Measuring the Transition Window in Conditional Automation

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ABSTRACT

Conditional (SAE driving automation level 3) automation is projected to see broader deployment by several manufacturers in multiple countries. Level 3 Automated Driving Systems (ADS) target performing the entire dynamic driving task (DDT) within an operational design domain (ODD), allowing the user to disengage while the system is active, but expect that the driver remains "takeover ready." In practice, one expectation of conditional automation is that the system will issue a request to intervene (RTI) prior to exiting its ODD, with a "sufficient" time window for the user to reengage in manual driving. To date, research has yet to provide an understanding of what a sufficient transition window will be in the context of near-production systems, specifically in those designed to operate in low-speed traffic jams. This study used an adaptive approach to adjust the timing of the request to intervene during transitions of control in a high-fidelity driving simulator. The transition adjusted from transition event to event based on whether participants were able to successfully take control in the previous event. Success was defined in reference to a baseline group who drove with expectations of being fully engaged in driving (i.e., SAE driving automation level 2). The results show that most participants were able to successfully make transitions with transition windows in the range of 4.5 to 5 seconds. However, some participants took several seconds longer to make successful transitions and for the subset of participants looking away from the forward road at the onset of the RTI, transition windows in the range of 7-7.5 seconds led to more successful transitions. This study provides a starting point for developing an objective definition of a "sufficient" transition window in the context of low-speed conditional Automated Driving Systems.

INTRODUCTION

Several Automated Driving Systems (ADS) with conditional automation are projected to be more widely deployed around the world in the next five years. Conditional automation (also known as SAE International (SAE) driving automation level 3) refers to an ADS capable of performing simultaneous lateral and longitudinal vehicle control along with object and event detection and response (OEDR; [1]).

SAE defines expectations for the ADS and the human operator in conditional automation. The ADS is expected to be capable of performing the entire DDT within its ODD, with the exception of fallback to a takeover-ready driver upon system's request. The ADS is also expected to be able to preview an exit from its ODD, at which point it issues a RTI to the human. The ADS would need to provide a "sufficient" time window for the human to transition back into manual control. The expectation is that the human operator will not be forced into a time-critical response situation. There are corresponding expectations for the human operator. With the ADS active within its ODD, the operator can fully disengage from the DDT and perform non-driving tasks (e.g., emailing on their phone). The operator must remain "receptive" to RTIs. The operator also functions as the "takeover-ready user." This means that the human operator is responsible for bringing the vehicle to a minimal risk state. For example, if a vehicle component malfunctions and impacts ADS operation, the system would issue an RTI and the takeover-ready human operator is responsible for resuming control to take necessary manual actions to assure safety of the vehicle.

A large body of research exists on Transition of Control (TOC) from SAE levels 2 or 3 to level 0. McDonald and colleagues [2] and Zhang and colleagues [3] wrote useful reviews of this literature. These reviews focus on the impact of different parameters (RTI timing and modality, secondary task engagement, etc.) on TOC performance. Importantly, this research has largely focused the crash-imminent transitions of control in unrestricted ODDs.

However, this situation does not meet the expectation laid out for level 3 ADS. By categorizing their ADS as level 3 according to the SAE J3016 definitions [1], the expectation is that the ADS will provide a sufficient transition window that is compatible with human capabilities for the driver to resume manual control. A recent report from the German Ethics Commission on Automated and Connected Driving states, "The software and technology in highly automated vehicles must be designed such that the need for an abrupt handover of control to the driver ('emergency') is virtually obviated" [4]. This includes so-called "silent" automation failures, where the ADS fails without notifying the user. This implies that the most common control transitions initiated by level 3 features will involve the ADS notifying the user of an upcoming exit of the ODD. The ADS is expected to provide a "sufficient" transition window for the user to reengage in driving before reaching the ODD limits [1].

To date, there is no consensus definition of what constitutes a sufficient transition window. Furthermore, most research on TOC in conditional automation has focused on relatively broad ODDs, despite the fact that the first deployments of these ADSs will be in well-defined ODDs, such as low-speed traffic jams.

The objective of this study was to examine what may constitute a minimum sufficient transition window (MSTW) in the context of low-speed traffic jam conditional automation. To achieve this objective, the study used an adaptive methodology, where the duration of the transition window changed from event-to-event based on success or failure in the TOC.

METHOD

Participants

The sample consisted of 50 licensed US adult drivers. The sample consisted of drivers between ages 21 and 65, with each group being comprised of 50% male and 50% female drivers. Participants were recruited from the National Advanced Driving Simulator's subject registry and through campus-wide emails. All study procedures were approved by the University of Iowa Institutional Review Board and all study participants provided written informed consent.

Simulator and Virtual Database

The NADS-1 simulator consisted of a 24-foot diameter dome enclosing a full-size 2015 Toyota Camry sedan with active steering and pedal feedback (Figure 1). A 13-degree of freedom motion system provided participants realistic acceleration, braking, and steering cues. Sixteen high-definition (1920x1200) LED (light emitting diode) projectors display seamless imagery on the interior walls of the dome with a 360-degree horizontal field of view. The data sampling rate was 240 Hz.

Figure 1. Interior Views of the NADS-1 Simulator

The study drive utilized a virtual database consisting of a divided interstate highway with three lanes of traffic in each direction. Within this 40-minute route, the drive alternated between periods of higher-speed (55mph) dense traffic and low-speed (22mph) traffic jams. Transition points, where Traffic Jam Auto Drive (TJAD) requested a manual takeover, occurred when TJAD identified an approaching ODD exit.

Traffic Jam Auto Drive (TJAD)

A level 3 ADS designed specifically for operation in congested traffic was to be used in this project. This system was called TJAD and mimicked the functionality and interfaces of near-production level 3 conditional automation (based on an earlier informal technology review). TJAD had the following ODD and functionality:

- Available only on divided multi-lane highways.
- Available only in dense traffic, with vehicles detected ahead and in the adjacent lane(s), traveling 35 mph or less.
- When ODD criteria are met, the user received notification that TJAD was available. It could be activated via a steering wheel button.
- When active, TJAD controlled the longitudinal and lateral control position of the vehicle. The user was told they could disengage from driving.
- When TJAD sensed an upcoming ODD exit, it issued an RTI to the user.

Non-Driving Task

To encourage disengagement from driving when TJAD was active, participants engaged in a demanding non-driving task during periods where TJAD was engaged. Participants were instructed to perform an email task using a provided smart phone. The inbox in the email application contained fictional messages that were either work-related, personal, or promotional. The participant was given rules for which actions to take with each type of message and told that their final compensation for their participation depended on how well they performed this task and how many emails they processed during the study drive.

Transition of Control and RTI

At the end of each traffic jam window, TJAD encountered one of two situations that fell outside its ODD, prompting the system to issue an RTI to the participant. There were 12 total TOC events. These events were a revealed stopped vehicle (6) and a revealed work zone (6). In both cases, the system identified a stationary object (either a vehicle or work zone) in the travel lane and issued an RTI. The RTI process for the two types of events was identical. The participant needed to take control and execute an avoidance maneuver around the object. Figure 2 shows timeseries diagrams of the two types of events. For all events, the object (i.e., stopped vehicle or work zone) was revealed at 15s time-to-collision based on the participant's speed. Because speed was controlled by TJAD, the reveal distance was nearly identical across all events. The direction of the reveal (left vs. right) was balanced across events. The order of events was fixed across participants.

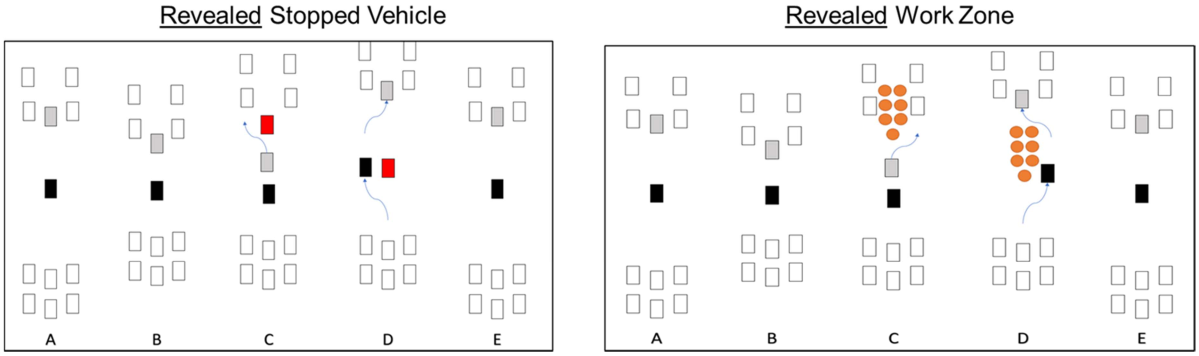

Figure 2. Study Drive Events

The RTI was designed to be representative of near-production systems. The RTI consisted of two auditory-visual stages, as shown in Figure 3. Stage 1 was intended to be a notification to the participant of an upcoming ODD exit. Stage 2 was intended to be a more severe alert prompting the participant to take control immediately. If participants did not take over by the end of the transition window, the system entered a failure mitigation strategy (FMS) where the vehicle began braking automatically. The transition window constituted the time from the start of RTI stage 1 until the start of the FMS.

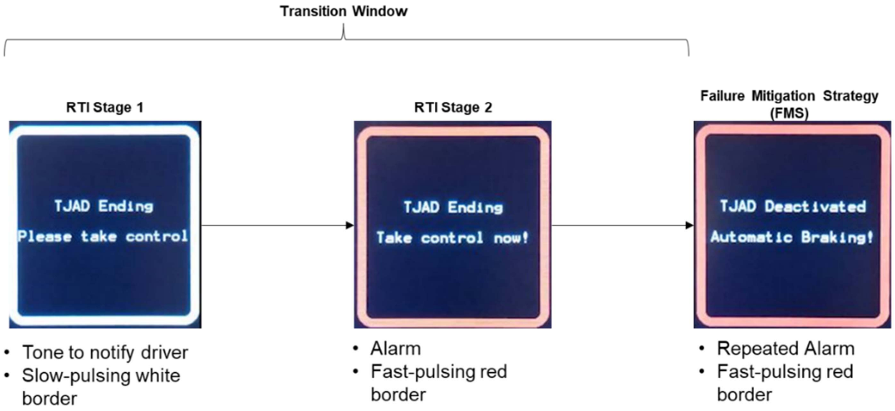

Figure 3. Request to Intervene

Adaptive Transition Window

The study was designed to estimate the MSTW using an adaptive approach, whereby the transition window changed based on whether the previous transition was successful or not. The duration of the transition window was adjusted from event to event by changing the timing of the RTI Stage 1 in relation to the object reveal. Figure 4 shows the sequence of the transition of control events. Note that RTI timing was adjusted based on time to collision (TTC).

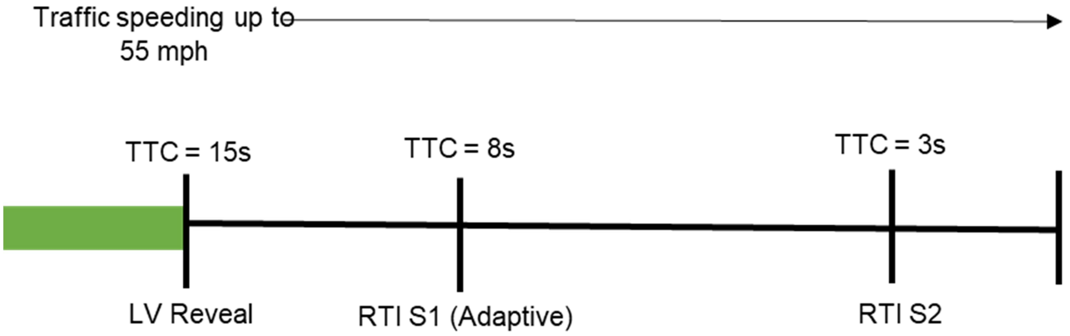

Figure 4. Transition of Control Event Sequence

To examine participant's MSTW, the step size (i.e., change to transition window) decreased across the events, as shown in Table 1. Note that this adaptive sequence was independent for the two types of events. For each event type, the initial transition window was 7.5s, which was also considered the maximum transition window (i.e., transition windows could not be longer than 7.5s). If participants responded successfully in all 6 events, they could reach a final transition window near 4s (for RTI stage 1).

Table 1. Adaptive Step Size

Trial	**Step Size (+/- s)**
1	-
2	1.6
3	0.8
4	0.4
5	0.2
6	0.1

Baseline Group

In order to determine success or failure during the transitions, data from a baseline group who remained engaged in the driving task (i.e., did not perform the email task) were collected before the main study. This group did not receive an RTI but were told they needed to take back control if they saw any stationary objects in the roadway, as these fell outside the system's ODD. For this baseline group, we calculated the TTC with the stationary object at the point where the participant began responding. Using the 85th percentile of this distribution of TTC values from the baseline group, we computed a success/failure threshold that was then used for the adaptive approach described above.

Procedure

Potential participants completed an online screening to verify they met the inclusion criteria for the study. Participants provided written informed consent and completed a driving questionnaire. During the study visit, participants received training on the simulator, TJAD, and the email task (other than the baseline group). Participants were instructed about TJAD's capabilities and its ODD, as well as the RTI sequence. Training provided information and practice for the email task and informed participants about the incentive for engaging in the non-driving task.

Participants then entered the simulator and completed a practice drive, where they practiced engaging and disengaging TJAD during traffic jams. They also practiced the non-driving email task while TJAD was active. Participants then completed a wellness questionnaire to screen for simulator sickness. Eligible participants then completed the study drive, which lasted approximately 35 minutes. This was followed by a second wellness questionnaire, a post-drive questionnaire, and debriefing.

RESULTS AND DISCUSSION

Data were reduced using custom MATLAB scripts. R statistical software was used to analyze and visualize the reduced data. Video data were coded using Boris open-source video coding software and synchronized with simulator data based on frame numbers.

Baseline Transition of Control

TTC was calculated at the point at which participants began their first response following the lead vehicle reveal. Responses could constitute either the first braking or steering response following the reveal. Braking was defined as a brake pressure of 5 pounds or greater. Steering response was defined as a change in steering wheel angle of 10 degrees or more. TTC represents the time before the participant would collide with the stationary object if no response was executed and speed remained constant. These thresholds were selected based on previous studies using the NADS-1 simulator platform. Larger TTC indicate that participants began responding with longer time gaps, indicating they would have more time to execute a safe response.

Figure 5 shows the distribution of TTC values for the baseline group. The vertical bar represents the 85th percentile of the distribution, which was 4.6s. This threshold was used as the cutoff to delineate success vs. failure for the main study. If responses occurred at a TTC of 4.6s or more, they were classified as successful. If responses occurred at less than 4.6s TTC, they were classified as unsuccessful.

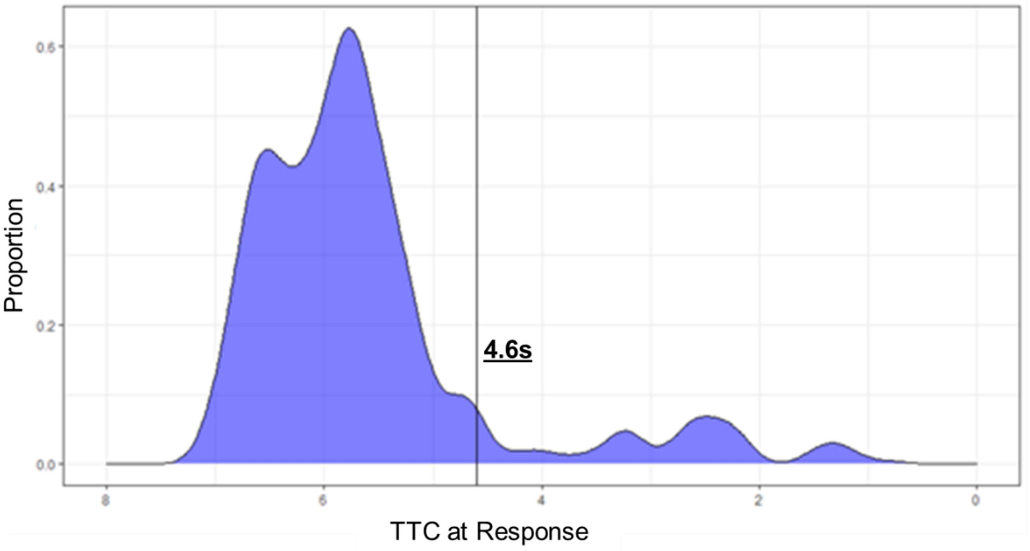

Figure 5. Time to Collision Distribution of Baseline Group

Adaptive Paths

Figure 6 shows the adaptive sequence for all participants (N = 40) in the main study. This figure traces the different paths through the adaptive sequence for each of the two types of events. The figure is color-coded for successful/unsuccessful responses.

Most participants showed a decreasing transition window for both event types over the course of the study. Each event type began with an initial transition window of 8s. By the end of the sequence for each event type, participants were able to successfully transition into control in a little more than half that initial time.

Minimum Window by First Failure

One way to think about the minimum sufficient transition window is the window where participants made their first unsuccessful transition (i.e., failure). Figure 6 shows that several participants (approximately 15% across the aggregated event types) failed with ~6s transition windows, resulting in the adaptive logic increasing the transition window. Figure 6 shows there was a subset of participants who struggled to transition into control successfully (compared to baseline) with transition windows ranging from 6-8 seconds.

One conclusion from these adaptive sequences is the variability between individuals with respect to transition of control success as a function of the transition window. Most participants were successful across the majority of events for each event type, consistently reducing the duration of the transition window. Importantly, however, the distribution of transition windows across each event (for each event type) shows long tails of the distribution, indicating the likelihood of outlier participants (or individual events).

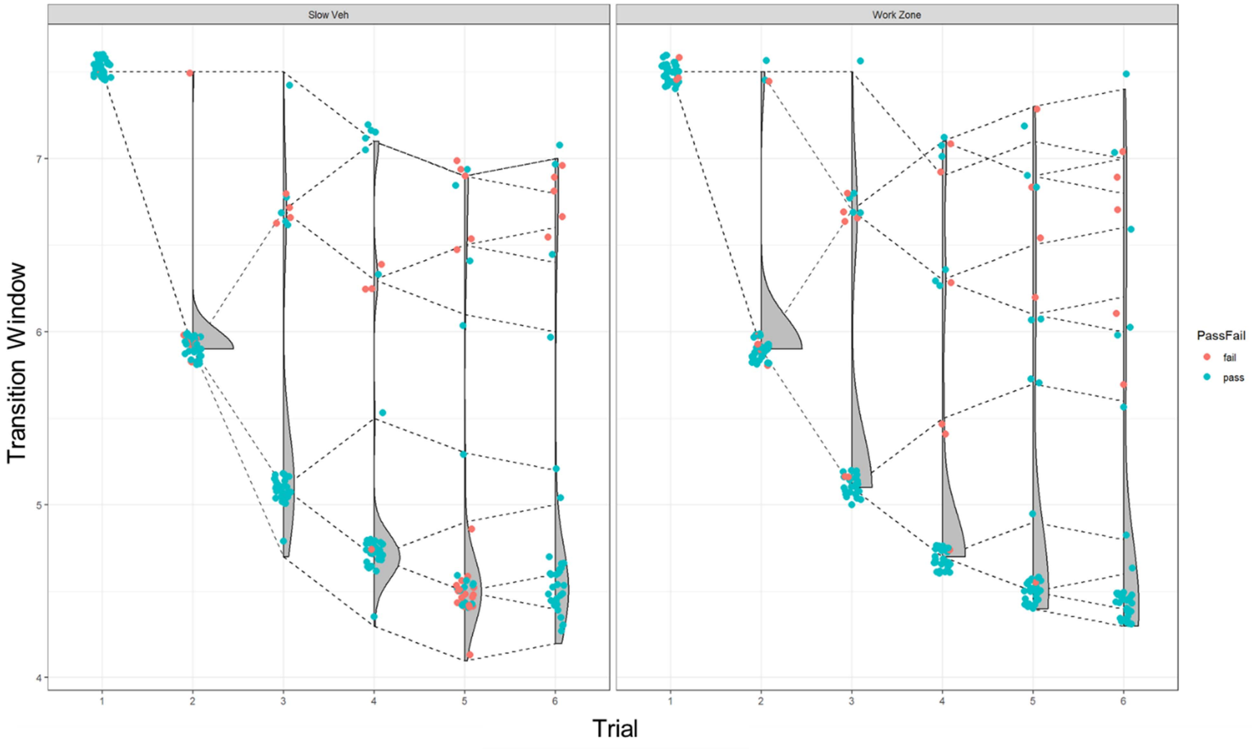

Figure 6. Adaptive Paths

Minimum Window by Final Event

Another way to estimate the minimum sufficient window is to examine the distribution of transition windows for the final event, which represent the conclusion of the adaptive sequence for each event type. These distributions are shown in Figure 7. Again, most participants achieved a final transition window between 4 and 5 seconds. However, it is also important to consider the tails of the distributions, as they may be the most important contributors to crashes and therefore key considerations in selection of system thresholds. The 85th percentile of the distributions was at approximately 6.5s.

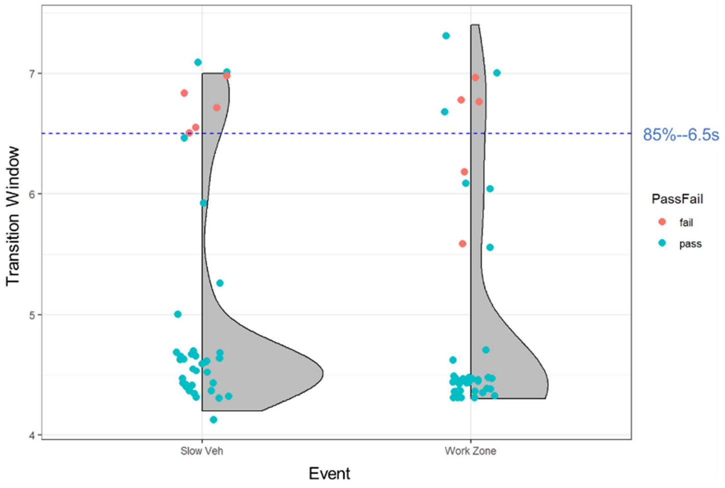

Figure 7. Distribution of Responses in Final Events. Blue line represents 85th percentile

Minimum Window by Glance Location

One consideration in the identification of thresholds for transition of control is the impact of the behaviors that precede the transition on the likelihood of transition success. Design needs to consider a range of potential user states, particularly in the context of conditional) automation where it is permissible for the user to fully disengage from the DDT while the system is active.

Review of driver-facing video suggested two distinct patterns of behavior, specifically visual attention in the form of glances to the forward road, preceding the transitions. One behavior pattern involved occasional or frequent glances forward, presumably to check on the driving task and potentially to anticipate upcoming transitions of control. The other pattern of behavior involved few if any checks forward.

To determine whether these different glance patterns contributed to transition of control success in the adaptive experiment, we coded glance location at the time of the reveal event. Using the frame where the reveal occurred, an independent rater coded glance location as either forward (i.e., at the road) or down (i.e., at the email task).

To examine the potential impact on transition success across the different transition windows captured in this study, we binned data based on the available preview time, which reflects the duration of the transition window. For example, a preview time of 7 seconds corresponds to a 7 second transition window where the RTI gives 7 seconds for the participant to transition into control (assuming the participant looks up at the RTI).

Figure 8 shows the success rates across different preview time bins. These success rates are divided based on the glance location at the RTI, looking up or looking down. For events classified as looking up, participants had high success rates across the range of transition window bins. In three cases, success was 100% when participants were looking up at the RTI. Importantly, even at the short transition window bins, success rates were high when participants were looking up.

Conversely, success rates were lower when participants were looking down at the RTI. Success rates were approximately 50% across all time bins for the subset of events where participants were looking down. Figure 8 also shows that, within the subset of looking down events, success rates were higher for transition windows in the 7-7.5s range (82%) compared to success rates in all the other shorter transition window bins. No other transition window range had success rates greater than 65%.

These results provide two important conclusions. First, glance location immediately preceding a transition of control has a key impact on the likelihood of transition success. When participants were looking forward at the time of the RTI, the duration of the transition window did not matter, and participants were able to successfully respond within even the shortest transition windows. Conversely, participants who were looking down were much less likely to show successful responses across all transition windows. This reiterates the importance of considering driver state in evaluation of transition of control and RTI design.

Second, for those participants who were looking down at the RTI, the longest transition window duration resulted in higher success rates than all shorter transition windows. This suggests that a transition window in the range of 7-7.5s may be necessary to enable successful transition of control in situations where drivers are disengaged from the DDT at the time the RTI is issued.

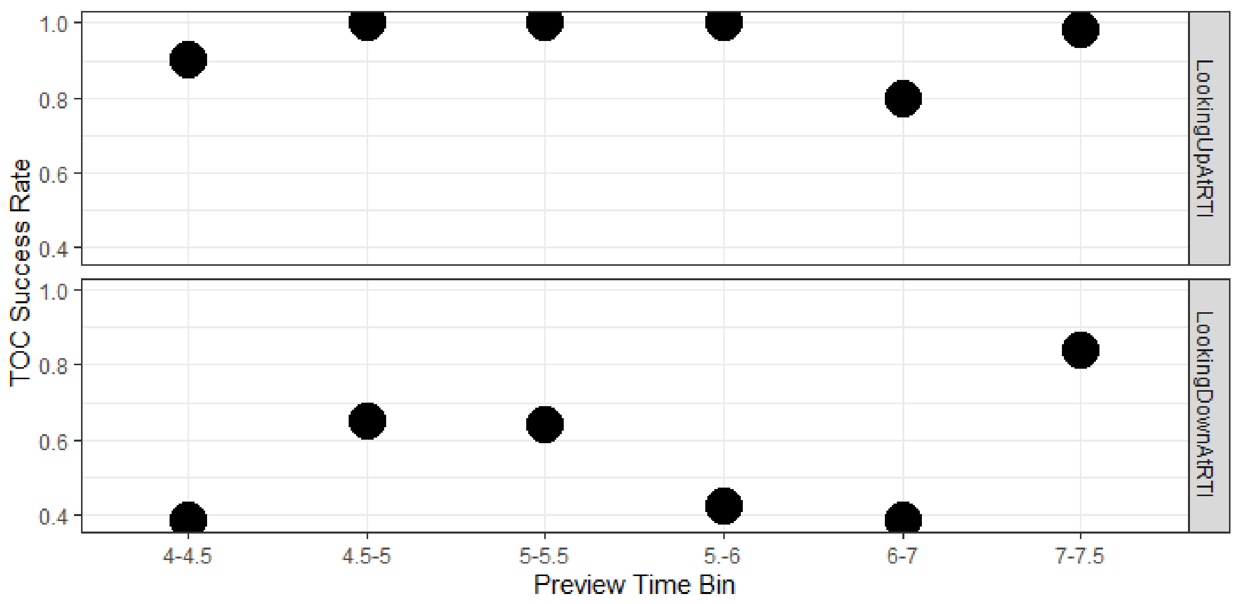

Figure 8. Transition of Control Success by Binned Transition Window (Preview Time) Duration

Limitations and Future Directions

Several limitations from the present study are worth noting. One potential limitation to consider in this study is the repeated nature of the transition of control events. It is possible that over time participants altered their visual attention strategy to better detect the onset of the lead vehicle reveal events. In real-world interactions with Automated Driving Systems, time-critical transitions of control will be rare. The majority of transitions are likely to be uneventful, allowing drivers larger time cushions to transition back into manual control. This study focused on quantifying the minimum sufficient window that may be necessary in rarer transition of control situations. While rare, such “edge case” events are likely to contribute disproportionately to crash risk during human-automation interactions.

This study used a high-fidelity driving simulator to assess transition of control performance. While simulation may lack some of the complexity of on-road driving, the motion cues provided by the simulator in this study mimicked those experienced by drivers in real vehicles and were likely important cues, particularly for disengaged drivers, in determining when TJAD might issue an RTI. There is a need for future research, particularly naturalistic driving data, to understand the myriad of ways in which drivers will behave when conditional automation is available. This will help inform the design of future experimental work, which can help inform the creation of objective best practices for some of the automated vehicle terminology.

The results of this study are best considered in the context of low-speed traffic jam conditional automation. The study focused on traffic jam systems because they were identified as one of the first likely deployment situations. Future research should focus on expanded and more diverse ODDs to understand whether the minimum sufficient transition windows identified in this study generalize to a wider range of systems and situations. Along these same lines, it will be important to further understand the impact of different RTI design characteristics (e.g., alert modality) on transition of control in conditional automation.

Finally, the results of this study highlight the importance of understanding individual differences with respect to driver interactions with vehicle automation. It is worth noting that some participants were consistent in their pattern of behavior (e.g., always executing check glances) while other participants changed their behavior from event to event. In addition to changing overall glance patterns, participants may have changed the frequency of their glances, which again may have impacted the likelihood of early detection of the reveal event. While beyond the scope of this study, analysis of glance behavior during periods of automated driving will be important for understanding the impact of individual differences on transition of control. Understanding the impact of individual differences and demographic characteristics on transition of control is another important avenue for future ADS research.

CONCLUSIONS

The objective of this study was to examine the minimum sufficient transition window in the context of traffic jam conditional automation. By using a unique adaptive design, the study procedure used a high-fidelity simulator to systematically tune the transition window necessary for participants to successfully regain manual control following periods of automated driving. The results indicate that many participants were able to make successful transitions of control with relatively short (4.5-5s) transition windows. However, the analysis also suggests that some participants, in particular those drivers who were looking away from the forward roadway at the onset of the RTI, required longer transition windows (i.e., 7-7.5 seconds). It should be noted that these absolute transition window durations may depend on factors such as travel speed, traffic density, and other operational design domain characteristics. Though more research is needed to understand what other factors may impact a human driver to successfully resume control in conditional automation after being disengaged from the driving task, this study provides empirical data of observed human driver needs related to the minimum transition window for the traffic jam conditional automation use-case. Other factors can only increase these observed transition windows.

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