ACCIDENT ANALYSIS AND PREVENTION

In-vehicle Displays to Support Driver Anticipation of Traffic Conflicts in Automated Vehicles

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- Color is not needed in print of any of the figures.
- Declarations of interest: none.

Highlights

- We tested in-vehicle displays to support driver anticipation in automated vehicles.
- TORAC displayed takeover request (TOR) + automation capability (AC) information.
- STTORAC displayed surrounding traffic (ST) information in addition to TOR and AC.
- STTORAC facilitated, while TORAC impeded anticipation.
- TORAC increased automation reliance; STTORAC supported appropriate reliance.

Abstract

Objective: This paper investigates the effectiveness of in-vehicle displays in supporting drivers' anticipation of traffic conflicts in automated vehicles (AVs). *Background:* Providing takeover requests (TORs) along with information on automation capability (AC) has been found effective in supporting AV drivers' reactions to traffic conflicts. However, it is unclear what type of information can support drivers in anticipating traffic conflicts, so they can intervene (pre-event action) or prepare to intervene (pre-event preparation) proactively to avert them. *Method:* In a driving simulator study with 24 experienced and 24 novice drivers, we evaluated the effectiveness of two in-vehicle displays in supporting anticipatory driving in AVs with adaptive cruise control and lane keeping assistance: TORAC (TOR + AC information) and STTORAC displays (surrounding traffic (ST) information + TOR + AC information). Both displays were evaluated against a baseline display that only showed whether the automation was engaged. *Results:* Compared to the baseline display, STTORAC led to more anticipatory driving behaviors (pre-event action or pre-event preparation) while TORAC led to less, along with a decreased attention to environmental cues that indicated an upcoming event. STTORAC led to the highest level of driving safety, as indicated by minimum gap time for scenarios that required driver intervention, followed by TORAC, and then the baseline display. *Conclusions:* Providing surrounding traffic information to drivers of AVs, in addition to TORs and automation capability information, can support their anticipation of potential traffic conflicts. Without the surrounding traffic information, drivers can over-rely on displays that provide TORs and automation capability information.

Keywords: Driving automation; anticipatory driving; SAE levels; driver behavior; visual attention; driving simulator

1. Introduction

Current implementations of automated driving systems available in the market still require drivers to monitor the driving environment, supervise the automation, and intervene when necessary (SAE On-Road Automated Vehicle Standards Committee, 2018). However, human operators are not well-suited for the task of supervising automation (Bainbridge, 1983), as is evident in the performance decrements observed during takeover events, i.e., events that involve transfers of control from an automated vehicle (AV) to a driver (e.g., Louw et al., 2015; Shen & Neyens, 2017). Thus, systems should be designed to support drivers to enhance safety during takeover events.

Research on supporting drivers during takeover events has mainly focused on takeover requests (TORs, i.e. warnings that alert the driver about the need to intervene; e.g., Louw et al., 2015; Melcher et al., 2015) as well as in-vehicle displays that provide information about the automation’s reliability (e.g., Helldin et al., 2013) or limits (e.g., Seppelt & Lee, 2007). While such interventions were found to be effective in improving driver reactions to takeover events, they were not particularly designed or evaluated for supporting AV drivers to be proactive, i.e., to anticipate potential traffic conflicts and avert them before they occur.

In-vehicle displays that provide information about surrounding traffic were found to be effective in supporting anticipatory driving in non-automated vehicles (Stahl, Donmez, & Jamieson, 2016). Research has shown that AV drivers are less aware of their surrounding traffic situation than drivers of non-automated vehicles (Stanton & Young, 2005). Thus, displays that provide surrounding traffic information may also support anticipatory driving in automated vehicles. In this paper, we examine this hypothesis. We present a driving simulator experiment that investigated the potential benefits of incorporating surrounding traffic information into an in-vehicle display that also includes commonly studied AV display components: TORs and automation capability information. Although vehicle sensors, such as radar, can in part make such in-vehicle displays a reality, additional useful information (e.g., a detailed road map with status of traffic devices and vehicles in distance) can be obtained through Intelligent Connected Vehicle (ICV) technologies that collect information from surrounding roadway and traffic through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication.

2. Background

As mentioned earlier, most of the research on supporting drivers during automated vehicle takeover events has focused on the use of takeover requests (TORs). TORs can reduce the need for drivers to monitor the environment, and have been found effective in facilitating transfers of control from the automation to the driver, for example, by decreasing driver's reaction time (Zhang et al., 2019). However, TORs may not always be adequate in supporting drivers of automated vehicles: drivers may not always understand why a TOR has been issued (Naujoks et al., 2017), and may need some time even after responding to a TOR to regain awareness of the driving environment (Vogelpohl et al., 2018). Further, the use of TORs may lead to overreliance on automation if the warnings are highly reliable (Lee & See, 2004) or to "cry-wolf" effects (Breznitz, 1984) if they have a high rate of false alarms. Therefore, when a TOR is issued, there is also a need for providing drivers with additional information to support them in identifying the need for their intervention and in performing the intervention. For example, in-vehicle displays can inform drivers about the limits (e.g., Seppelt & Lee, 2007) and the reliability (e.g., Helldin et al., 2013) of an automated driving system. In combination with TORs, such displays can help clarify to drivers why a TOR has been issued and increase their awareness of the situation (Naujoks & Neukum, 2014; Naujoks et al., 2015).

Although the displays described above have been effective in supporting AV drivers' responses to hazards, there is still a need to investigate how to support these drivers in anticipating future traffic conflicts and acting upon them based on relevant cues in the environment (i.e., anticipatory cues). The anticipatory driving skill is beneficial in the control of non-automated vehicles and should be supported (He & Donmez, 2018, 2020; Stahl, Donmez, & Jamieson, 2014; Stahl et al., 2016; Stahl, Donmez, & Jamieson, 2019). AV drivers may require even more support for anticipatory driving, given that they are less aware of their surrounding traffic than drivers of non-automated vehicles (Stanton & Young, 2005). In fact, Merat and Jamson (2008) found that drivers in AVs were slower to respond to anticipatory cues indicating a future traffic conflict (e.g., a vehicle merging into the driver's lane in front of the lead vehicle, indicating that the lead vehicle may brake) compared to drivers in non-automated vehicles. However, to the best of our knowledge, no study to date has investigated how to support AV drivers in performing anticipatory behaviors.

The performance of anticipatory driving behaviors requires more than a simple hazard-response reaction (He & Donmez, 2020; Stahl et al., 2014) and relies on drivers' awareness of the road situation and their ability to project the development of the situation based on anticipatory cues. It is expected that in an automated driving context, anticipatory drivers would have more time to prepare for road conflicts that require their intervention, which would then enhance their takeover performance (Merat et al., 2014; van den Beukel & van der Voort, 2013). These drivers would need both an awareness of the road situation and an awareness of the automation's capabilities to be able to predict the future traffic situation and decide on a course of action (i.e., whether to intervene in the control of the vehicle or to continue to delegate the vehicle control to the automation). Thus, a display that lacks surrounding traffic information (e.g., one that combines only TORs and automation capability information) may not be adequate in supporting anticipatory driving.

Surrounding traffic information can be incorporated into in-vehicle displays through ICV technologies. Previous research has shown safety benefits of ICV technologies for non-automated vehicles. For example, Osman, Codjoe and Ishak (2015) found that providing drivers with time-to-collision information through V2V communication can help improve driving safety among aggressive drivers, and Ali et al. (2020) found that providing drivers with surrounding traffic information can lead to safer lane changing behaviors. In terms of anticipatory driving behaviors, Stahl et al. (2016) showed that in-vehicle displays that highlight anticipatory cues from the environment, which can be gathered through V2V or V2I communication, are successful in facilitating anticipatory driving behaviors for novice drivers, who in general lack this skill (Stahl et al., 2014). Although such ICV-enabled displays may also help support AV drivers in anticipating events that may require their intervention, to the best of our knowledge, no research has focused on investigating such displays particularly for anticipatory driving in AVs.

2.1. The Current Study

To fill the research gaps identified earlier, in this study, we investigated the effectiveness of two different in-vehicle displays in supporting anticipatory driving in automated vehicles. The TORAC (TOR + Automation Capability (AC) information) display provided a TOR to indicate an event that required the driver’s intervention and provided dynamic information about the automation capability. The STTORAC (Surrounding Traffic (ST) information + TOR + AC information) display also provided a TOR and automation capability information, but additionally provided information about the surrounding traffic situation which can be realized through ICV technologies like V2V and V2I communication. Both displays were compared against a baseline display that only showed static information about whether the automation was engaged. The aim of the study was to assess whether providing surrounding traffic information enhanced anticipation in automated vehicles where TORs and automation capability displays would be available. The study was conducted using a driving simulator equipped with adaptive cruise control (ACC) and lane keeping assistance (LKA) systems, which provided sustained longitudinal and lateral control of the vehicle.

Given that drivers may exhibit different behaviors in situations with different criticality (Eriksson & Stanton, 2017), we investigated anticipatory driving scenarios with two criticality levels: one version of the scenarios did not necessitate an action from the driver to avoid a collision, whereas the other version did. Drivers were allowed to engage in a visual-manual secondary task throughout the experiment given that drivers are more likely to engage in non-driving-related tasks in automated vehicles (Carsten et al., 2012; de Winter et al., 2014) and that anticipatory driving behaviors can be impeded by distraction (He & Donmez, 2018, 2020). The secondary task was self-paced so that the drivers could modulate their distraction engagement based on their anticipation of how the surrounding traffic could evolve. Further, in previous work, we found that compared to novice drivers, experienced drivers exhibit more anticipatory driving behaviors in non-automated driving (He & Donmez, 2018, 2020; Stahl et al., 2014, 2016, 2019), and that they are more efficient at modulating their secondary task engagement in automated driving (He & Donmez, 2019). Thus, we also considered driving experience as a factor in this study.

The remainder of this paper is organized as follows: Section 3 describes the study, including detailed descriptions of the TORAC and STTORAC displays, the driving and secondary tasks, and the analysis approach; Section 4 presents our results and is followed by discussion (Section 5) and conclusion (Section 6) sections.

3. Methods

3.1. Participants

A total of 48 participants completed the experiment. Participants were mainly recruited through advertisements posted on the University of Toronto campus, in online forums, and in nearby residential areas. Both novice and experienced drivers were recruited based on the criteria from Stahl et al. (2016) and He and Donmez (2018, 2020), which are simulator studies that focused on anticipatory driving in non-automated vehicles. In particular, experienced drivers had a full driver's license (G in Ontario or equivalent elsewhere in Canada or the U.S.) for at least 8 years with > 20,000 km driven in the past year. Novice drivers obtained their first learners' license (G2 in Ontario or equivalent elsewhere in Canada or the U.S.) less than 3 years prior with < 10,000 km driven in the past year. All participants were also screened for their proneness to simulator sickness. To make our participant sample representative of the general driver population, we did not filter participants based on their experience with ACC and LKA systems. However, data on participants' experience with automation was collected in the screening questionnaire: prior to participating our experiment, 6 participants reported having used ACC only (5 of them used ACC less than once a year; and 1 used ACC several times a year), 3 participants reported having used LKA only (1 used LKA less than once a year; 1 used LKA several times a year; and the other one used LKA several times a month), and 8 participants reported having used both ACC and LKA (1 used ACC and LKA almost every day; 1 used ACC and LKA several times a month; 1 used ACC several times a month and LKA almost every day; 3 used ACC and LKA several times a year; 2 used ACC less than once a year and LKA several times a year).

The experiment took about 2.5 hours. Participants were compensated at a rate of C$14/hr. An additional C$8 monetary incentive was used to encourage drivers to engage in the secondary task while also prioritizing driving safety. The study received approval from the University of Toronto Research Ethics Board (REB#36674).

3.2. Experiment Design

The experiment was a 2 × 3 × 2 mixed design with driving experience (novice vs. experienced) and display type (baseline, TORAC, STTORAC) as between-subjects factors, and the scenario criticality (action-necessary vs. action-not-necessary) as the within-subject factor. Each participant experienced four action-necessary (A-N) scenarios and four action-not-necessary (A-not-N) scenarios. In A-N scenarios, the driver had to intervene to avoid a collision (by either taking over control of the vehicle or adjusting the settings of the automation, e.g., by changing ACC speed) as the required response exceeded the automation capabilities. In the A-not-N scenarios, it was not necessary for the driver to intervene in the driving task to avoid a collision, as the automation was able to perform the response. The order of scenario criticality was counterbalanced as described in Section 3.5.

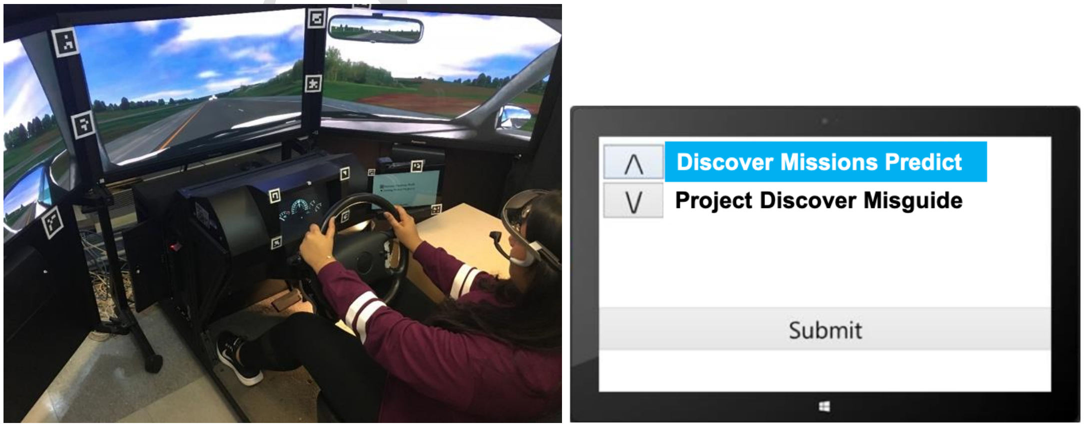
The different combinations of experience and display type led to 6 distinct groups of participants, with 8 participants in each group, balanced for gender (i.e., 4 females and 4 males). Table 1 presents participants' age information across these between-subject factor levels. As expected, experienced drivers were older than novice drivers in general (mean difference = 13.0 years, F(1,42)=86.69, p<.0001), but as desired, there was no difference in the mean ages of drivers assigned to different types of displays, p=.9, and no interaction of experience and display type was found, p=.97.

Table 1: Between subject factors (i.e., display type and driving experience) and participant age.

Display Type	**Driving Experience**	**Mean Age (Min - Max, Standard Deviation)**
Baseline display	Novice (n = 8)	20.0 (18 - 26, 2.5)
	Experienced (n = 8)	33.5 (25 - 47, 7.4)
TORAC display	Novice (n = 8)	21.3 (18 - 26, 2.9)
	Experienced (n = 8)	34.0 (27 - 48, 7.0)
STTORAC display	Novice (n = 8)	20.4 (18 - 25, 2.7)
	Experienced (n = 8)	33.3 (29 - 41, 4.0)

3.3. Apparatus

The experiment was conducted using a fixed-base MiniSim Driving Simulator by NADS (Figure 1a) with three 42-inch screens, creating a 130° horizontal and 24° vertical field at a 48-inch viewing distance. The simulator collects driving data at 60 Hz. A Surface Pro 2 laptop with a 10.6" touchscreen was mounted to the right of the dashboard and was used to display the secondary task. A Dikablis head-mounted eye tracking system by Ergoneers was used to record drivers' eye movements at 60 Hz and was equipped with a forward-facing camera that captured the forward view. A camera mounted below the dashboard recorded drivers' foot pedal movements and another camera mounted on a tripod beside the driver's seat recorded drivers' hand movements.



(a) (b)

Figure 1: (a) NADS MiniSim driving simulator; (b) Screenshot of secondary task display.

3.4. Secondary Task

A self-paced, visual-manual secondary task developed by Donmez, Boyle and Lee (2007) was used in this experiment (Figure 1b). The task simulated drivers' interaction with in-vehicle infotainment systems (e.g., searching for and selecting a song in a playlist) and has been shown to degrade non-automated driving performance in simulator studies (Chen, Hoekstra-Atwood, & Donmez, 2018; Merrikhpour & Donmez, 2017). Participants were shown 10 three-word phrases and were asked to select the one phrase that had "Discover" as the first word (e.g., "Discover Missions Predict"), or "Project" as the second word (e.g., "Dilemma Project Misguide"), or "Missions" as the third word (e.g., "Disagree Proceed Missions"). Two phrases were displayed on the screen at a time and participants pressed up and down arrows on the touchscreen to scroll through the list. Participants then selected their choice and pressed the submit button on the touchscreen to enter their selection. They then received feedback on whether their entry was correct, after which a new set of 10 phrases became available. The task was available throughout the drive; participants decided when to start the task and did so by hitting a start button. All participants reached nearly 100% correct rate in the secondary task.

3.5. Driving Task

The driving automation implemented in the simulator consisted of adaptive cruise control (ACC) and lane keeping assistance (LKA). Both systems could be engaged and disengaged using buttons on the steering wheel. The desired cruise speed of the ACC could also be adjusted using buttons on the steering wheel, but the gap time (i.e., distance from back bumper of the lead vehicle to the front bumper of the ego-vehicle divided by the speed of ego-vehicle) setting was fixed to 2 seconds for all participants, a value that is commonly recommended for highway safety (e.g., New York State Department of Motor Vehicles; Road Safety Authority in the

Government of Ireland). In addition, the ACC could be disengaged using the brake pedal and the LKA could be disengaged by turning the steering wheel over 5 degrees. Participants were instructed to use the automation (both ACC and LKA) as much as possible and were informed about the limitations of automation (see Section 3.7). They were also instructed to set the ACC speed at the speed limit and were told that safety was their first priority. On average, participants were found to use the ACC 91.2% of the time with a standard deviation (SD) of 4.5%, and LKA 97.2% of the time (SD: 2.4%).

There were four different types of anticipatory scenarios used in the experiment that were designed to allow for the anticipation of upcoming events (Scenarios A, B, C, D, Table 2). The scenario types were adapted from the ones used by previous studies (He & Donmez, 2018, 2020; Stahl et al., 2014, 2016, 2019). An A-N version and an A-not-N version of each scenario type was generated by manipulating the relative positions of the road agents (e.g., lead vehicles) and the ego-vehicle. Each participant completed four experimental drives (~5 minutes each), two of which were on a rural road and two of which were on a highway. The average drive duration was 6.05 min (standard deviation (SD): 0.37, min: 5.11, max: 6.87). The speed limit was 80.5 km/h (50 mph) for rural roads and 96.6 km/h (60 mph) for highways. There was moderate traffic on the opposite lanes, and one or two following vehicles that were far away from the ego-vehicle; there were no pedestrians. The surrounding vehicles that were not relevant to the anticipatory scenarios were programmed to move away from the ego-vehicle before the beginning of these scenarios. Participants were required to follow the lead vehicle and stay on the designated lane when possible, unless it was necessary to change lanes. Each drive had two anticipatory scenarios (one A-N and one A-not-N). Thus, each participant experienced all 8 anticipatory scenarios in one of the four orders presented in Figure 2; every two (one female and one male) out of the eight participants in each driving experience and display type combination underwent one of the four different orders. The average intervals between two scenarios in Drives 1 to 4 were 3.61 (SD: 0.11, min: 3.23, max: 3.81), 2.56 (SD: 0.08, min: 2.37, max: 2.84), 2.57 (SD: 0.07, min: 2.48, max: 2.70), and 3.91 (SD: 0.07, min: 3.80, max: 4.19) minutes.

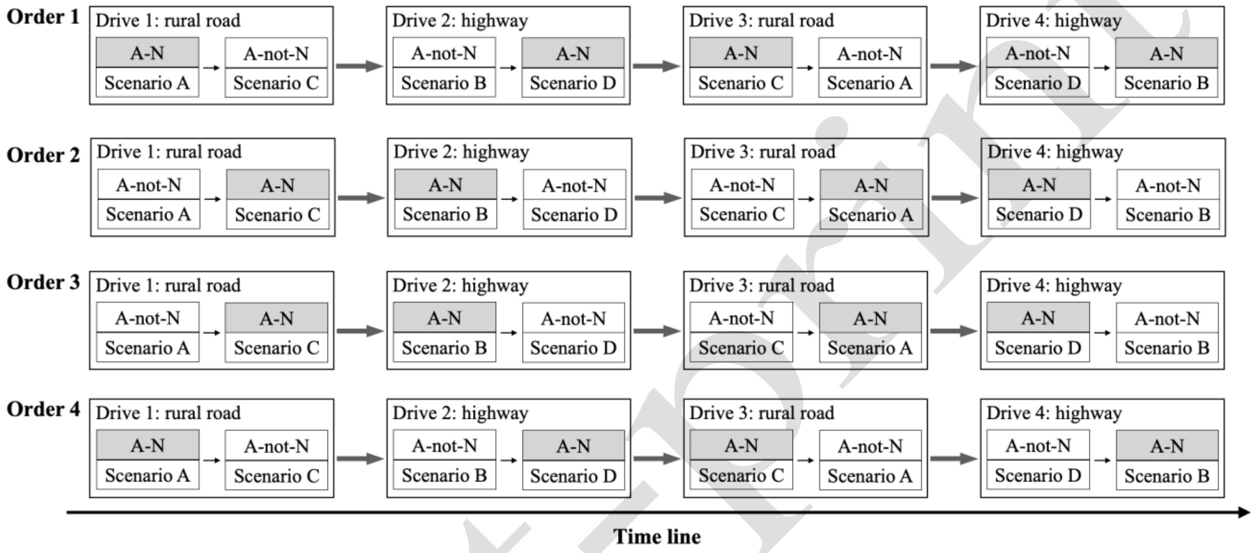
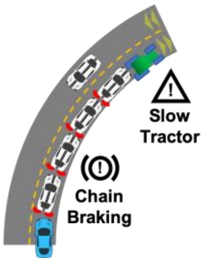
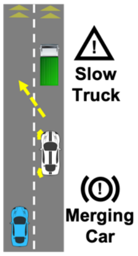
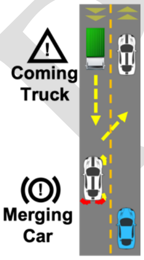
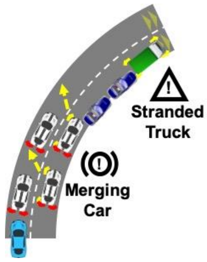


Figure 2: Order of anticipatory scenarios; participants were assigned to one of four orders.

The beginning of an event (event onset) in each scenario was marked by an action of a lead or overtaking vehicle that would unambiguously indicate the upcoming event; e.g., a directional signal from the following vehicle in Scenario B as shown in Table 2. Anticipatory cues, in contrast, did not necessarily indicate a clear conflict. For example, again in Scenario B, the decreasing distance between the truck and the following vehicle can be considered an anticipatory cue suggesting that the following vehicle may merge left in front of the ego-vehicle; however, the following vehicle may still slow down and merge behind the ego-vehicle.

Table 2: Description of the anticipatory driving scenarios used in the experiment.

Scenario Image	Scenario Description
	*Scenario A: Chain Braking Event Due to Slow Tractor* Ego-vehicle followed a chain of four vehicles (in white) on a two-lane rural road with moderate oncoming traffic, traveling at 80.5 km/h (50 mph). The frontmost vehicle was d_1 away from the ego-vehicle. Due to a slow tractor ahead on a curve, traveling at 40.2 km/h (25 mph), the front vehicle started to brake when within d_2 of the tractor, with a deceleration of a_1. The other lead vehicles braked consecutively. *Anticipatory cues*: slow tractor, reduced distance between lead vehicles, successive braking of lead vehicles (except the one directly ahead) *Event onset*: brake lights of the lead vehicle directly ahead of the ego-vehicle ***Action-necessary* version** • d_1= 152.4 m (500 feet) • d_2 = 61.0 m (200 feet) • a_1 = 10 m/s^2 ***Action-not-necessary* version** • d_1= 213.4 m (700 feet) • d_2= 30.5 m (100 feet) • a_1= 8 m/s^2
	*Scenario B: Merging Event Due to Slow Truck* Ego-vehicle traveled at 96.6 km/h on the left lane while driving on a four-lane divided highway. The ego-vehicle approached a truck and a following vehicle on the right lane, initially traveling at 72.4 km/h (45 mph). As the distance between the truck and the ego-vehicle fell under d_1, the truck slowed down to be 36.1 km/h (22.4 mph) slower than ego-vehicle, forcing the following vehicle to slow down to be 10.8 km/h (6.7 mph) slower than the ego-vehicle. After about t_1, the following vehicle signaled left and merged into the participant's lane with its speed v_1 slower than the ego-vehicle, trying to pass the truck. About t_2 seconds later, it accelerated to drive away after merging left. *Anticipatory cues*: reduced distance between the truck and the following vehicle *Event onset*: left signal of the merging vehicle ***Action-necessary* version** • d_1= 79.0 m (260 feet) • t_1 = 11 s • v_1 = 24.1 km/h (15 mph) • t_2 = 6 s ***Action-not-necessary* version** • d_1= 92.2 m (302 feet) • t_1 = 10 s • v_1 = 8.1 km/h (5 mph) • t_2 = 4 s
	*Scenario C: Merging Event Due to Oncoming Truck* The ego-vehicle followed a lead vehicle on a rural road. At a moment, the vehicle directly behind (overtaking vehicle) signaled left with high beams, pulled into the opposite lane, and accelerated to be v_1 faster than the ego-vehicle to overtake the ego-vehicle. Because of an oncoming truck (relative speed of v_2 to the ego-vehicle), the overtaking vehicle had to slow down to be 72.4 km/h (45 mph), cut in front of the ego-vehicle abruptly after signaling right, when the distance between the ego-vehicle and the truck fell under d_1. The overtaking vehicle accelerated after merging right. *Anticipatory cues*: left signal and left merging of the overtaking vehicle, emerging of the oncoming truck *Event onset*: right signal of the overtaking vehicle ***Action-necessary* version** • v_1 = 16.1 km/h (10 mph) • v_2 = 144.8 km/h (90 mph) • d_1 = 259.1 m (850 feet) ***Action-not-necessary* version** • v_1 = 25.8 km/h (16 mph) • v_2 = 136.8 km/h (85 mph) • d_1 = 274.3 m (900 feet)



Scenario D: Chain Braking Event Due to Stranded Truck

The ego-vehicle was driving on the left of the highway. Because of a stranded truck and two police cars behind, two lead vehicles on the right lane were forced to brake in sequence with a deceleration of 5m/s^2, and merged left after signaling left, when the distance between the first lead vehicle on the right lane and the police car behind fell below $\boldsymbol{d_1}$. This forced the two lead vehicles on the left lane to brake. At this moment, the distance between the ego-vehicle and the lead vehicle directly ahead on the left lane was $\boldsymbol{d_2}$ and the lead vehicle was forced to brake for $\boldsymbol{t_1}$ with a deceleration of $\boldsymbol{a_1}$.

> *Anticipatory cues*: the truck and the police vehicles becoming visible, the merging of two vehicles on the right, the braking of all other vehicles except the one directly ahead of the ego-vehicle, and the reducing distances between all vehicles except the distance between the ego-vehicle and the lead vehicle directly ahead.
>
> *Event onset*: brake lights of vehicle directly ahead

***Action-necessary* version**

- $\boldsymbol{d_1}$ = 134.1 m (440 feet)
- $\boldsymbol{d_2}$ = 30.5 m (100 feet)
- $\boldsymbol{t_1}$ = 2.5 s
- $\boldsymbol{a_1}$ = 10 m/s^2

***Action-not-necessary* version**

- $\boldsymbol{d_1}$ = 137.2 m (450 feet)
- $\boldsymbol{d_2}$ = 100.6 m (330 feet)
- $\boldsymbol{t_1}$ = 2 s
- $\boldsymbol{a_1}$ = 8 m/s^2

Note: In the sketches, the ego-vehicle is blue; the truck or tractor is green; other vehicles are white except the police cars in Scenario D. The dashed yellow arrows show the potential paths of different road agents.

3.6. Display Designs

We investigated two types of displays for their effectiveness in supporting anticipatory driving in automated vehicles: the TORAC display provided TORs and automation capability information, while the STTORAC display provided TORs, automation capability information, and surrounding traffic information. These two displays were also evaluated against a baseline display that used static indicators overlaid on the road to inform the driver whether or not the ACC and LKA systems were engaged (as shown in Figure 3). All participants were introduced to their respective display type through a video demo followed by practise drives.

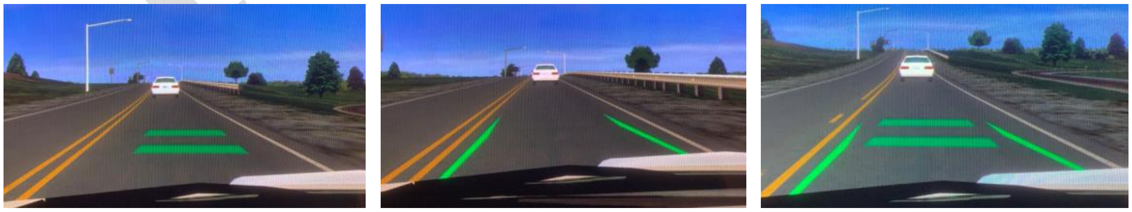
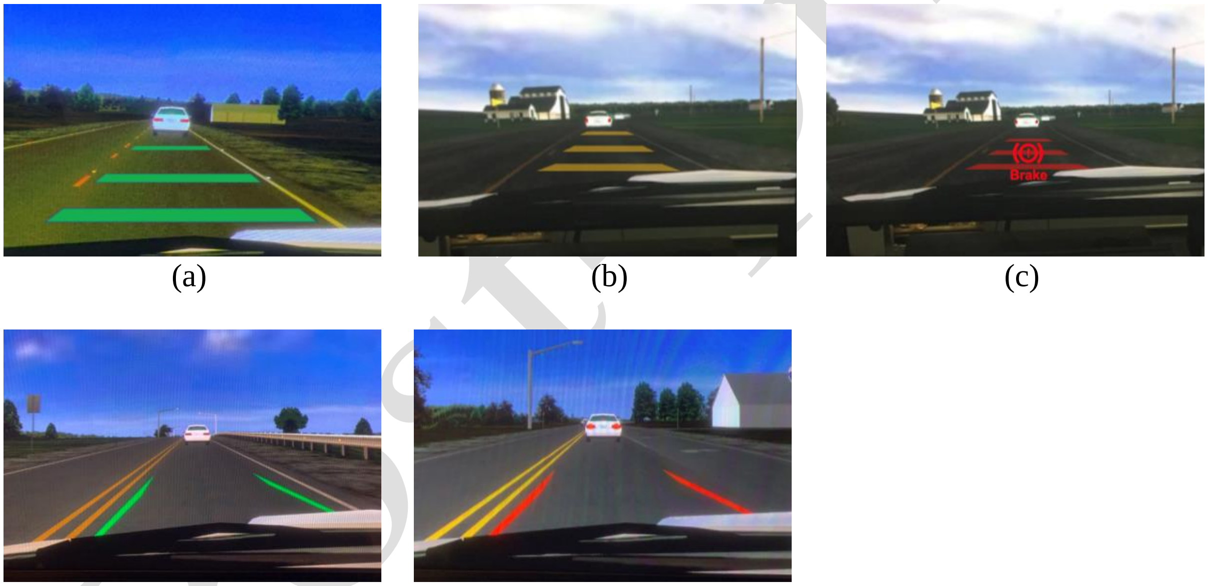

(a) (b) (c)

Figure 3: ACC and LKA states in baseline display: (a) ACC is engaged; (b) LKA is engaged; (c) both ACC and LKA are engaged.

3.6.1. TORAC: TOR + Automation Capability (AC) Information

In our TORAC display design, ACC and LKA system capability information was presented using an augmented reality display on the windshield. Augmented reality displays have been shown to be effective in reducing response time to automation failures (Damböck et al., 2012; Debernard et al., 2016). TORs were provided through the same windshield displays visually; auditory warnings (three beeps provided 0.05 seconds apart at 4kHz, each around 0.05 seconds long) were also used as the auditory modality, which has been demonstrated to be more suitable than the visual modality for conveying high priority messages (Politis, Brewster, & Pollick, 2014; Walch et al., 2015). The braking distance of the ACC system was used to display ACC capability similar to Tonnis, Lange and Klinker (2007), and the visibility of lane markings was used to display LKA capability similar to implementations in production vehicles (e.g., Ford Motor Company, 2016). In our study, the maximum deceleration of the ACC system in the ego-vehicle was 0.3g (~2.94 m/s^2). Thus, it was possible that the ACC could not stop the vehicle in time to avoid a collision if a lead vehicle braked hard and at a close distance.

The display communicated the capability of the ACC to handle lead vehicle braking via horizontal bars overlaid on the road in front of the ego-vehicle. The participants were informed that there could be up to four bars presented to them. From the farthest bar to the closest, the bars represented the minimum safe gap distance when a lead vehicle braked at an infinite deceleration (sudden stop), a deceleration of 0.8g (~7.84 m/s^2), 0.6g (~5.88 m/s^2), and a deceleration of 0.4g (~3.92 m/s^2). These deceleration rates were chosen based on how they were perceived in our simulator, going from intensive braking to slight braking. Figure 4a presents three of the four bars, meaning that the lead vehicle is at a gap distance where the ACC can respond safely if the lead vehicle is to brake at deceleration equal or less than 0.8g. Whenever a lead vehicle braking event occurred that could be handled by the ACC system without driver intervention, the green bars turned orange (Figure 4b). However, if the ACC could not stop the vehicle safely, a TOR was issued with the green bars turning red, and a “brake” icon appearing in the middle of the screen accompanied by an auditory warning requiring the driver to take over immediately (Figure 4c). The TOR was only triggered in A-N scenarios, if the driver did not proactively intervene before event onset. For these situations, TOR was triggered at the moment the brake lights of the vehicle directly ahead were activated (Scenarios A and C), or when the following (Scenario B) or overtaking vehicles (Scenario D) started to cross the lane markings in front of the ego-vehicle.



(a) (b) (c)

(d) (e)

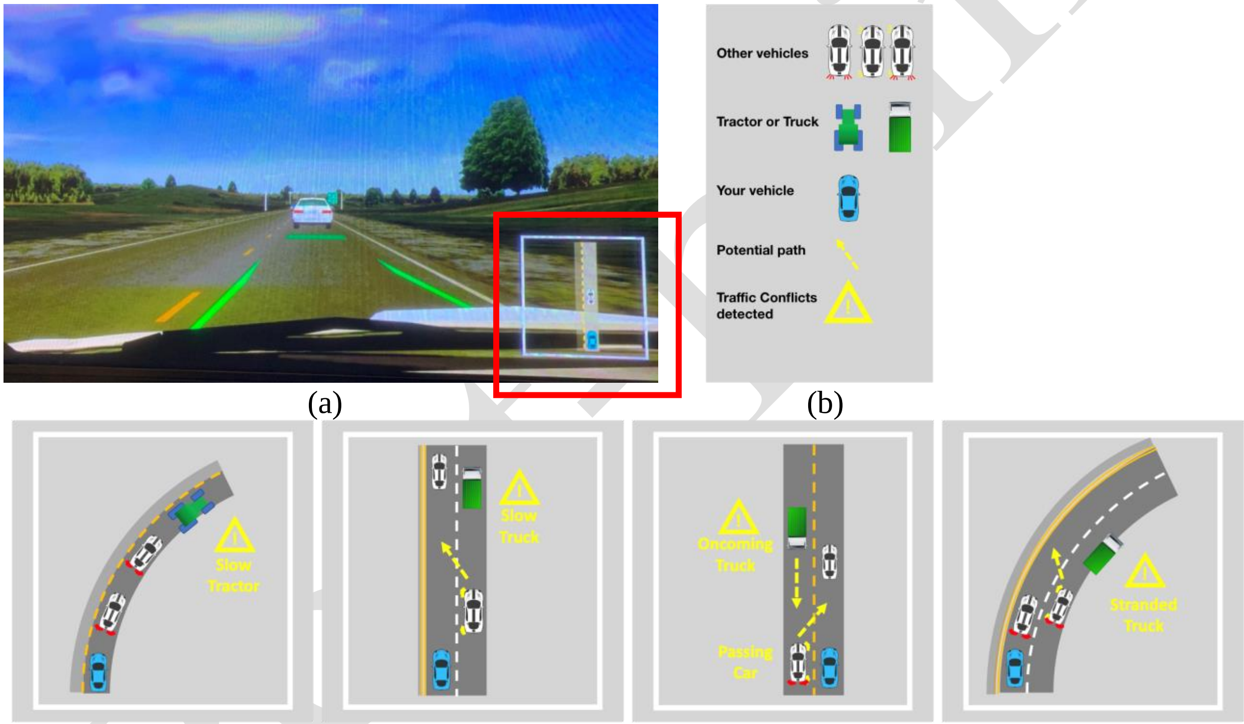
Figure 4: Automation capability information and visual component of TORs: (a) ACC indicators when there is no braking event and ACC can handle braking events with deceleration equal to or less than 0.8g (four bars were visible if the ACC could handle a sudden stop of the lead vehicle, fewer bars were visible if ACC could only handle less intensive braking events); (b) ACC indicators when the lead vehicle brakes but ACC can handle the braking event; (c) ACC indicators and the visual component of the TOR when the ACC cannot handle a braking event; (d) LKA can detect lane markings; (e) visual component of the TOR when LKA cannot detect lane markings.

To display the capabilities of the LKA system, two vertical bars were overlaid on the road parallel to the lane markings in front of the ego-vehicle (Figure 4d). The participants were told that if no lane markings were detected, the bars would turn red (Figure 4e) and the same auditory warning used for ACC failures would be heard, indicating that they would need to take over steering. Although participants were told that both systems could require their intervention, we only focused on critical events that can be anticipated based on the development of the traffic in front of the participant's vehicle, and therefore, none of the scenarios involved failures of the LKA system.

3.6.2. STTORAC: Surrounding Traffic (ST) Information + TOR + Automation Capability (AC) Information

In addition to the TORAC display presented above, drivers in the STTORAC condition were also presented with a surrounding traffic information display (Figure 5) similar to what was used in Stahl et al. (2016). A limitation of the Stahl et al. (2016) study is that their displays only appeared when anticipatory cues for the events became visible to the driver, and thus drivers may have been reacting to the appearance of the display, rather than acting based on an understanding of the traffic information conveyed by the display. In our study, the display showing the surrounding traffic information was available and was updated continually throughout the entire drive. It should be noted that in both our study and in Stahl et al. (2016), the information on the surrounding traffic displays (e.g., GPS position and speed of surrounding vehicles, the road map and potential vehicle paths) was provided by the driving simulator software directly rather than through actual technologies such as GPS, and V2V and V2I communications. If implemented in actual vehicles on the road, such a display would heavily rely on such ICV technologies.

Figure 5 shows the placement of the surrounding traffic display on the windshield, the different icons it used to convey traffic information, and images of how the scenarios described in Table 2 were presented on the display. It should be noted that to minimize clutter, the display represented an abstraction of the traffic situation and only presented the road agents that were relevant to the road conflicts and were visible to the drivers. It also presented traffic conflicts and potential vehicle paths.



(a) (b)

(c)

Figure 5: Surrounding traffic information display: (a) Location of the display on the windshield (on the right bottom corner, as highlighted via a red rectangle in this figure); (b) Display legend presented to the participants during training (not presented while driving); (c) Surrounding traffic information for Scenarios A to D (from left to right).

3.7. Procedures

Upon participant arrival to the experiment session, the experimenter verified participant eligibility and obtained informed consent. The experimenter then introduced the participant to driving the simulator and performing the secondary task and asked the participant to practice the secondary task without driving the simulator. This was followed by the experimenter giving verbal instructions on the operation of the ACC and LKA systems, then asking the participant to practice operating them. During this training, the experimenter emphasized that the automated driving system may not be able to navigate some intense braking events because of the limited braking capability of the ACC, and that the LKA may not work when lane markings are faded or are missing. Then, participants completed a 10-minute practice drive, on a route similar to the ones in the experimental drives in terms of traffic density and road type, but without any supporting displays or anticipatory driving scenarios. For the first 5 minutes of this practice drive, participants were required to drive the vehicle without automation; after 5 minutes, they were instructed to engage and disengage the ACC and LKA twice and then keep using these systems until they felt comfortable driving with them. Participants were also required to practice interacting with the secondary task during this practice drive. Before this practice drive, participants were informed about simulator sickness and were asked to indicate in case they experienced any of its symptoms. The experimenter also monitored the participants for signs of sickness. No cases of simulator sickness were observed.

Participants were then introduced to the automation displays based on the condition they were assigned to (i.e., baseline, TORAC, or STTORAC), and performed another practice drive to familiarize themselves with the displays. Next, participants completed one more practice drive, but they were told that this was an experimental drive (this was done to minimize their ability to figure out the purpose of the study). This additional practice drive included two braking events that were not designed to elicit anticipatory behaviors; they were abrupt-onset hazards (sudden lead vehicle braking events). One of the braking events was A-N, i.e., it required the participant to take over vehicle control to avoid a collision. This additional drive aimed to improve participants' understanding of the automation's capabilities, as experiencing transfers of control from the automation, compared to verbal instructions only, can better calibrate drivers' trust in and reliance on the automation (Körber, Baseler, & Bengler, 2018). In this practice drive and the following experimental drives, participants were asked to prioritize driving safety, use ACC and LKA as much as possible, and take over the control of the vehicle only when necessary.

After these practice drives, participants completed the four experimental drives. After each experimental drive, participants were asked to respond to questionnaires. They completed the NASA Task Load Index (NASA-TLX), which captures workload through six constructs (i.e., mental demand, physical demand, temporal demand, performance, effort and frustration) assessed on a scale ranging from "0: very low" to "100: very high" (Hart & Staveland, 1988). Then, they rated their trust in the automated driving system they used (i.e., "I can trust the system"), from 1 (not at all) to 7 (extremely). Finally, they completed the System Acceptance Questionnaire (Van Der Laan, Heino, & De Waard, 1997), which measured their perceived usefulness of and satisfaction with the automated driving system, both ranging from -2 (negative) to 2 (positive).

3.8. Dependent Variables and Statistical Analysis

Four categories of variables were analyzed:

1) whether the participant exhibited anticipatory driving behaviors,
2) measures of glance behaviors to anticipatory cues and secondary task display,
3) minimum gap time during an event as a driving safety measure,
4) questionnaire responses on perceived workload, trust, and acceptance.

For the identification of anticipatory driving behaviors, we first investigated whether drivers performed any pre-event actions, i.e., control actions performed prior to the event onset in anticipation of an event, in a manner similar to anticipatory driving behavior identification in non-automated vehicles (He & Donmez, 2018, 2020; Stahl et al., 2014, 2016). For the automated vehicle context, we operationalized pre-event actions as control actions the driver performs before an event onset to intervene the automation. The possible pre-event actions for our study included control actions aimed to slow down the vehicle for all scenarios (i.e., disengaging the ACC by pressing the brake pedal or the cancel button, or reducing the set speed of the ACC system through buttons on the steering wheel), or speed up the vehicle for Scenarios B and C (i.e., pressing the gas pedal or increasing the set speed of the ACC system through steering wheel buttons). In addition to pre-event actions, we considered pre-event preparation as another type of anticipatory driving behavior when a pre-event action was not performed. Pre-event preparation was defined as an observed intention by the drivers to intervene in the driving task before event onset, for example, by moving their foot towards the brake or accelerator pedals, moving their hands towards the steering wheel, or hovering their finger above one of the control buttons that could disengage the automation or adjust its settings (e.g., ACC speed).

Three raters blind to the participants’ level of driving experience used the videos of the forward view, the driver’s feet, and the driver’s hands to independently judge whether the participants exhibited any anticipatory driving behaviors (pre-event action or pre-event preparation) in a given scenario. The raters were trained on the concept of anticipatory driving and the possible anticipatory driving behaviors the participants could exhibit in each scenario. The raters were not provided with strict criteria; instead, they were asked to make their own judgement. Conflicts were resolved by asking the raters to re-watch the recorded data (videos and eye-tracking data) and discuss their findings. The raters reached a substantial inter-rater reliability (Fleiss' κ=0.73) before resolving the conflicts. Finally, for cases where a pre-event action or a pre-event preparation was identified, if the driver exhibited no glances toward any of the anticipatory cues before event onset, then these cases were re-categorized as no action and no preparation. This was done to avoid including coincidental foot or hand movements as anticipatory driving behaviors.

According to the ISO 15007-1:2014(E) standard (International Organization for Standardization, 2014), a glance was defined to initiate at the moment when the direction of gaze started to move towards an area of interest (e.g., secondary task display) and to end at the moment when it started to move away from it. The glance measures used in our analysis are listed in Figure 6; cue onset refers to the moment when the first anticipatory cue became visible. It should be noted that if a participant never looked at a cue, the time until first glance was regarded as the duration from the cue onset to the event onset. Glances that fell partially on a data extraction period were handled following the method in Seppelt et al. (2017) and He and Donmez (2020). Two seconds was used as the threshold for long glances based on crash risk research conducted in non-automated driving (Klauer et al., 2006) as no equivalent threshold exists for automated driving. In addition to the glance measures listed in Figure 6, mean glance duration and rate of glances at the anticipatory cues and at the secondary task were analyzed but are not reported in this paper, as these measures did not provide any additional insights and we could explain drivers' visual attention allocation using primarily the variables listed in Figure 6. It should also be noted that although the number of cues was different across the four scenario types, this did not affect our analysis as we were not interested in comparisons across scenario types.

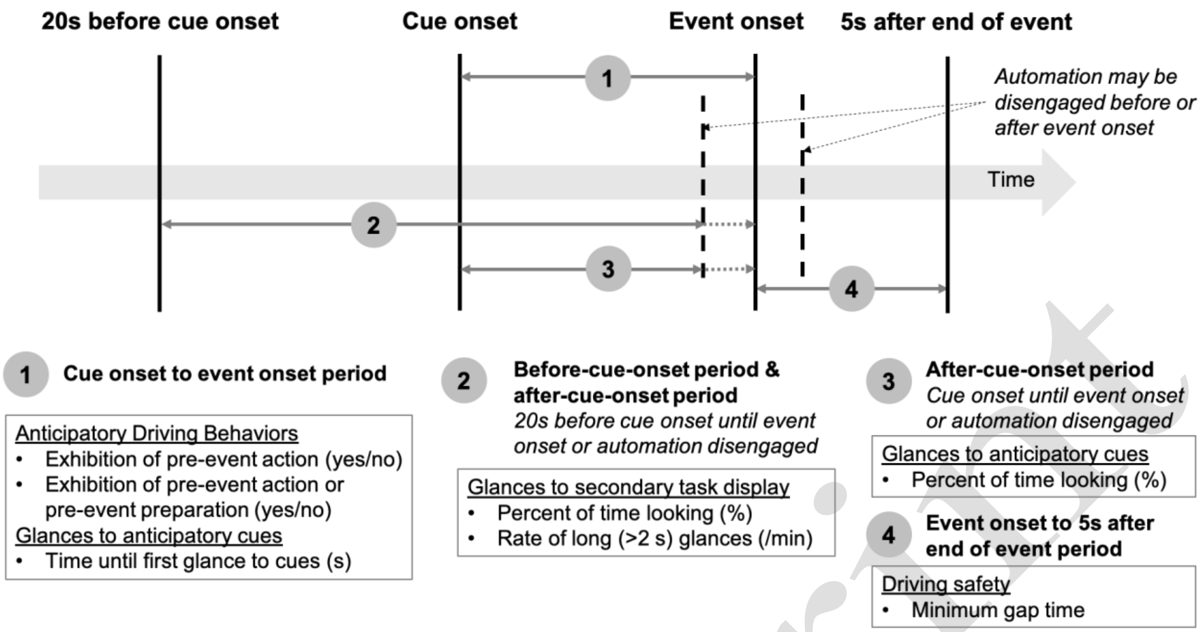


Figure 6: Time periods used to extract anticipatory driving, glance, and driving safety measures. The mean duration of the after-cue-onset period was 36.6 sec (SD: 5.5) for Scenario A, 10.4 sec (SD: 1.2) for Scenario B, 9.6 sec (SD: 1.5) for Scenario C, and 13.0 sec (SD: 3.2) for Scenario D. The duration from event onset to end of event was 4 sec for Scenario A, Scenario C, and A-not-N version of Scenario B, 6 sec for A-N version of Scenario B, 2 sec for A-not-N version of scenario D, and 2.5 sec for A-N version of Scenario D.

Minimum gap time during an event was extracted from the "event onset to 5s after end of event" period, where the "end of event" was the moment the braking or merging vehicle accelerated to drive away in each scenario. It was calculated as the "the distance from the front bumper of the ego vehicle to the rear bumper of the lead vehicle, divided by the speed of the ego vehicle". If a collision occurred, the minimum gap time was marked as 0. Overall, there were 17 collisions in a total of 384 scenarios, thus collisions were not analyzed but were captured in the calculation of minimum gap time. In a collision, participants received only visual feedback: the ego-vehicle overlapped with the other vehicle for a brief period.

All statistical analyses were conducted in SAS University Edition V9.4. For information on experimental design and analysis methods, the reader is referred to Oehlert (2010). In addition to the analysis of independent variables that were part of the experiment design (i.e., experience, display type, and scenario criticality), one more independent variable, “cue-onset”, was created to investigate whether drivers’ behavior changed as cues became visible. The “cue-onset” variable had two levels: before-cue-onset (i.e., the period from 20 seconds prior to cue onset until cue onset) and after-cue-onset (i.e., the period from cue onset to event onset or automation disengaged, whichever is earlier). Binary dependent variables (e.g., whether drivers exhibited pre-event actions) were analyzed using logistic regression models. The rate of long (>2s) glances toward the secondary task was analyzed using a negative binomial model given that over-dispersion (variance: 2.98 > mean: 1.83) was detected; the length of the data extraction period (i.e., before-cue-onset and after-cue-onset periods) was used as the offset variable. The repeated measures (i.e., four scenarios for each participant) in the logistic regression and the negative binomial models were accounted for using generalized estimating equations. All other variables were analyzed using linear mixed models, with participant introduced as a random factor and with a compound symmetry variance-covariance structure. Dependent variables were transformed when necessary to satisfy mixed model assumptions. Significant main and interaction effects were followed by pairwise comparisons; only the significant ($p<.05$) pairwise comparisons are reported in the results section. We did not however remove non-significant factors from our models, as with a designed experiment, all effects are potentially important, and a null effect can have an important theoretical consequence.

4. Results

4.1. Anticipatory Driving Behaviors

The statistical results from the models built to analyze pre-event actions and anticipatory driving behaviors can be found in Table 3. Drivers experiencing the TORAC display (TOR and automation capability information) did not exhibit any pre-event actions in any of the anticipatory driving scenarios (see Figure 7). Thus, a model was built to compare the odds of performing pre-event actions when drivers were provided with the STTORAC display (TOR, automation capability, and surrounding traffic information) versus the baseline display, and no significant effects were observed. A significant display effect was observed when the dependent variable was exhibiting anticipatory driving in general (pre-event action or pre-event preparation) vs. not exhibiting any: the odds of exhibiting anticipatory driving behaviors was the highest with the STTORAC display, followed by the baseline, and then the TORAC display (*STTORAC vs. baseline*: Odds Ratio (OR)=2.58, 95% CI: 1.29, 5.16, $\chi^2(1)= 7.17$, p=.007; *STTORAC vs. TORAC*: OR=9.77, 95% CI: 3.40, 28.04, $\chi^2(1)=17.94$, p<.0001; *baseline vs. TORAC*: OR=3.79, 95% CI: 1.41, 10.22, $\chi^2(1)=6.93$, p=.009).

Table 3: Statistical results for anticipatory driving behaviors (* p<.05). The main and interaction effects are reported.

Dependent Variables	**Independent Variables and Interactions**	**df**	χ^2	***p***
Pre-event action vs. No pre-event action	Display **(STTORAC vs. Baseline only)**	1	0.18	.67
	Experience	1	1.32	.25
	Scenario criticality	1	2.25	.13
	Experience*Display	1	0.83	.36
	Experience*Scenario criticality	1	0.93	.33
	Scenario criticality*Display	1	3.51	.06
Anticipatory driving behavior (Pre-event action or pre-event preparation) vs. No anticipatory driving behavior	Display	2	18.95	<.0001*
	Experience	1	0.96	.33
	Scenario criticality	1	0.79	.37
	Experience*Display	2	1.57	.46
	Experience*Scenario criticality	1	0.01	.90
	Scenario criticality*Display	2	3.30	.19

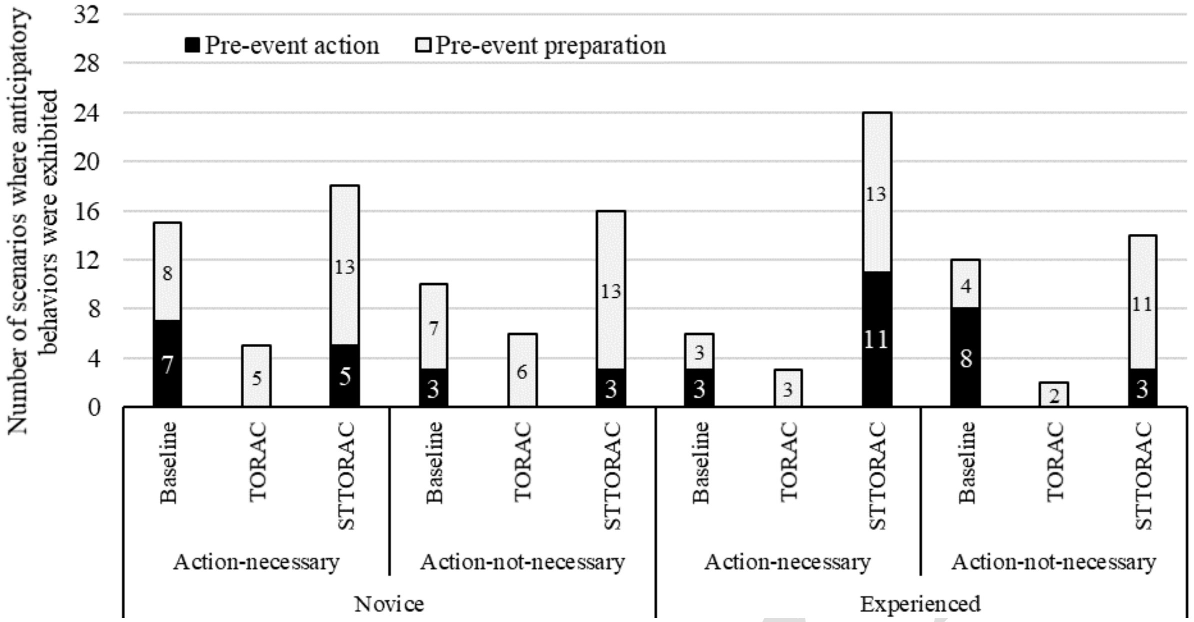


Figure 7: Number of scenarios where anticipatory driving behaviors were exhibited. The total number of scenarios for each experimental condition is 32 (8 participants per condition who experienced 4 scenarios for a given level of scenario criticality).

4.2. Glance Behaviors

The statistical results for glance models are presented in Table 4. As also demonstrated in Figure 8a and Figure 8b, the TORAC display led to a longer time until first glance and lower percent of time looking at cues compared to both STTORAC (t(42)=4.42, p<.0001 and t(42)= -4.39, p<.0001) and baseline displays (t(42)=2.89, p=.006 and t(42)= -3.37, p=.002).

Table 4: Statistical results for glance and driving safety measures (* p<.05). The first column lists the independent variables investigated in the analysis and their interactions; the other columns present the statistical results for different dependent variables. A dash ("-") indicates that the corresponding independent variable was not applicable for that measure and was not included in its statistical analysis (e.g., cue-onset is not a relevant variable for analyzing % time looking at cues; this measure has a value of zero before cue-onset).

	Dependent Variables									
	Visual attention to cues				**Visual attention to secondary task display**				**Driving safety**	
	Time until 1st glance		% of time looking		% of time looking		Rate of long glances		Minimum gap time	
Independent Variables and Interactions	*F*-value	*p*	*F*-value	*p*	*F*-value	*p*	χ^2-value	*p*	*F*-value	*p*
Display	F(2,42)=10.08	.0003*	F(2,42)=10.57	.0002*	F(2,42)=7.40	.002*	$\chi^2(2)=3.86$	.15	F(2,40.5)=5.41	.008*
Experience	F(1,42)=0.44	.51	F(1,42)=0.02	.89	F(1,42)=0.18	.67	$\chi^2(1)=0.06$	.80	F(1,40.5)=1.44	.24
Scenario criticality	F(1,332)=1.20	.28	F(1,332)=0.17	.68	F(1,711)=0.11	.74	$\chi^2(1)=0.49$	.48	F(1,326)=207.7	<.0001*
Cue-onset	-	-	-	-	F(1,711)=129.7	<.0001*	$\chi^2(1)=28.26$	<.0001*	-	-
Experience*Display	F(2,42)=0.40	.67	F(2,42)=0.14	.87	F(2,42)=0.30	.74	$\chi^2(2)=7.14$	.03*	F(2,40.5)=3.35	.045*
Experience*Scenario criticality	F(1,332)=1.26	.26	F(1,332)=0.96	.33	F(1,711)=1.39	.24	$\chi^2(1)=8.46$	.004*	F(1,326)=0.46	.50
Experience*Cue-onset	-	-	-	-	F(1,711)=0.12	.73	$\chi^2(1)=0.70$	.40	-	-
Scenario criticality*Display	F(2,332)=0.40	.67	F(2,332)=0.32	.73	F(2,711)=0.19	.83	$\chi^2(2)=0.69$	.71	F(2,326)=8.11	.0004*
Scenario criticality*Cue-onset	-	-	-	-	F(1,711)=0.62	.43	$\chi^2(1)=1.14$	.28	-	-
Display*Cue-onset	-	-	-	-	F(2,711)=43.14	<.0001*	$\chi^2(2)=19.64$	<.0001*	-	-
Gap distance at event onset	-	-	-	-	-	-	-	-	F(1,328)=22.27	<.0001*

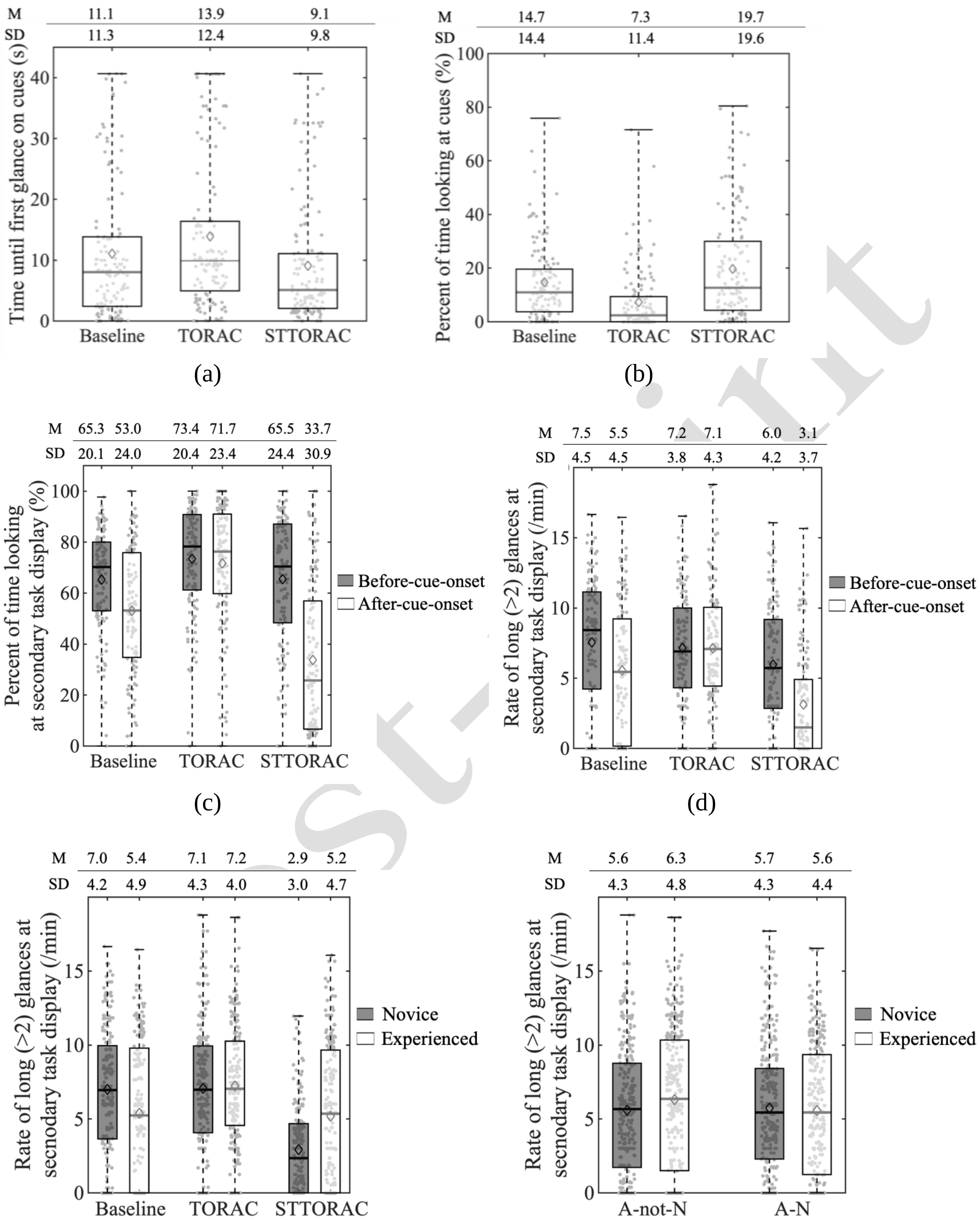


Figure 8: Boxplots of visual attention measures representing significant main and interaction effects. In this and the following plots, boxplots present the minimum, 1st quartile, median, 3rd

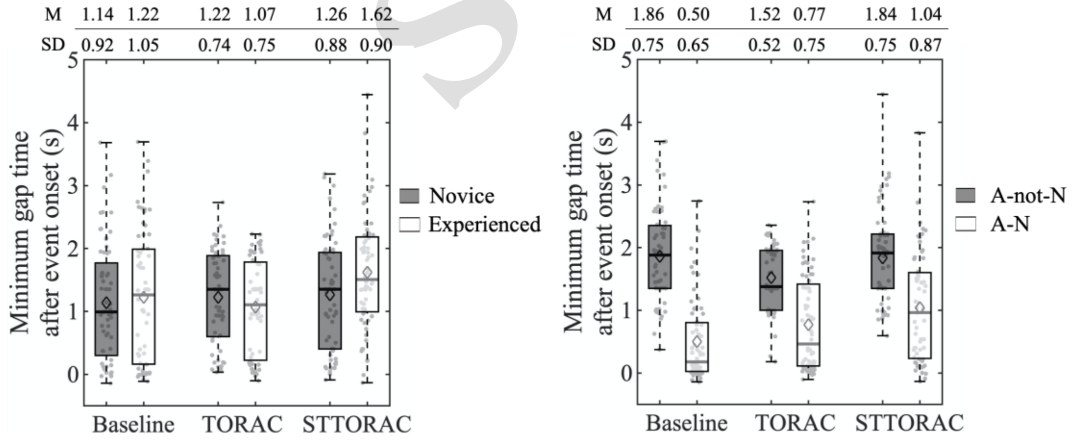
quartile, and maximum, along with the mean depicted through a hollow diamond. The mean (M) and standard deviation (SD) values are also provided at the top of each plot: (a) time until first glance at cues by display, (b) percent of time looking at cues by display, (c) percent of time looking at secondary task display for display and cue-onset interaction, (d) rate of long glances at secondary task display for display and cue-onset interaction, (e) rate of long glances at secondary task display for display and experience interaction, and (f) rate of long glances at secondary task display for experience and scenario criticality interaction.

Interaction effects were found between display type and cue-onset for the percent of time spent looking at (Figure 8c) and rate of long glances towards the secondary task (Figure 8d). Specifically, it was found that with both the STTORAC and the baseline displays, both measures decreased from before cue-onset to after cue-onset (*percent of time*: t(711)= -13.69, p<.0001 for STTORAC and t(711)= -5.30, p<.0001 for baseline; *rate of long glances*: $\chi^2(1)=15.13$, p<.0001 for STORRAC and $\chi^2(1)=21.05$, p<.0001 for baseline). In the after-cue-onset period, percent time looking at the secondary task was highest for TORAC, followed by baseline, and then STTORAC (*TORAC vs. baseline*: t(48.5)=3.01, p=.004; *TORAC vs. STTORAC*: t(48.5)=6.11, p<.0001; *baseline vs. STTORAC*: t(48.5)=3.10, p=.003). Similarly, compared to STTORAC, TORAC resulted in a higher rate of long glances to the secondary task in the after-cue-onset period, $\chi^2(1)=9.19$, p=.002.

Experience was found to interact with display type (Figure 8e) as well as scenario criticality (Figure 8f) for rate of long glances. Novice drivers had lower rates of long glances to the secondary task compared to experienced drivers when provided with the STTORAC display, $\chi^2(1)=4.17$, p=.04. Further, novice drivers had lower rates of long glances to the secondary task display when provided with the STTORAC display compared to baseline, $\chi^2(1)=12.71$, p=.0004, and the TORAC display, $\chi^2(1)=6.18$, p=.01. Further, experienced drivers had lower rates of long glances toward the secondary task in A-N scenarios compared to A-not-N scenarios, $\chi^2(1)=10.35$, p=.001.

4.3. Driving Safety

For minimum gap time (Figure 9), display type was found to interact with experience and scenario criticality. Experienced drivers had a longer minimum gap time with the STTORAC compared to the TORAC, t(40.8)=3.97, p=.0003, and the baseline displays, t(41.6)=2.80, p=.008. Further, experienced drivers had a longer minimum gap time than novice drivers with the STTORAC display, t(40.8)=2.56, p=.01. A-not-N scenarios led to higher minimum gap time than A-N scenarios for all displays (*baseline*: t(326)=11.64, p<.0001; *TORAC*: t(326)=6.64, p<.0001; *STTORAC*, t(326)=6.97, p<.0001). In A-N scenarios, the STTORAC display led to the longest minimum gap times, followed by TORAC, and then the baseline displays (*STTORAC vs. TORAC*: t(113)=2.14, p=.03; *STTORAC vs. baseline*: t(114)=4.14, p<.0001; *TORAC vs. baseline*: t(113)=2.02, p=.046), while in A-not-N scenarios, both the STTORAC and the baseline displays led to longer minimum gap times compared to the TORAC display (*baseline*: t(113)=2.68, p=.008; *STTORAC*: t(113)=2.50, p=.01).



(a) (b)

Figure 9: Boxplots of minimum gap time representing significant interaction effects: a) by display type and driving experience, b) by display type and scenario criticality.

4.4. Subjective Responses

Display type influenced the perceived usefulness of, F(2,42)=4.43, p=.02, and the satisfaction with, F(2,42)=5.48, p=.008, the automation. The automation with TORAC display was perceived as more useful and more satisfactory compared to the automation with the baseline display, (*usefulness*: Δ=0.70, 95% CI: 0.22, 1.18, t(42)=2.97, p=.005; *satisfying*: Δ=0.78, 95% CI: 0.30, 1.27, t(42)=3.24, p=.002), and more satisfactory compared to the automation with the STTORAC display (Δ=2.11, 95% CI: 0.17, 4.05, t(42)=2.19, p=.03). Display type also had a significant effect on trust, F(2,42)=6.96, p=.002. Both the TORAC display, Δ=1.59, 95% CI: 0.73, 2.46, t(42)=3.71, p=.0006, and the STTORAC display, Δ=0.94, 95% CI: 0.07, 1.80, t(42)=2.18, p=.03, led to higher self-reported trust in the automated driving system compared to the baseline display. No significant effects of driving experience, display type, or their interactions were observed for the perceived workload (p>.05). The average scores of NASA-TLX were 40.3 (SD: 21.1), 31.2 (SD: 17.5), and 34.5 (SD: 23.0) for the baseline, TORAC, and STTORAC displays, respectively.

5. Discussion

We found that the STTORAC display (with surrounding traffic information, TOR, and automation capability information) resulted in the highest likelihood of anticipatory driving behaviors (including pre-event action and pre-event preparation); it also resulted in the longest minimum gap time in scenarios in which a control action by the driver was necessary to avoid a collision (that is, action-necessary scenarios). These findings suggest that providing surrounding traffic information in an automated driving context supports drivers' anticipation of events in the environment and enhances the quality of their responses to critical events. The TORAC display, in contrast, resulted in the lowest likelihood of anticipatory driving behaviors compared to both the STTORAC and the baseline displays. However, the TORAC display still showed some benefit in terms of driving safety in scenarios where driver intervention was necessary: there was an increase in minimum gap time compared to the baseline display.

An examination of drivers' glances at the anticipatory cues provided further insights on how each display impacted anticipatory driving. Drivers were the slowest with the TORAC display to direct their visual attention (longest time until first glance) to anticipatory cues and paid the least attention to them (lowest percent of time looking at cues). This aligns with previous findings from non-automated driving (He & Donmez, 2018, 2020; Stahl et al., 2019), which revealed a positive association between visual attention to anticipatory cues and anticipatory driving behaviors. No significant difference was found between the STTORAC and the baseline displays in terms of visual attention to anticipatory cues, yet, the STTORAC display led to an increase in anticipatory driving behaviors compared to the baseline display. Thus, the exhibition of anticipatory driving behaviors depends on more than just cue perception and appears to be supported by a combination of display elements.

TORs and automation capability displays have been proposed and evaluated in previous research to support takeover performance in automated driving systems (Seppelt & Lee, 2007; Walch et al., 2015). Our results indicate that drivers provided with TORs along with automation capability information (TORAC display) may develop overreliance on automation, whereas providing surrounding traffic information along with TORs and automation capability information (STTORAC display) seems to resolve this issue of possible overreliance. Both STTORAC and TORAC displays led to higher trust in automation compared to the baseline display, with the TORAC display rated as more useful and more satisfying than the STTORAC display. However, the TORAC display resulted in the highest level of engagement in the secondary task as indicated by percent time looking. Further, as stated earlier, the TORAC display had the lowest likelihood of anticipatory driving behaviors. In fact, drivers with the TORAC display did not exhibit any pre-event actions and some only intervened after a TOR was provided, even though they showed some preparation before the TOR (pre-event preparation), implying that they may have realized potential conflicts but chose not to act on them until a TOR was issued. These findings suggest that drivers with the TORAC display may have assigned more “responsibility” to the automation, while those who received additional surrounding traffic information (through the STTORAC display) developed a better understanding of the traffic situation and thus more appropriate reliance. Although in our experiment TORs were 100% reliable, they would not be so in reality, and over-relying on the driving automation to monitor the environment and provide a TOR when the driver action is needed would lead to safety issues. Workload associated with monitoring the roadway and the automation can be seen as a potential reason as to why drivers may have assigned more responsibility to the TORAC display than they did to the other two displays. However, we did not observe differences in perceived workload across the different experimental conditions. Further, the magnitude of the NASA-TLX responses did not indicate information overload associated with any of the conditions, although the response variance was relatively high. Thus, further data is needed to test the relation between perceived workload and reliance on vehicle automation.

We found driving experience to interact with display type and with scenario criticality. When provided with the STTORAC display, experienced drivers had longer minimum gap time compared to novice drivers, even though they had spent a higher percent of time looking at the secondary task and had a higher rate of long (>2s) glances at it. A possible explanation for these differences is that more experienced drivers developed a better and quicker understanding of the traffic information presented in the STTORAC display, and thus were able to exhibit safer driving behaviors despite engaging with the secondary task more. Experienced drivers also appeared to adapt their secondary task engagement based on scenario criticality, having a reduced rate of long (>2s) glances toward the secondary task in scenarios where their intervention was necessary compared to those that the automation could handle. This result aligns with findings of Underwood (2007), indicating that experienced drivers can adapt their visual scanning behaviors more effectively than novice drivers based on the complexity of the traffic environment. We did not screen out participants based on their experience with ACC and LKA. Although this decision can lead to a sample that is more representative of the driving population, drivers' experience with ACC and LKA may still have skewed the results. Future research may consider adopting more strict criteria to better differentiate the effects of displays on different driver populations.

The way we studied anticipatory driving in this research was by investigating observable behaviors, and thus did not capture drivers who may have anticipated conflicts but chose not to physically act or prepare for them. We also were not able to understand why some drivers chose to act whereas others showed preparation without intervening the automation. Future work can incorporate measures on risk perception and tolerance along with other individual differences that may further explain differences in driver response. Further, as stated above, the displays that we evaluated (e.g., TORs) were 100% reliable and our participants experienced these displays only for a short period of time. More research is needed to identify whether our findings would hold true with long-term use and when drivers experience display failures. Lastly, we only adopted limited types of scenarios in our study. Future research should consider validating our findings in a wider variety of anticipatory driving scenarios.

It should also be noted that the automated driving systems (ACC and LKA) studied in our experiment corresponded to SAE level 2 automation (SAE On-Road Automated Vehicle Standards Committee, 2018), and further research is needed to extend these findings to higher levels of driving automation. Although the use of TORAC and STTORAC displays might indicate an implementation of SAE Level 3 automation, the TOR implemented in our experiment was not issued in advance of the braking or merging events, and thus would still require the drivers to monitor the roadway. So even with the TORAC or STTORAC displays, the driving automation implemented in our experiment cannot be categorized as SAE Level 3, although the displays may create a system more advanced than the Level 2 systems currently in use. This also points to limitations in the SAE taxonomy of levels of driving automation, particularly in relation to SAE Level 3, or conditional driving automation, as also discussed by other authors (e.g., Biondi, Alvarez, & Jeong, 2019; Inagaki & Sheridan, 2019).

6. Conclusion

In this driving simulator experiment, we investigated the effectiveness of two types of displays for supporting anticipatory driving in automated vehicles. Both displays were evaluated against a baseline display that only showed whether the automation (ACC and LKA) was engaged. The TORAC display, which provided a takeover request (TOR) along with automation capability (AC) information, was similar to those used in previous studies and found effective in supporting drivers during takeover events (e.g., Gold et al., 2013; Seppelt & Lee, 2007; Tonnis et al., 2007). The STTORAC display incorporated the information conveyed by the TORAC display with additional information regarding the surrounding traffic environment. Display elements representing surrounding traffic information were adapted from a display evaluated in a previous study on supporting anticipatory driving in non-automated vehicles (Stahl et al., 2016). The surrounding traffic information conveyed in these displays can be made available through ICV technologies.

Our results suggest that displays providing both TORs and automation capability information (TORAC in our study) can improve driving safety in critical events but may also lead to overreliance on automation and impede anticipatory driving. Including surrounding traffic information on these displays (STTORAC in our study) can better calibrate drivers' reliance on automation and facilitate anticipatory driving.

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