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Timing of Unstructured Transitions of Control in Automated Driving

Brian Ka-Jun Mok*, Mishel Johns*, Key Jung Lee‡, Hillary Page Ive†, David Miller†, Wendy Ju*
*Department of Mechanical Engineering and †Department of Communication
Stanford University, Stanford, CA, USA
{brianmok, mishel, pageive, davebmiller, wendyju} @stanford.edu
‡Robert Bosch LLC. Palo Alto, CA, USA
Key.Lee@us.bosch.com

Abstract— **With automated driving systems, drivers may still be expected to resume full control of the vehicle. While structured transitions where drivers are given warning are desirable, it is critical to benchmark how drivers perform when transition of control is unstructured and occurs without advanced warning. In this study, we observed how participants (N=27) in a driving simulator performed after they were subjected to an emergency loss of automation. We tested three transition time conditions, with an unstructured transition of vehicle control occurring 2 seconds, 5 seconds, or 8 seconds before the participants encountered a road hazard that required the drivers' intervention. Few drivers in the 2 second condition were able to safely negotiate the road hazard situation, while the majority of drivers in 5 or 8 second conditions were able to navigate the hazard safely. Similarly, drivers in 2 second condition rated the vehicle to be less likeable than drivers in 5 and 8 second conditions. From the study results, we are able to narrow in on 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.**

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 conditions and rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. So this allows drivers to have "sufficiently comfortable transition time" when taking back control [1]. While it is important to study these structured takeovers and what amount of time is "sufficiently comfortable," it is also important to benchmark how long drivers need in the event of an unstructured emergency transition of control. By examining this worst case scenario, we can discover additional insight on how to design automated driving systems and more structured takeovers of control. This paper, thus, examines the minimum time necessary for drivers to safely regain control of vehicle in an unstructured transition after a period of automated driving.

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Brian Mok, Mishel Johns, and Wendy Ju are with the Center for Design Research, Department of Mechanical Engineering at Stanford University, Stanford, CA 94043. Hillary Page Ive and David Miller are with the Department of Communication at Stanford University, Stanford, CA 94043 USA (phone: 626-201-9179; e-mail: brianmok@stanford.edu).

Key Jung Lee was with the Department of Communication at Stanford University, Stanford, CA 94043 USA. She is now with Robert Bosch LLC. (e-mail: Key.Lee@us.bosch.com).

Figure 1: The Stanford Driving Simulator

In this study (N=27), we used a simulated driving environment (Fig. 1) where control of the vehicle can be alternately shared between the human drivers and the car's automated driving system. Participants were not given any secondary tasks to perform while the automated driving was enabled, but most monitored the road. In our simulation scenario, the car is performing automated freeway driving when it comes upon an unexpected road hazard. At that point, the driver is expected to immediately retake control of the car after notice from the vehicle. We have tested three different transition conditions, where the transition occurs 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 control of vehicle so that they are able to successfully assess the situation and safely negotiate the imminent road hazard.

II. BACKGROUND AND RELATED WORKS

While the issues of the unstructured transitions have not been extensively examined, various studies have explored the structured takeover for automation. For takeovers, as Endsley et al. [2] indicated, drivers are required to maintain a sufficient amount of situation awareness in order to respond. With structured takeover scenarios, Gold et al. [3] studied the point in time when an automated driving system must "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 with poorer quality than those with longer takeover request times. Additionally, they found that drivers in the automated driving condition performed worse than drivers in the control group, who did not experience automation.

Radlmayr et al. [4] 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. [5] 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. [6] 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 six seconds were sufficient for most participants to accomplish these tasks. With eight seconds, almost all the 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.

Naujoks et al. [7] studied the modality of effective takeover requests, examining "the behavioral effects of visual vs. visual-auditory take-over requests" on distracted drivers in various scenarios of varying difficulty. Naujoks et al. found that drivers given visual-auditory take-over requests had shorter mean reaction times and better lane keeping performance than drivers given purely visual take-over messages. Research studies conducted on driving performance, warnings, and takeovers outside the realms of highly automated driving are relevant as well. Naujoks et al. [8] also examined the effectiveness and acceptance of warnings at times of zero, one, two, three, and four seconds before a critical event. They found that information about upcoming conflicts must be provided at least one second prior to the last possible warning moment, better still, two seconds beforehand, in order to have a positive effect on driving behavior and the situation's associated criticality.

As shown in the findings of related prior research, it is important to understand how transitions of control should occur for driving tasks, with much emphasis in warning messages and appropriate timing. As this understanding needs to be comprehensive for automation, we have decided to focus our work on the worst case, unstructured transitions. While the majority of research in automation is focused on structured takeovers, this transition of control paradigm needs to be further examined to determine how drivers perform in this extreme scenario.

III. Methodology

A. Simulator

The Stanford Driving Simulator (Fig. 1) is an immersive automotive simulator that consists of a whole car and a visual display system. The car, a modified Toyota Avalon, provides participants with a realistic interface for the simulation. Both the steering wheel and pedals use motors and pneumatics simulation to provide realistic haptic feedback to the participants. Surrounding the car is a 270-degree field of view screen. This 22-foot diameter cylindrical display utilizes five projectors to display a seamless simulated driving environment. Another projector is used to display the rear view, and LCD panels are installed in the side view mirrors to provide participants with the side views. Several wide angle cameras and microphones are installed in the cabin of the car to record the driver's behavior during the study. One of these cameras also provides a video feed of the driver's face for automated emotion analysis with the FACET algorithm, using the Attention Tool software by iMotions, Inc.

The simulation course is first built in Internet Scene Assembler as a VRML file. Various road segments such as two-lane streets and four-lane highways can be combined together to form a course. Models of vegetation, buildings, and other objects can be inserted to increase the driver's immersion. Additionally, sensors linked to Javascript can be inserted to manipulate the environment and to control the behavior of cars as well as pedestrians. 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 set traffic density and limits. Once the simulation course is completed, this VRML file is used by Realtime Technologies' SimCreator software to create the simulation, providing the audio and video outputs.

B. Course

The course was designed to vary the time and distance that drivers were given to regain control after a transition from automation. As shown in Fig. 2, the course had three distinct sections. The first section contained a five-minute practice for the participants to become accustomed to the simulated driving environment. In this segment, participants would experience driving in straight roads, curves, intersections, and a transition from a two-lane road to a four-lane road. After the first section, the participants were asked to enable automated driving and the vehicle drove on the second sector for ten minutes. A large 50 foot Gorilla model, inspired by Simons and Charibis [9], was placed in the middle of this second section. It served as a manipulation check to allow for assessment of alertness and situation awareness of participants in the post-drive questionnaire. While mainly containing straight roads, this section also had a curve near the end, used to demonstrate to the participants that the automated driving mode was capable of successfully negotiating curves. This is important given the nature of the critical event found in the third section.

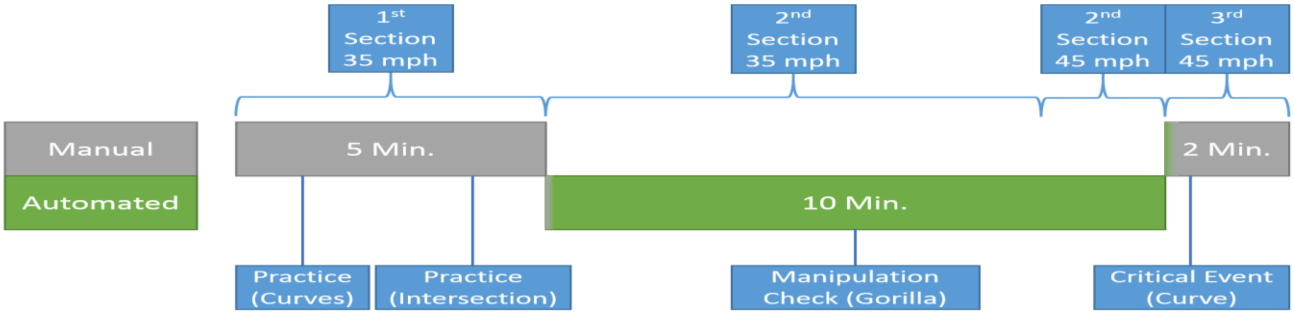

Figure 2: Diagram of the Simulated Driving Course containing three sections and two transitions of control.

In the final section, control of the car was returned to participants a few seconds (i.e. 2, 5 or 8 seconds depending on the participant's randomly assigned condition) before the critical event. A curve at the beginning of the 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 an emergency transition of control, as they not only needed to react, but also to understand the situation in order to safely traverse the road hazard. The normal road texture, 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.

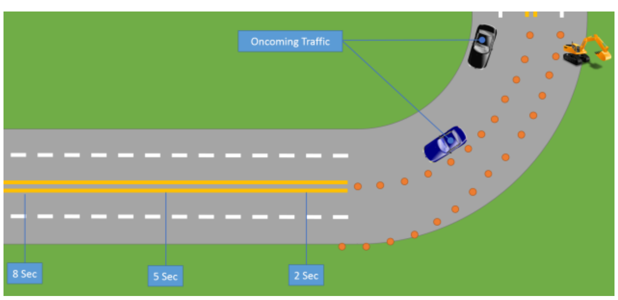

Figure 3: Diagram of the Critical Event. Participants must negotiate this segment with the presence of a lane closure.

Participants experienced one of three possible conditions, where the unstructured transition occurred 2 seconds, 5 seconds or 8 seconds to the critical event. These conditions 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. 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. 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 experienced two more minutes of manual driving before reaching the end of the course.

C. *Procedure*

Upon arrival at the lab, 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. Random order sets of the time condition were generated beforehand, so the participants were given the next condition in the list. 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. In the current study, participants were not given any secondary tasks while the car was driving. This naturally led them to monitor the road when they were not driving the car. 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. Overall, it took each participant an average of 45 minutes to complete the study.

D. *Participants*

In this study, we recruited a total of 27 participants. Approximately 52% of participants were male and 48% were female. The majority of participants were from the Stanford University undergraduate and graduate student pool.

However, there were also several adults (18-65 years) and seniors (65+ years) who participated in our study. They were evenly distributed over the three time conditions. Consequently, the ages of our participants population ranged from 19 to 81 years old (M=28.9 years, SD=19.1 years). Their reported years of driving experience, similarly, ranged from 1 year to 62 years (M=12.4 years, SD=18.3 years). 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 transfer of control from automated to manual mode) were marked in the data. The following driving metrics were selected to examine how participants performed on the curve. Certain other traditional metrics for transition, such as time to evasive action, did not appear appropriate given how the transition and critical event were designed. The data was analyzed using Python to extract measures of driving performance and *R* to perform various statistical tests.

1) Variation of Road Offset

As indicated by Verster et al. [10] and Brookhuis et al. [11], the variation in road offset - the distance from the centerline of the road could be used as a measure of driving performance. The standard deviation of the road offset (in meters) in the curved section of the road showed significant differences between the conditions when an ANOVA was performed. It was determined that the distribution was not normal (see Fig 4) using the Shapiro-Wilk Normality test (p-values < 0.01). Thus, the non-parametric Kruskal-Wallis rank sum test was used. The test showed significant differences between the transition time conditions, (χ^2=10.04, df=2, p<0.01). Conducting the post-hoc pairwise analysis using the Wilcoxon rank sum test with Bonferroni correction showed differences between the 5 second (M=0.02, SD=0.05) and 2 second (M=1.03, SD=1.12) conditions (p<0.01) and moderately significant differences between the 8 second (M=0.24, SD=0.06) and 2 second conditions (p<0.1).

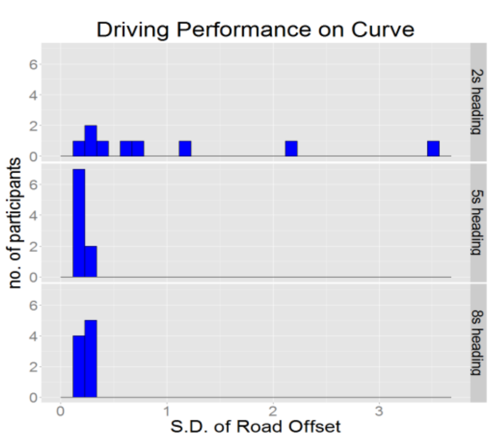

Figure 4: Histograms of Road Offset Standard Deviation for the 2. 5. 8 Second Conditions.

2) Variation of Steering Wheel Position

A related measure, the standard deviation of the steering wheel position (in radians) was also indicated by Brookhuis et al. [11] to be a measure of steadiness in driving. This measure over the curved section of the road 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 5). The test showed significant differences between conditions (χ^2=16.67, df=2, p<0.001). Performing the post-hoc pairwise analysis using the Wilcoxon rank sum test with Bonferroni correction showed differences between the 5 second (M=0.25, SD=0.18) and 2 second (M=0.65, SD=0.41) conditions (p<0.005) and the 8 second (M=0.14, SD=0.03) and 2 second conditions (p<0.001).

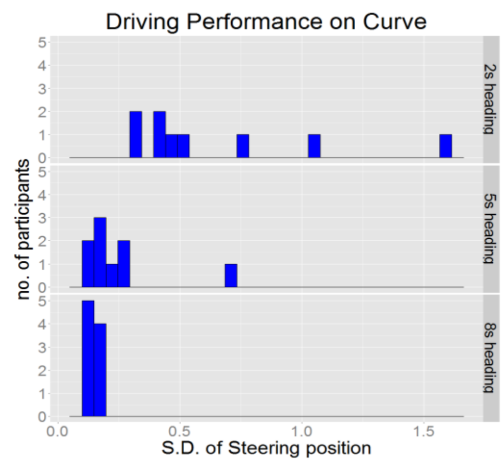

Figure 5: Histograms of Steering Wheel Position Standard Deviation for the 2, 5, 8 Second Conditions.

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 showed a significant difference between conditions on the Chi Squared test (χ^2=6.75, df=2, p<0.05). All participants in the 5 second and 8 second conditions managed to negotiate the curve successfully, while 3 of the 9 participants in the 2 second condition failed (Fig. 6). Video analysis also confirmed this finding.

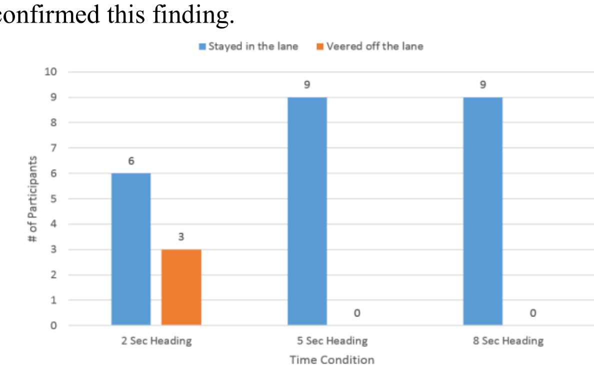

Figure 6: The number of participants who stayed in the lane vs veered off the lane for the 2, 5, 8 Second Conditions.

B. Self-Reported Attitudinal Data

In part of the post-drive questionnaire, participants were asked how well certain words or phrases describe the car. A 7-point Likert scale was used (1=*describes poorly*; 7=*describes well*). Negative items, such as *Frustrating and Annoying* were reversely coded so that greater values indicated that participants liked the car more. Through a principal component analysis (PCA), we found that five items -- *Likeable*, *Enjoyable*, *Trustworthy*, *Frustrating*, and *Annoying* -- formed an index describing the *likeability of the car*. These five items were found to be highly correlated, with a Cronbach's Alpha of α=0.89.

The participants were also asked which of the two bipolar statements (e.g., "I felt unsafe" vs. "I felt safe") better described how they felt when a transition of control occurred. With these questions using a 10-point scale, lower values indicated that the first statement was more representative, while higher values indicated that the second statement was more representative. A PCA found a three-item index that described the *comfort* in the car. The three statements were: "*I had faith in the car's driving ability*," "*I felt safe*," and "*I was calm*." These three items were also found to be highly correlated, with a Cronbach's Alpha of α=0.93. Analysis of this data was performed using *R*.

1) Likeability

The likeability index was subjected to a one-way between-subject analysis of variance (one-way ANOVA) test. The transition time was used as the independent variable for the ANOVA. There was a significant main effect, with respect to the transition time on the likeability of the automated system, ($F(2,23)=5.40$, $p=.011$). A post-hoc Tukey HSD test revealed that only the 2 second ($M=3.27$, $SD=0.85$) and 5 second ($M=5.10$, $SD=0.79$) transition time conditions differed significantly (with $p=.017$). The 8 second condition ($M=4.38$, $SD=1.62$) was not significantly different from the other two conditions. The results for this index are shown in Figure 7.

Figure 7: Study Results of the Likability Index for the 2, 5, and 8 Second Conditions.

2) Comfort

The same one-way ANOVA test was conducted for the *comfort* index. There was a significant main effect, with respect to the transition time, on the comfort of the automated system, ($F(2,23)=21.58$, $p<0.001$). A post-hoc Tukey HSD test revealed that every transition time condition was significantly different from each other. The 2 second condition ($M=3.17$, $SD=1.39$) significantly differed from the 5 second condition ($M=5.18$, $SD=2.14$) with $p<0.05$. The 2 second condition also differed significantly from the 8 second condition ($M=8.71$, $SD=1.03$) with $p<0.001$. Finally, the 5 and 8 second conditions also differed significantly with $p<0.001$. The results of this index are shown in Figure 8.

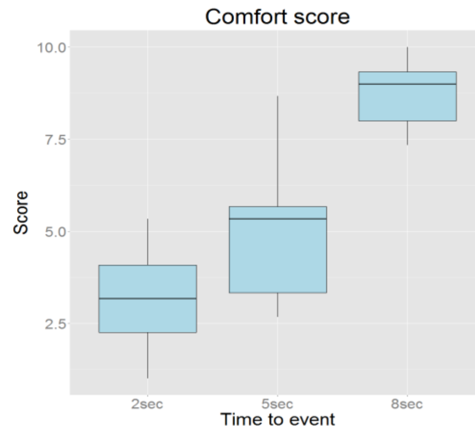

Figure 8: Study Results of the Comfort Index for the 2, 5, and 8 Second Conditions.

V. Results and Discussion

From the driving behavioral data, it appeared that 2 second transition time condition did not provide a sufficient amount of time for 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 both significantly less likable and comfortable. The 2 second condition was the only one in which participants hit the critical event's pylons. Three participants in this condition were unable to stay in the left lane, with one participant driving off the road, one driving into oncoming traffic lanes, and one hitting the excavator. It was clear that any unstructured transition from automation should occur more than two seconds before the critical event.

Conversely the 5 second condition appeared 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 did not induce any lane deviation or collisions with pylons, with all participants successfully negotiating the critical event. Also, participants found the 5 second condition to be significantly more likeable and more comfortable than the 2 second condition. Although 5 seconds might not be the absolute minimum amount of time required to successfully take over and negotiate a critical event, it was the shortest of the tested transition times that yielded good driver performance, as seen in the driving behavior analysis.

Even though the 8 second condition gave participants more time than the 5 second condition, similar to the previous findings [6], participants in both conditions performed equally well when negotiating the critical event. We did 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 appeared to generate significantly greater levels of comfort. Compared to the other conditions, 8 second condition definitively provided the participants with a greater sense of ease.

Interestingly, there was no significant difference in participants' likability toward the car between 5 and 8 second conditions. One of the causes of this might be due to the lack of a perceivable concern and emergency. After the drive, some participants in the 8 second condition indicated that they were originally confused as to why the car initiated the transition. Because the participants regained control 8 seconds from the critical event, some of them could not see the pylons/road construction. This might have affected the participants' perception of the car. There is a Gricean maxim of communication that one should provide enough but not too much information [12]. When there is not an obvious hazard, more elaboration to explain the loss of automation would be expected; anything less would seem uncooperative.

VI. Conclusion and Future Work

This study on the transfer of control with an automated driving system had yielded significant results. We were able to identify that there was indeed a minimum amount of time that participants needed in order to safely and comfortably to perform takeover. Although the participants in the current study were not performing secondary tasks while the car was driving, the 2 second condition appeared to be insufficient. The participants did not perform well and liked the car less. Additionally, participants' comfort in the car was also lower in the 2 second condition. Hence, it is recommended to give warnings or relinquish control more than 2 seconds in advance. While not necessarily the minimum required time, 5 second condition from a critical event appeared to be sufficient for drivers to perform the takeover successfully and negotiate the problem. While the results of this study indicated that there was a minimum amount of time needed for transition of control, this was true when the drivers only monitored the car's activity and did not perform secondary tasks. It is possible that these results can change if the drivers are occupied with other activities.

In the second phase of our study, we plan to examine the effects of different types of distractions on driving performance. The participants will be given a task to do while the car is driving in the automated mode. The task will either be a passive distraction (such as watching a movie) or an active distraction (such as playing a game). We also plan to utilize the manipulation check data to determine if the participants are engaged in these activities. The same course, procedure, and unstructured transition times will be used so that these results can be compared to those of phase 1, the current study, where the drivers had no distraction.

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