in continuing this line of work, investigating applied questions to promote the safe and effective delivery of signage and other information to drivers in both manual and automated driving.

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