Emergency, Automation Off: Unstructured Transition Timing for Distracted Drivers of Automated Vehicles

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Abstract*—In future automated driving systems, drivers will be free to perform other secondary tasks, not needing to stay vigilant in monitoring the car's activity. However, there will still be situations in which drivers are required to take-over control of the vehicle, most likely from a highly distracted state. While highly automated vehicles would ideally accommodate structured takeovers, providing ample time and warning, it is still very important to examine how drivers would behave when they are subjected to an unstructured emergency transition of control. In this study, we observed how participants (N=30) in a driving simulator performed after they experienced a loss of automation. We tested three transition time conditions, with an unstructured transition of control occurring 2 seconds, 5 seconds, or 8 seconds before the participants encountered a road hazard that required the drivers' intervention. Participants were given a passive distraction (watching a video) to do while the automated driving mode was enabled, so they needed to disengage from the task and regain control of the car when the transition occurred. Few drivers in the 2 second condition were able to safely negotiate the road hazard situation, while the majority of drivers in the 5 or 8 second conditions were able to navigate the hazard safely. Similarly, drivers in the 2 second condition rated the vehicle to be less trustworthy than drivers in the 5 and 8 second conditions. From the study results, we are able to narrow down a minimum amount of time in which drivers can take over the control of vehicle safely and comfortably from the automated system in the advent of an impending road hazard.

Keywords—Controlled Study, Autonomous Driving Simulation, Transition of Control, Driving Performance, Human Factors.

I. INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) defines five levels of vehicle automation that are differentiated by the number of specific control functions allocated to the driver or car [1]. Systems of Level 3, or Limited Self-Driving Automation, "enable the driver to cede all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control." This level of automation allows drivers to have "sufficiently comfortable transition time" when taking back control. However, NHTSA has not defined "sufficiently comfortable transition time" and thus has indicated that further evaluation is required to determine how this level of automated system should function. In our view, it is equally important that a worst-case benchmark be established to help determine what is "sufficiently comfortable." Thus, this paper examines the minimum time needed for drivers to safely regain control of vehicle in an unstructured (or unplanned) transition after a period of automated driving.

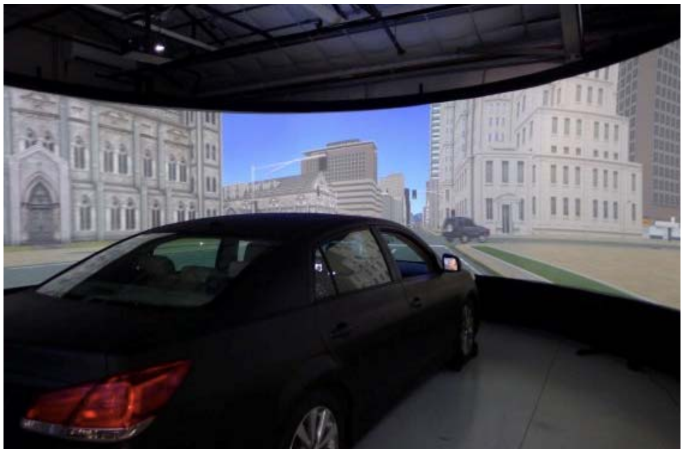

Figure 1: The Stanford Driving Simulator

In this study (N=30), we used a simulated driving environment (Fig. 1) where control of the vehicle could be alternately shared between the human drivers and the car's automated driving system. Participants were given a passive distraction task (i.e., watching a movie) to perform while the car's automated driving system was in control. In our simulation scenario, the car was performing automated freeway driving when it came upon an unexpected road hazard. At that point, the driver was expected to immediately disengage from the distraction task and retake control of the car after a takeover notification from the vehicle. We tested three different transition conditions, where the transition occurred 2 seconds, 5 seconds, or 8 seconds before the road hazard. This critical event is not only the likely motivation for the unstructured transition, but also acts as the major test of post-transition driving performance. Thus, it is important to determine how much time it takes for the drivers to react and also regain the control of vehicle so that they are able to successfully assess the situation and safely negotiate the imminent road hazard.

II. BACKGROUND

The goal of this study is to characterize drivers' reactions to an abrupt release from automated control, where the drivers experience an unstructured transition from automated driving. Unplanned driver takeover time has not been extensively studied in the frame of automated vehicles − specifically, what will happen when the driver is given control of the vehicle shortly before encountering a curve or road hazard. The specifics of how a driver will react to an unstructured transition need to be explored in order to characterize a worst-case scenario − and thus to establish a minimum acceptable transfer time for the design of structured transitions.

Research by Endsley et al. [2], described the need for operators of complex systems (such as aircraft) to maintain situation awareness. This would be difficult to reacquire after a period of exerting supervisory control with low task engagement. With an automated vehicle, drivers might be required to maintain a level of situation awareness while disengaged from driving, maintaining vigilance similar to that of an aircrew overseeing an autopilot. De Waard et al. [3] studied a quiet failure of an automated driving system, where the driver was cut-off shortly after the automated system shut off with only a subtle visual alert on the instrument panel. Without an obvious alert, only 50% of drivers took active control of the simulated vehicle, illustrating the threat of inattention, even in a study without the driver otherwise occupied. With structured takeover scenarios, Gold et al. [4] studied the point in time when an automated driving system had to "engage the attention of the driver in order to ensure a successful take-over process." They found that participants given shorter takeover request times reacted more quickly but performed poorer in regaining control than those with longer takeover request times.

Radlmayr et al. [5] examined the influence of different traffic situations and non-driving related tasks on the takeover process during highly automated driving. The study compared the takeover performance of drivers who were engaged in different secondary tasks in automated driving systems. Beukel et al. [6] observed the effect of varying headways on response time of distracted drivers in an automated car. The study found a significant positive relationship between advanced warning time and rates of successfully avoided collisions. Damböck et al. [7] explored how drivers' reaction time to take control of the vehicle varied, dependent on post-takeover task. The study instructed participants to perform various driving tasks of increasing complexity after takeover. Damböck et al. found that a six second transition was sufficient for most participants to accomplish these tasks. With eight seconds, most participants performed equivalently to those who did not transition from automated control. This indicated that notifications greater than eight seconds ahead might not increase post-transition driving performance.

Research had also been done examining how different types of tasks affect driving performance. Thiffault et al. [8] examined the effects of different types of driving tasks on drivers' performance. They found that drivers in a monotonous driving condition demonstrated poorer driving performance than drivers in a more varied environment. A study by Maltz et al. [9] on manual driving with an imperfect warning system found drivers distracted by a secondary task and given a less reliable warning system maintained longer headways than those who were given a more reliable driving system, implying that over-reliance on warnings could be more detrimental to safe driving.

The issues underlying difficulty in taking control of a vehicle are allocation of cognitive resources and situation awareness (Young et al. [10]). While there has been significant debate about the amount of cognitive capacity and attention that there is to be shifted between 'threads' (to use a computing metaphor from Salvucci et al. [11]), there is also significant agreement that rapidly shifting attention focus, especially to a highly demanding task results in poor task performance. If a driver is to go from watching a video to controlling the vehicle in a demanding environment, poor performance is to be expected. While many studies of transfer of control in automated driving have included additional driver tasks, this may not be significantly different than taking control after a period of prolonged supervision (e.g., Mok et al. [16]) where the available pool of attentional resources has been reduced as a result of a low arousal level. As such, research on switching from an alternate task (e.g. media consumption) can give hints to how well a driver will perform when switching rapidly from a low-arousal vigilance task to a high-arousal driving task under challenging conditions.

Therefore, we want to characterize drivers' reactions to these unstructured transitions, where the driver must re-engage in driving immediately and without any structured assistance from the car. If an unexpected transition occurs, how long will it take for a driver to reestablish sufficient situation awareness and to effectively exercise control over the vehicle? Considering automation failure to be an inevitable, if rare, occurrence, what will happen in these situations? While the majority of research in automation is focused on structured takeovers, studying an unstructured transition, where there is an immediate release to driver control will fill in a gap in the knowledge space regarding automated driving.

III. METHODOLOGY

A. Simulator

An immersive automobile simulator, the Stanford Driving Simulator (Fig. 1) is composed of two parts: a whole car and a visual display system. The first component is a Toyota Avalon that has been modified to provide participants with a realistic interface for the simulation. Both the steering wheel and pedals provide haptic feedback to drivers, which, as Ijsselsteijn et al. indicated, providing a high degree of presence [12]. The other component, which surrounds the car is a 270-degree field of view screen. Utilizing five projectors, this 22-foot diameter cylindrical display is able to blend the video projections together to create seamless simulated driving environment. A fifth projector is used to display the rear view, and LCD panels are installed in the side view

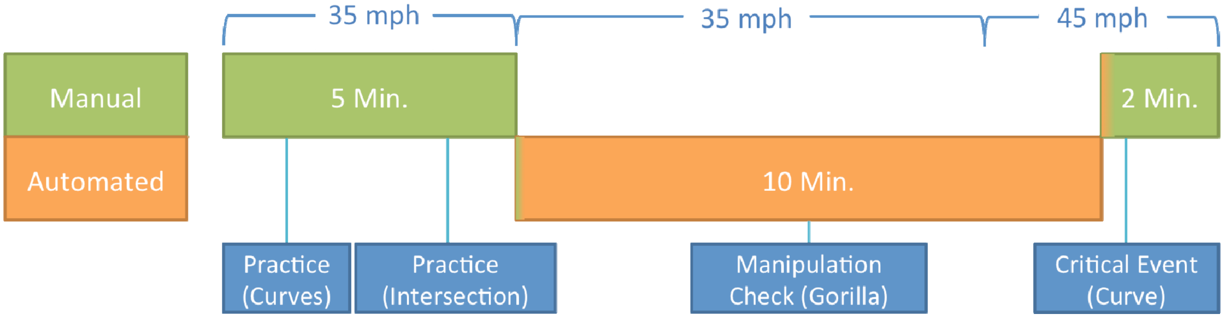

Figure 2: Diagram of the Simulated Driving Course containing three sections and two transitions of control.

mirrors to provide participants with the side views. To monitor and record the driver's behavior during the study, we have installed several wide angle GoPro cameras and microphones inside the Avalon's cabin. As we are also interested in examining the driver's emotional state, one of the GoPros inside the cabin is set up to provide an additional video feed of the driver's face for automated emotion analysis. Utilizing the FACET algorithm incorporated into the Attention Tool software by iMotions Inc., we are able to receive real time emotion coding.

The simulation course is a VRML file that is built using the Internet Scene Assembler software. To create the course, we can combine various road segments, such as two-lane streets and four-lane highways, together. Various cultural features, such as buildings and vegetation, are added along the road segments to help increase the driver's immersion. The behavior of the environment, as well as objects within the environment, can be altered through the use of Javascript, which we can link to sensors placed in the course. For example, when the participant's car crosses a sensor, a pedestrian can cross the road or a car can perform a cut-off event. Javascript can also be used to ambient variables, such as traffic density. When completed, the course can be used by Realtime Technologies' SimCreator software to create the simulation, providing the audio and video outputs.

B. Course

Composed of three distinct sections, the course contained sections where the participants would be driving the car manually, and sections where the automated driving system would be in control. As seen in Fig. 2, the first section contained a five-minute practice for the participants to become accustomed to the simulated driving environment. Containing straight roads, curves, intersections, and a transition from a two-lane road to a four-lane road, this segment contained a full assortment of roads for the participants to experience. The second section contained a long segment of straight road. Participants were asked to enable automated driving and the vehicle drove on for ten minutes. A curve appeared at the end of this section and was used to demonstrate to the participants that the automated driving mode was capable of successfully negotiating curves. Because of the nature and design of the critical event, it is important that the automated driving mode's abilities are demonstrated to the participants.

In the final section, control of the car was returned to participants a few seconds (i.e., 2, 5 or 8 seconds) before the critical event. A curve at the beginning of this section was designed to appear as though construction was in progress, with a lane blocked by heavy equipment and surrounded by traffic pylons (Fig. 3). This critical event provided a realistic scenario in which the car's automated driving system might have difficulty in negotiating this segment due to the lack of lane markings. This scenario enabled us to explore the participants' ability to regain control after transition, as they not only needed to react, but also to understand the situation in order to safely traverse the road hazard. The normal road textures, with lane demarcations, were replaced with textures of blank asphalt. A set of pylons was placed to indicate where the center divider was located. Another set of pylons was used to close off the right lane, where an excavator was placed. This forced participants to merge and stay in the left lane.

The occurrence of the unstructured transition was indicated by an audible alert: “Emergency, Automation Off.” At the beginning of the audio alert, control was instantly and automatically given back to the participants. The car was returned to the participants in the drive mode, with the steering wheel centered, and with no additional input to the brake or throttle. Once the car entered the critical event, additional traffic was spawned in the oncoming traffic lanes to encourage the participants to stay between the rows of pylons. After exiting the construction zone, the participants

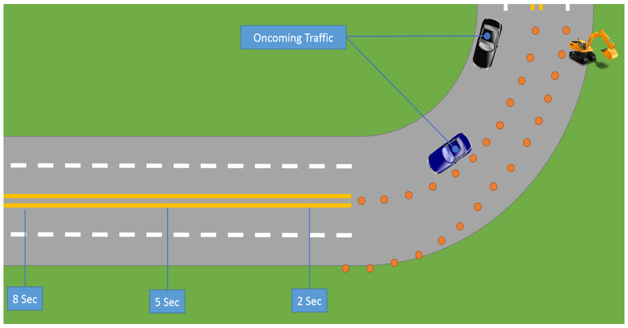

Figure 3: Diagram of the Critical Event. Participants must negotiate this segment with the presence of a lane closure.

experienced two more minutes of manual driving before reaching the end of the course, where they were asked to pull over and park the car.

C. *Takeover Time Manipulation*

The three takeover times – 2 seconds, 5 seconds, and 8 seconds − were defined to be the amount of time it took for the car (moving at the speed of 45 mph at time of transition) to reach the beginning of the lane closure.

D. *Secondary Task and Manipulation Check*

When the car's automated driving mode was enabled, participants were tasked with an activity. They were given a passive distraction in the form of watching a video on an iPad. The video was a combination of two animated short videos, which had a greater total time than the 10 minute automated driving segment. This was important as participants would still likely be watching the video (near its climax) when they encountered the critical event. To keep this timing consistent, we created a simple iOS app to play the video. The app would prevent the participants from pausing or scanning through the video. To see how participants would naturally disengage with this distraction task, they were not specifically instructed on what to do with iPad in the advent of an emergency.

The study included a manipulation check to determine whether participants were aware of the external environment. In the post-drive questionnaire, participants were presented with the questions to indicate which objects they had seen on the roadside. These were consisted of 'likely and present items' (including a stop sign), 'likely and not-present items' (such as a cow), 'unlikely and not-present items' (including a beached whale), and 'unlikely and present item' (a giant gorilla, an homage to Simons and Chabris' "Invisible Gorilla") [12]. Analyzing these questions allowed for screening participants' attention − an attentive participant would indicate that he or she saw the 'present items' but did not see the 'non-present items.' An example is shown in Figure 4, with the gorilla.

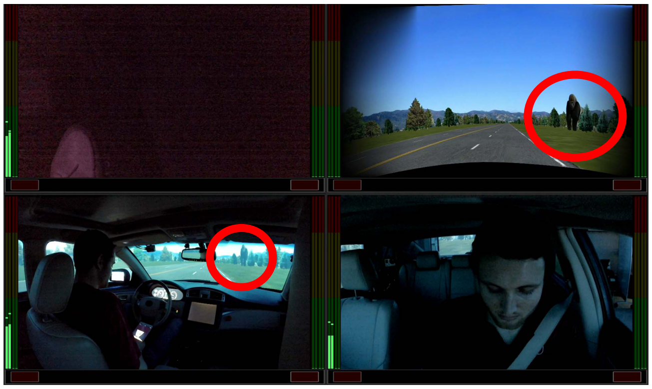

Figure 4: Participant engaged in the task, missing the gorilla.

E. *Procedure*

Upon arriving, the participants were given the study and video consent form for them to read and sign. Afterwards, the participants were asked to complete the pre-drive questionnaire. As the participants worked on this task, the experimenter started up the simulation and selected the appropriate transition time. Each participant was randomly assigned to only one of three experimental conditions, where the unstructured transition of control occurred in 2 seconds, 5 seconds or 8 seconds before the critical event. Once the participants finished the pre-drive questionnaire, they were led into the simulator room. To prevent unforeseen distractions from occurring, the participants were asked to silent their electronic devices during the course of the drive.

After getting in the car, participants were asked to make appropriate seating and mirror adjustments so that they would be properly situated. The experimenter then calibrated the FACET software to the participants' faces and started the video capture software to record video streams from the cameras inside the car. Participants were then briefed on the vehicle's automated driving system. They were instructed that the car had an automated driving feature that would enable the car to control its steering and speed, and that throughout the experiment there would be times during which they should either control the car or employ its automated system. Participants were also advised that audio and visual alerts would signal for the car to transition to the automated driving mode. At that time, participants were told to push a button on the steering wheel to enable the automated driving system when the command from the simulator was delivered. While in automated driving mode, participants were told to watch the short videos. After additional information of the driving tasks and rules of the road were discussed, the participants were then allowed to drive. The overall driving tasks typically required 15 to 20 minutes to complete. Once the participants were done with the driving component, they were asked to complete the post-drive questionnaire, the last step of the study.

F. *Participants*

We recruited a total of 30 participants. The majority of participants were from the Stanford University undergraduate and graduate student pool. The ages of our participants population ranged from 19 to 33 years old (*M* = 21.67 years, *SD* = 2.76 years). Their reported years of driving experience ranged from 1 year to 15 years (*M* = 5.3 years, *SD* = 2.63 years). Gender of the participants was equally distributed across each condition, 50% male and 50% female. Each session of the study required an average time of 45 minutes to complete and participants were compensated with either a gift certificate or, in the case of some students, academic credits.

IV. ANALYSIS

A. *Driving Behavior Data*

Driving data (including the simulated vehicle dynamics, distance to nearest vehicles, position in the road and driver inputs) was collected at 60Hz. Important time-points (such as the point of transition of control from automated to manual mode) were marked in the data. To examine how participants performed on the critical event's curve, we utilized the following metrics. Given the nature of the event, we decided that certain traditional metrics concerning transition of control, such as time to evasive maneuver, were not appropriate. For example, in the 8 second condition, some participants did not instantly detect the impending threat as they were still far away from the critical event, leading to a slower reaction. The data was analyzed using a Python script to extract measures of driving performance and *R* to perform the statistical tests.

1) *Standard Deviation of Road Offset*

One measure that both Verster et al. [10] and Brookhuis et al. [11] had indicated as a usable measure of driving performance was the variation in road offset (the distance from the centerline of the road). As the steering wheel was centered when control was returned to the participants, there should not be any detrimental artifacts on the standard deviation of road offset caused by the steering wheel position at the point of transition. The standard deviation of the road offset (in meters) in the critical event's curved section of road shows significant differences between the conditions when an ANOVA was performed. However, it was determined that the distribution was not normal using the Shapiro-Wilk Normality test (p-values < 0.01). Thus, the non-parametric Kruskal-Wallis rank sum test was used. The test shows significant differences (see Fig 5) between the transition time conditions, χ^2=15.68, df=2, p < 0.01. Conducting the post-hoc pairwise analysis using the Wilcoxon rank sum test with Bonferroni correction shows significant differences between the 5 second (*M* = 0.25, *SD* = 0.10) and the 2 second (*M* = 1.28, *SD* = 1.01) conditions (p < 0.001). There is also a significant difference between the 8 second (*M* = 0.25, *SD* = 0.10) and 2 second conditions (p < 0.001).

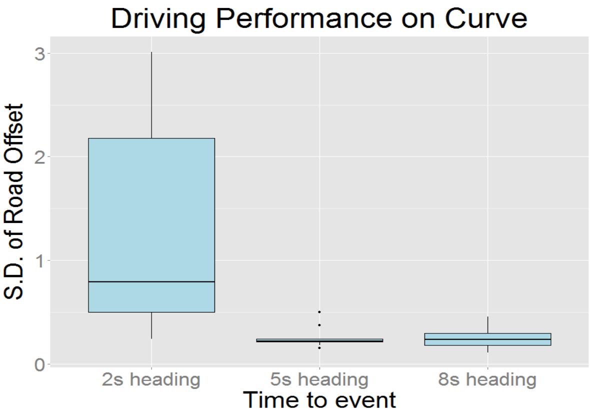

Figure 5: Road Offset Std. Dev for the 2, 5, 8 Second Conditions.

2) *Standard Deviation of Steering Wheel Position*

As indicated by Brookhuis et al. [11], another related measure that could be used to measure driving performance and steadiness was the standard deviation of the steering wheel position (in radians). When performing the turn at the critical event, the standard deviation was expected to be small, as the steering wheel angle should be kept mostly constant during this stretch. Measured over the curved section of the road, this variation in steering angle was also found to have a non-normal distribution (Shapiro-Wilk test, p < 0.01). Thus again, the Kruskal-Wallis non-parametric test was used (see Fig 6). The test shows significant differences between conditions (χ^2=18.61, df=2, p<0.001). Performing the post-hoc pairwise analysis using the Wilcoxon rank sum test with Bonferroni correction shows differences between the 5 second (*M* = 0.21, *SD* = 0.08) and 2 second (*M* = 1.22, *SD* = 0.84) conditions (p<0.001) and the 8 second (*M* = 0.18, *SD* = 0.09) and 2 second conditions (p<0.001).

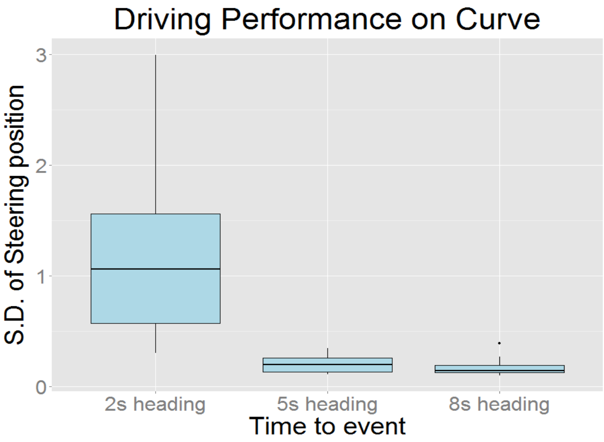

Figure 6: Steering Wheel Position Std. Dev for the 2, 5, 8 Second Conditions.

3) *Negotiating the Critical Event*

We explored if any of the participants deviated from the path set by the pylons. To do so, we used the location of the pylons and the road offset of the car when it hit those pylons to create two equations governing whether the car was still in the appropriate lane. A binary measure of whether the curve was successfully completed without a collision into the pylons. It shows a significant difference between conditions on the Chi Squared test (χ^2=12, df=2, p < 0.005). All participants in the 5 second and 8 second conditions managed to negotiate the curve successfully, while 5 of the 5 participants in the 2 second condition failed (Fig. 7). Video analysis has also confirmed this finding.

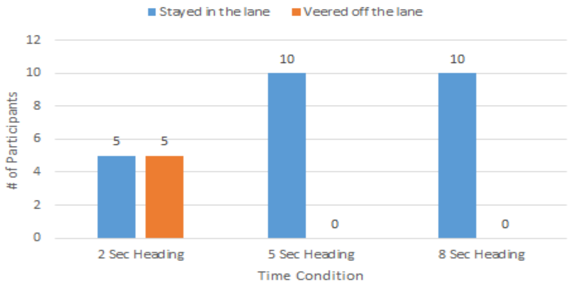

Figure 7: The number of participants who stayed in the lane vs veered off the lane for the 2, 5, 8 Second Conditions.

B. *Attitudinal Data*

In part of the post-drive questionnaire, participants were asked how well certain words described the automated driving system that they drove. A 7-point Likert Scale was used (1 = *describes poorly*; 7 = *describes well*). Through a principal component analysis (PCA), we found three items - *reliable, dependable,* and *trustworthy* that formed an index describing the *trustworthiness of the automated driving system* ($M = 4.20$, $SD = 1.59$). The three items are highly correlated with a Cronbach's Alpha of .95.

The *trustworthiness* index was entered into a one-way between-subject Analysis of Variance (one-way ANOVA) test with transition time as the independent variable. There is a significant main effect with respect to the transition time on the trustworthiness of the automated driving system, $F(2,25) = 12.34$, $p < .001$. A post-hoc Tukey HSD test reveals that all three transition time conditions are significantly different from each other. The 2 second condition ($M = 2.85$, $SD = 1.33$) differs significantly from the 5 second condition ($M = 4.17$, $SD = 1.34$, with $p = .055$) and the 8 second condition ($M = 5.59$, $SD = 0.68$, with $p < .001$). The 8 second condition also differs significantly from the 5 second condition, $p = .035$. The results are shown in Figure 8.

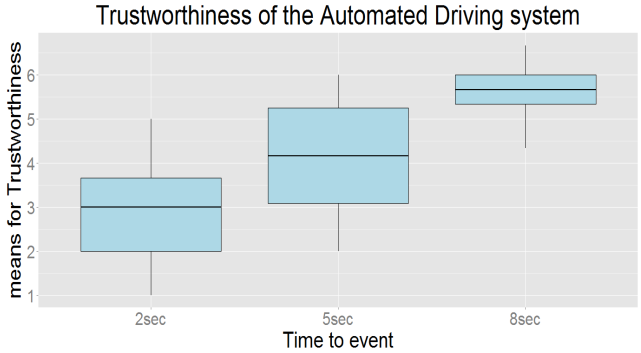

Figure 8: Study Results of the Likability Index for the 2, 5, and 8 Second Conditions.

C. *Manipulation Check*

In another part of the post-drive questionnaire, participants were asked which of the following objects they saw in the environment during the drive. Only two of the objects were actually present. The first one was a stop sign, a likely object that appeared during the first section where the participants were driving manually. As the stop sign was facing away from the participants, it is understandable that only 12 out of 30 (Fig. 9) participants marked that they saw the object. The second object was a gorilla. As the tallest object in the simulation, the gorilla towered above the trees and stood on the driver's side of the road. As the car was passing the gorilla during the automated driving section, participants were unlikely to see it if they were concentrating on the video activity. Consequently, only 2 out of 30 participants indicated that they saw the gorilla. On closer inspection, these two participants did not indicate seeing the stop sign, they only marked seeing the gorilla.

We also noted that there were also 19 instances where the participants indicated that they saw an object that was absent from the environment. While many of the distinctive and unlikely objects were not marked as seen (such as a beached whale), the objects more likely to be present in the environment were marked as seen by some participants. Upon closer inspection, two participants accounted for a majority of incorrect selections, marking off every likely object. These two participants were the only two drivers who had correctly selected the stop sign, but they had also incorrectly selected other objects.

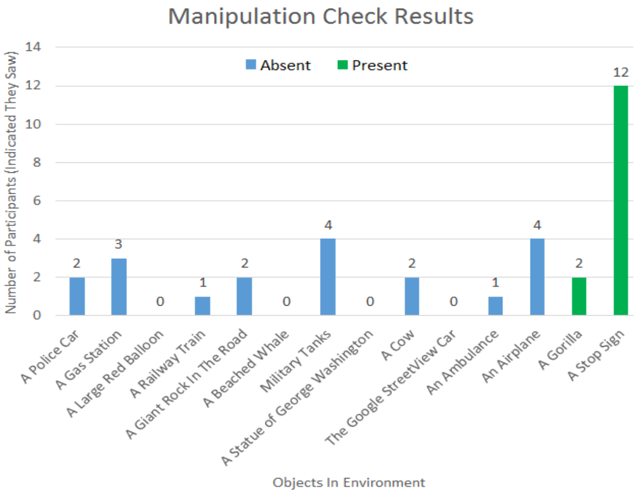

Figure 9: Total number of participants who indicated seeing each environmental object.

V. DISCUSSION AND RESULTS

From the driving behavioral data, it appears that the 2 second transition time condition does not provide a sufficient amount of time for the participants to regain sufficient control. In this 2 second condition, participants performed significantly worse than the other two conditions. Also, when compared the driving behavior data with the other conditions, the participants in the 2 second condition exhibited both a significantly greater road offset standard deviation and steering wheel standard deviation. Similarly, when examining the self-reported attitudinal data, participants in the 2 second condition rated the car to be significantly less trustworthy. The 2 second condition is the only one in which participants hit the critical event's pylons. Five participants in this condition were unable to stay in the left lane, with some participants driving into oncoming traffic lanes, some participants hitting the excavator, some participants driving off the road, and one performing all three. It is clear that any unstructured transition from automation should occur more than two seconds before the critical event.

Conversely the 5 second condition appears to be sufficiently long enough for participants to properly regain control of the vehicle. This can be seen by the significantly better driving behavior results for this condition. Unlike the 2 second condition, the 5 second condition does not induce any lane deviation or collisions with pylons, with all participants successfully negotiating the critical event. Also, participants have indicated that the 5 second condition to be significantly trustworthy than the 2 second condition. Although 5 seconds may not be the absolute minimum amount of time required to successfully take over and negotiate a critical event, it is the shortest of the tested transition time that has yielded good driver performance, as shown in the driving behavior analysis.

Even though the 8 second condition gives participants more time than the 5 second condition, similar to the previous findings [6, 16], participants in both conditions performed equally well when negotiating the critical event. We do not see any significant difference in the variation of road offset or steering wheel position. Like those of the 5 second condition, the participants of the 8 second condition did not seem to deviate from the critical event's left lane or hit any of the pylons. However, the additional time appears to generate significantly greater levels of trust. Compared to the other conditions, 8 second condition definitively provides the participants with a greater sense of ease.

VI. CONCLUSION AND FUTURE WORK

This study has yielded significant results on how drivers performed post transition with automated driving systems. We are able to identify that drivers do require a certain amount of time to be able to regain control of the automated vehicle. The 2 second condition appears to be greatly insufficient as the participants perform poorly and they trust the car less. Additionally, participants' *trust* towards the car is also lower in the 2 second condition. Hence, it is recommended to give warnings or relinquish control more than 2 seconds in advance. While 5 second condition is not necessarily the minimum required time, this amount of time from the critical event appears to be sufficient for drivers to perform well after transition and negotiate the problem. The results of this study indicate that there is a minimum amount of time needed for transition of control between 2 seconds and 5 seconds. It is interesting to note that the results of this study (where the participants were given a passive distraction task) match closely with those of our previous study (where the participants were not given any distraction task). In both studies, 2 second condition is not long enough, and 5 second condition is adequate [16].

In this current study, we had participants who were adult drivers. This may not illustrate the range of variation in driving and emergency handling capability that a study using a wider demographic in its participants would show. Hence, in future studies we will consider the effect of different age groups on unstructured transition performance.

In the next phase of our study, we plan to examine how participants perform under an even greater state of distraction. We will examine the effects of an active distraction on drivers' performance. The participants will be given a task with a higher level of engagement to do while the car is driving in the automated mode. The task will most likely manifest in the form of playing a game or an activity that requires the participants to provide input. The same course, procedures, and unstructured takeover times will be used in the new study so that it can be compared with the results of this study (where the participants were engaged at passive distraction task) and our prior study (where the participants were not given a secondary task to do) [16].

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