The Relationship Between Takeover Request Lead Time and Drivers' Situation Awareness for Freeway Exiting in Conditionally Automated Driving

Xiaomei Tan, Yiqi Zhang
Pennsylvania State University, University Park

Conditionally automated vehicles require the out-of-the-loop driver to intervene when the system is unable to handle forthcoming situations, such as freeway exiting. The takeover request (ToR) for exiting a freeway can be scheduled in advance. Upon a ToR, the driver needs to gain situation awareness (SA) and resume manual control. This study examined how the ToR lead time affects driver SA for resuming control and when to send the ToR is most appropriate for freeway exiting. A web-based, supervised experiment was conducted with 31 participants. Each participant experienced 12 levels of ToR lead time (6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 45, and 60 s). The results showed positive effects of longer ToR lead times (16–60 s) on driver SA for resuming control to exit from freeways in comparison to shorter ToR lead times (6–14 s), and the effects level off at 16–30 s.

INTRODUCTION

The conditional driving automation, namely Level 3 automation (SAE International, 2016), enables the human driver to engage in non-driving related activities with no need to monitor the traffic, but still requires the driver to serve as a fallback for the automation. When the system reaches its limit for handling an upcoming situation, the driver needs to intervene upon the request by the system and resume manual control. One typical situation that limits the SAE Level 3 automated vehicles is navigating freeway off-ramps.

According to McDonald et al.'s (2019) conceptual model, the control transition from automation system to human driver is initiated by a takeover request (ToR) and it involves the driver's subsequent reactions: First, redirect the gaze from non-driving related activities to the driving task, which is followed by scanning the environment to gather information. Based on that, the driver establishes the cognitive readiness for takeover and determines actions to be taken after resuming control. In the meanwhile, the motor readiness is achieved, and then the control transition is executed. In this process, the lead time of ToR, which is referred to as the time budget for taking over control of the automated vechile, is an influential factor that determines the situation awareness (SA) obtained by the driver (Lu et al., 2017).

The present study explores how ToR lead time affects driver SA when the driver takes over control of the vehicle in non-time-critical situations, specifically exiting a freeway. A generally accepted SA definition by Endsley (1988) is a person's *perception* of the elements in the environment (Level 1 SA), the *comprehension* of their meaning (Level 2 SA), and the *projection* of their future status (Level 3 SA). It is an important human factor construct worth studying in the conditional driving automation, as the driver who originally has little to no SA during automated driving needs to acquire SA for executing takeover maneuvers safely (Forster et al., 2017; Miller et al., 2014). Drivers' ability to resume control safely is positively associated with their increased level of SA (Van den Beukel & Van der Voort, 2013).

Previous studies on the scheduled takeovers for freeway exiting mostly focused on the driving performance and subjective evaluation after takeovers (Holländer & Pfleging, 2018; Langlois & Soualmi, 2016; Metz et al., 2020; Nobari et al., 2020; Pampel et al., 2019; Petermeijer et al., 2017; Wörle et al., 2020; Yun & Yang, 2020). These studies adopted a wide range of ToR lead time (i.e., 10–60 s) for freeway exiting scenarios. However, they did not offer much insight into the driver SA as a function of ToR lead time. An exception is the video-based study by Lu et al. (2017), which looked into driver SA over the ToR lead time ranging from 1 to 20 s. The length of video clips denotes the duration between ToR and takeover action. Results showed a positive effect of longer video lengths on driver SA as for drivers' better performance of reproducing the scenario layout; the effect saturates at 7–12 s. Nevertheless, the video clips used in the experiment did not include freeway exiting scenarios, and the study did not require participants to execute any takeover actions. A simulator study by Pampel et al. (2019) only compared planned, 50 s ToRs for exiting from highways with unplanned, 5 s ToRs caused by system limit; it concluded that drivers gained more SA that enabled better longitudinal vehicle control after control transitions when they were given longer ToR lead time (50 s) as compared to the shorter ToR lead time (5 s). Holländer and Pfleging (2018) suggested providing drivers with a dynamic visualization of pre-warning 1 minute prior to the ToR for freeway exiting with the purpose to improve the driving performance after takeover. To the best of the authors' knowledge, no existing studies have examined the appropriateness of ToRs over a wide range of lead time up to 1 minute prior to exiting a freeway from the perspective of driver SA. The present study aims to fill this research gap.

The present study includes a web-based experiment to investigate the association between ToR lead time and driver SA at the moment when the driver disengages the automation mode and resumes control to exit from freeways. We hypothesized that, the longer ToR lead time, the higher driver SA for takeover; the effect might saturate or even decline when the ToR lead time is up to a certain point caused by unexpected distraction.

METHOD

Participants

A total of 31 subjects participated in the study. Thirty participants (12 males, 17 females, and 1 unspecified) remained for the analysis after removing 1 participant's invalid data because of technical issues. Participants were aged between 21 and 53 (*Mean* = 28.8, *SD* = 8.4). All were licensed drivers with driving experience of 11.2 years (*SD* = 8.3) and annual mileage of 7,860 miles (*SD* = 5,158.4) on average. Each participant received a $20 eGift Card as compensation.

Experiment Design

The experiment adopted a within-subjects design with the ToR lead time as the independent variable. The ToR lead time is defined as the remaining time before the subject vehicle needs a swerve to exit if it maintains the automated driving speed. A wide range of ToR lead time including 12 levels (i.e., 6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 45, and 60 s) was tested to investigate the relation between ToR lead time and driver SA when executed the takeover action. The sequence of 12 trials was randomized for each participant.

To reduce the carry-over effect, the driving scenario varies across trials. Examples of scenarios are shown in Table 1. It was assumed that the SAE Level 3 automated vehicle would be able to change to the exit lane automatically when the planned route requires freeway exiting. Therefore, when the ToRs were issued in the experiment, the subject vehicle was always driving in the exit lane. In each trial, there was a car driving 300 feet ahead of the subject vehicle in the same lane and a car driving 250 feet ahead of the subject vehicle in the adjacent lane, which are denoted by Car 1 and Car 2 in Table 1, respectively. At most one of the two cars in a scenario activated turn signals to exit (for Car 1) or to change lanes to exit (for Car 2). Their exit maneuvers were always performed at the last moment before arriving at the exit.

The exits in half of trials were exit only in which cars typically did not need to signal their intention to exit (see 6 s and 45 s trials in Table 1). The other half of trials included a 300 feet long exit ramp that branched off from the original lane (see 16 s and 60 s trials in Table 1), which required drivers to activate turn signals if intended to exit. In this experiment, the subject vehicle would turn on its signal lights automatically 10 s before arriving at the exit if the participant did not resume control by pressing the spacebar.

Freeway Scenario Stimuli

The STISIM Drive® M300WS-Console system was used to create freeway scenarios, which varied in the number of lanes in the driving direction (i.e., 2, 3, or 4), which side of the road an exit was on (i.e., left or right), and whether or not the exiting lane was exit only. Each scenario was 17,000~18,000 feet long (about 3.5 minutes' driving). The web-based experiment was developed and conducted using Gorilla Experiment Builder (gorilla.sc; Anwyl-Irvine et al., 2020). The video stimuli were produced by recording the main display screen of the driving simulator while it was running each scenario file.

A ToR was issued when the remaining time before the subject vehicle arrived at the exit was equal to the ToR lead time. The audio ToR consisted of a 1 kHz warning tone followed by a speech message in a digitized female voice with a speech rate of ~150 words/min. When a ToR was sent out, the navigation map on the dashboard started to display the information including the exit type, the distance away from the exit when the ToR was issued and the speed limit at the exit ramp. Fig. 1 showed a screenshot of video stimuli. The video stopped playing as soon as the participant pressed the spacebar on laptop to simulate deactivating the automation mode. Drivers' takeover reaction time was output from Gorilla.sc. If the participant did not intervene, the video would reach the end when the subject vehicle passed the freeway exit.

Figure 1 A example of a screenshot of video stimuli.

Dependent Variables

Driver SA was measured using Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1987), which is a probe recall technique. The video simulation froze and it jumped to the next webpage presenting SA queries once the participant pressed the spacebar on laptop. In each trial, there were 4 sets of SA queries about Car 1, Car 2, SV's speed, and SV's turn signals, which are essential information for exiting a freeway safely. Each set included three single-choice questions that corresponded to three SA levels. The questions were listed as below.

For Car 1 and Car 2,

- *(Level 1) When the video stops, is [the corresponding car] turning its turn signal on?*
- *(Level 2) When the video stops, what is [the corresponding car] intending to do?*
- *(Level 3) Now you have taken over control of your car (by pressing the spacebar), what do you need to do to cope with [the corresponding car]?*

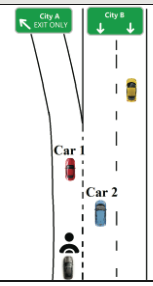
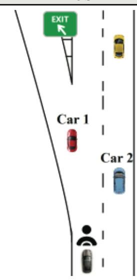
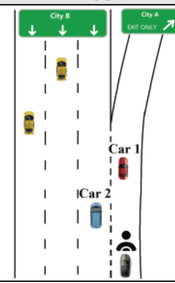
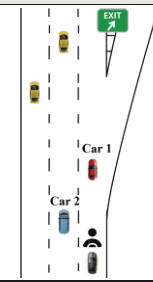
For SV's speed,

- *(Level 1) What is the speed of your car?*
- *(Level 2) Is your car driving at an appropriate speed to exit the freeway (within speed limit ± 5 mph)?*
- *(Level 3) Now you have taken over control of your car (by pressing the spacebar), do you need to brake to conform with the speed limit of the exit road?*

For SV's turn signal,

- *(Level 1) When the video stops, is your car turning the turn signal on?*
- *(Level 2) While driving in the current lane, do you need to signal your intention to exit from freeway?*

Table 1 Examples of driving scenarios in video stimuli

ToR lead time	6s	16s	45s	60s
Diagram				
Exit type	Exit only	Not exit only	Exit only	Not exit only
Turn signals	Car 1, Car 2, and SV had their turn signals off.	Car 1 had its left turn signals on. Car 2 had its turn signal off. SV activated its left turn signals 10 s prior to exiting.	Car 2 had its right turn signals on. Car 1 and SV had their turn signals off.	Car 1 had its turn signals off. Car 2 had its right turn signals on. SV activated its right turn signals 10 s prior to exiting.
Speed limit	SV drove at 50 mph. Speed limit to exit was 40 mph.	SV drove at 50 mph. Speed limit to exit was 50 mph.	SV drove at 60 mph. Speed limit to exit was 45 mph.	SV drove at 60 mph. Speed limit to exit was 50 mph.
ToR message	In 0.1 mile, exit the freeway on the left side to DeWitt. Please take over!	In 0.26 mile, exit the freeway on the left side to San Diego. Please take over!	In 0.75 mile, exit the freeway to Morristown Mahwah. Please take over!	In 1 mile, exit the freeway to Danbury. Please take over!

Subject vehicle (SV) — Car 1 drove 300 ft ahead of SV in the same lane

Other vehicles — Car 2 drove 250 ft ahead of SV in the adjacent lane

- *(Level 3) Now you have taken over control of your car (by pressing the spacebar), do you need to manually turn on the turn signal?*

The score for each SA query was determined by checking the participant's answer against the video recorded during the experiment, resulting in either 1 for correct answer or 0 for incorrect answer. Based on the scores, the participant's response accuracy, namely the percentage of correct answers, for all the 12 SA queries as well as for the 4 queries in each one of three SA levels were calculated.

Procedures

The experiment was supervised using Zoom. After joined the meeting, participants were asked to show their driver license in the web camera and log in to the Gorilla.sc platform. To start with, participants were instructed about the study and freely checked the boxes in the consent form to confirm their will to participate and their consent for video recording. Then the participants filled in a demographic survey and were given instructions on the task. Before the formal test, participants were instructed through a 2-minute practice. In the formal testing, while the subjective vehicle was driving in the automation mode, participants were required to play a game named 2048 5×5 on their smart phones. As requested by the ToR, participants performed the takeover task by pressing the spacebar when they believed they were able to take over control of the AV and exit the freeway safely. When the video stopped playing once the spacebar was pressed, participants completed the SA queries and started a new trial afterwards.

RESULTS

Data Analysis

The analysis removed data of 35 trials with exiting failures in view of the fact that it was no longer meaningful to evaluate driver SA after they had missed the exit. Ten trials with video uploading delay caused by low internet connection speeds were also removed from the analysis. The sample size for each level of ToR lead time is summarized in Table 2.

As a within-subjects design was adopted with 12 trials nested in 30 participants, the analysis followed a "build-up" strategy for model testing in the multilevel modeling (Heck et al., 2013). First, to examine whether the between-subjects variance was significant, the random intercept model (i.e., the linear mixed model with no lower-level predictors included) was tested for each one of SA measures. The Wald Z tests (at a significance level of .025 for one-tailed test) and ICCs (at a threshold of .05) indicated substantial clustering of data in the response accuracy of overall SA (Z = 2.77, p = .006; ICC = .21), Level 1 SA (Z = 2.72, p = .007; ICC = .21), Level 2 SA

Table 2 Means (standard deviations) of driver SA measures

ToR lead time (s)	6	8	10	12	14	16	18	20	25	30	45	60
Sample size	27	20	28	28	29	24	29	27	28	26	26	25
Overall SA (%)	63.6 (16.4)	57.1 (16.9)	63.4 (22.8)	69.4 (22.4)	68.7 (24.5)	84.0 (15.5)	77.9 (18.4)	72.2 (21.4)	72.9 (25.8)	75.0 (17.8)	73.7 (24.6)	67.3 (20.1)
Level 1 SA (%)	60.2 (29.6)	47.5 (18.0)	59.8 (31.4)	66.1 (32.8)	71.6 (28.9)	84.4 (19.2)	87.9 (22.8)	77.8 (26.3)	83.0 (27.3)	80.8 (19.1)	82.7 (29.8)	80.0 (17.7)
Level 2 SA (%)	63.9 (23.3)	67.5 (21.6)	71.4 (20.1)	75.0 (22.6)	68.1 (29.0)	84.4 (20.6)	75.0 (25.9)	69.4 (29.7)	71.4 (29.4)	67.3 (29.0)	70.2 (30.8)	56.0 (32.5)
Level 3 SA (%)	66.7 (20.8)	57.5 (29.4)	58.9 (28.2)	67.0 (25.5)	66.4 (27.0)	83.3 (17.5)	70.7 (23.2)	69.4 (22.3)	64.3 (30.0)	76.9 (23.4)	68.3 (25.1)	66.0 (24.9)

*Note: Only the trials with successful exits and no uploading delay were included.

Table 3 Mixed model results of overall SA response accuracy

Effect	*F* value	Variance	Wald Z	Estimate	SE	*df*	*t* value	*p*
Fixed effects								
Intercept				85.32	6.27	311.97	13.61	< .001
Remaining time to exit				-.56	.16	290.20	-3.58	< .001
ToR lead time[a]	5.27					288.63		< .001
Sequence of trial[a]	2.79					288.44		.002
Random effects								
Intercept		113.06	3.04					.002
Residual		278.24	11.98					< .001

Note: a. A categorical variable (12 levels). Estimates and t values for the first 11 levels contrasting the last reference category were omitted.

(Z = 2.64, p = .008; ICC = .17), and Level 3 SA (Z = 2.24, p =.025; ICC = .13), which supported the linear mixed modeling with 30 participants as higher-level units. Then, models were tested after adding lower-level predictors (i.e., ToR lead time, *sequence of trial* within participants, and *remaining time to exit*) to the random intercept model. The *remaining time to exit* was calculated by ToR lead time subtracting the takeover reaction time. It was included in the models as a covariate, as we assumed drivers would be more aware of the situation (e.g., exit type, movement of surround cars) as they approached the exit. On this basis, higher-level predictors (e.g., driver's age and annual mileage) were added. As no significant improvement was observed by incorporating higher-level predictors to the models, the final mixed models were obtained. The predictors were ToR lead time (lower level), *sequence of trial* (lower level), and *remaining time to exit* (lower level).

Response Accuracy

Overall SA. The results revealed significant effects of ToR lead time on the overall SA response accuracy, F (11, 288.63) = 5.27, p < .001. The results of linear mixed model were presented in Table 3. In general, providing longer ToR lead times significantly improved the overall driver SA for resuming control. The trend graph in Fig. 2 showed that the overall SA was higher in 16–60 s trials than in 6–14 s trials. When the ToR lead time was longer than 16 s, no significant increase was found in the overall SA. The pairwise comparison test found that the overall SA was significantly higher at 60 s, 45 s, and 30 s than 6–14 s; higher at 25 s, 20 s, and 18 s than 6–10 s; higher at 16 s than 6–14 s and 20 s; higher at 14 s and 12 s than 8 s (see Table 2).

The significant effect of *sequence of trial* on overall SA was also observed, F (11, 288.44) = 2.79, p = .002. The pairwise comparison test showed that the first two trials within participants resulted in significantly lower overall SA response accuracy than the subsequent trials in general. The *remaining time to exit* also significantly affected the overall SA, b = *-.56*, t (290.20) = -3.58, p < .001, 95% CI [-.86, -.25]. The overall SA response accuracy was approximately 0.6% higher as participants took over 1 s later to exit from freeways.

Level 1 SA. The ToR lead time was a significant predictor of Level 1 SA response accuracy, F (11, 287.80) = 6.80, p < .001. Similar to Fig. 2, Fig. 3 showed that the Level 1 SA significantly increased with the ToR lead time in general. There was a dramatic increase in Level 1 SA when the ToR lead time was between 6 s and 18 s; then the increase tended to be gentle for trials with a ToR lead time longer than 18 s. Results of pairwise comparisons showed that Level 1 SA was significantly higher at 60 s, 45 s, and 18 s than 6–14 s; higher at 30 s, 25 s, 20 s, and 16 s than 6–12 s; higher at 14 s than 6–10 s; higher at 12 s, 10 s, and 6 s than 8 s (see Table 2).

Level 2 SA. The ToR lead time was significantly associated with Level 2 SA response accuracy, F (11, 289.93) = 2.41, p = .01. Fig. 4 did not show any obvious change in Level 2 SA along with the ToR lead time. Nevertheless, the pairwise comparison test revealed positive effects of ToR lead times on Level 2 SA. Specifically, Level 2 SA was significantly higher at 60 s than 6 s, 8 s, and 14 s; higher at 45 s and 16 s than 6–10 s, 14 s, and 20 s; higher at 30 s, 25 s, and 18 s than 6 s and 8 s; higher at 12 s than 6 s (see Table 2).

Level 3 SA. The ToR lead time significantly affect Level 3 SA response accuracy, F (11, 288.26) = 3.20, p < .001. Fig. 5 did not show obvious pattern change in Level 3 SA. The pairwise comparison test revealed that Level 3 SA was significant higher at 60 s, 45 s, 20 s, and 18 s than 8 s and 10 s; higher at 30 s and 16 s than 6–14 s and 18–25 s (see Table 2).

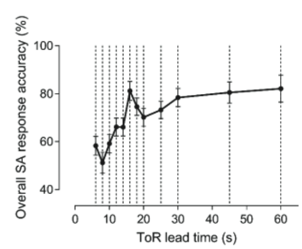


Figure 2 Trend line of overall SA*.

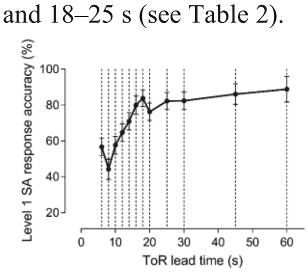


Figure 3 Trend line of Level 1 SA*.

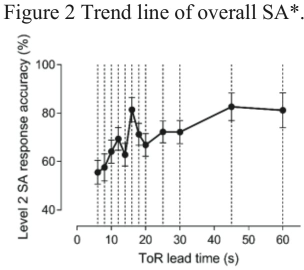


Figure 4 Trend line of Level 2 SA*.

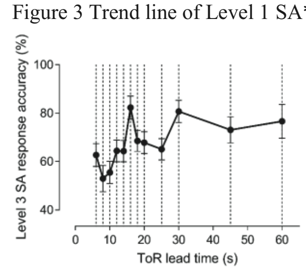


Figure 5 Trend line of Level 3 SA*.

*EMMs (error bars: ± 1 SD)

DISCUSSION

The results show that longer ToR lead times helped drivers obtain better SA for resuming control in non-time-critical takeover situations. The positive effect of longer ToR lead times on the overall SA was saturated at 16–30 s, which took longer compared with 7–12 s in Lu et al. (2017). Such difference could be resulted from the different task demand in two studies. Lu et al. (2017) asked drivers to view video clips about automated driving on freeways with no need to execute any takeover actions. After each video, the driver reproduced the traffic layout (e.g., the number, positions, and speed of surrounding cars) at the end of the video. In comparison, our study required drivers to first disengage from the mobile game, then pay attention to and comprehend multiple elements (i.e., exit type, movement of two cars ahead, subjective vehicle's signal lights and speed, and speed limit), and finally take over control in a self-paced manner. The higher task demand in the present study may lead to the longer lead time required by drivers to gain sufficient SA.

When look at three SA levels separately, the trend line of Level 1 SA is very similar to that of overall SA, suggesting that longer ToR lead times helped drivers perceive the environmental information, and the effect levels off at 18–45 s. Whereas, the trend lines of Level 2 and Level 3 SA do not show such apparent saturation of effects as for drivers' comprehension of information and their projection of future status. Based on the findings, we recommend a ToR with the lead time of 16–60 s for good driver SA for exiting a freeway, specifically for drivers' better perception of necessary information. In addition, Level 2 and Level 3 SA is not as high as Level 1 SA for ToR lead times longer than 16 s. To help drivers enhance SA at the comprehension and projection levels, additional system assistance and operational level of advice are recommended for drivers better understanding the situation and preparing for the manual control after takeover.

The results also show that the sequence of trial within subjects was a significant factor to driver SA. Drivers, in general, had more SA queries answered correctly in the later trials compared with the first few trials. It is noteworthy that the levels of ToR lead time were randomized for each subject to minimize the carry-over effect; the analyses have included the sequence number of trials in the models so that the results about driver SA are not affected. As the same SA queries were used for all the trials, it is possible that drivers paid attention to the elements being queried intentionally after experiencing the first few trials. One implication of this finding is that offering drivers training on obtaining SA for specific takeover situations could bring safety benefits to automated driving.

As in-person laboratory experiments were prohibited due to COVID-19 pandemic, we conducted an online experiment as a preliminary study. Several limitations need to be considered. First of all, although the purpose was to reduce the carry-over effect, the different driving scenarios among 12 levels of ToR lead times may affect the results. Secondly, the low-fidelity simulation of automated driving does not allow the post-takeover driver performance to be collected as implied driver SA. As the simulation stops once the driver presses the spacebar, it is unknown whether he/she is able to exit from the freeway successfully after takeover. Future studies in the laboratory will combine SAGAT with driving data and eye movement measures for more compelling results. Moreover, the browser-based experiment needs participants downloading videos on their ends, which depends on the internet connection speed. Ten trials with video loading delay occurred in this study resulted in inaccurate takeover reaction time outputted from Gorilla.sc, and accordingly inaccurate *remaining time to exit* calculated based on takeover reaction time. Therefore, these trials were removed from the analysis. Lastly, this study focused on the ToR lead time using a baseline human-machine interface, which may limit the generalizability of data in real world settings. Follow-up studies on combined ToR characteristics are expected to address the limitation.

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