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The Impact of Driver's Mental Models of Advanced Vehicle Technologies on Safety and Performance

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Title

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Foreword

Advances in vehicle technology have evolved significantly in recent years and are changing the role and responsibilities of drivers. Complex automation can now control the vehicle's speed, headway, and lane position, and capabilities continue to expand. Drivers need to understand these new vehicle features in order to use them effectively and appropriately. The understanding of automation—often couched as a driver's mental model—has been an important topic of discussion in recent years among the research community and other stakeholders.

This report summarizes a study—the first of its kind—examining how different qualities of mental models map onto performance outcomes in a variety of automation edge-case scenarios. The results should help researchers, the automobile industry, and government entities better understand driver performance, behavior, and interactions in vehicles with advanced technologies.

This report represents one of the first outcomes of a cooperative research program between the AAA Foundation for Traffic Safety and the SAFER-SIM University Transportation Center.

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About the Sponsors

AAA Foundation for Traffic Safety
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Founded in 1947, the AAA Foundation for Traffic Safety in Washington, D.C., is a nonprofit, publicly supported charitable research and education organization dedicated to saving lives by preventing traffic crashes and reducing injuries when crashes occur. Funding for this report was provided by voluntary contributions from AAA/CAA and their affiliated motor clubs, individual members, AAA-affiliated insurance companies, and other organizations or sources.

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SAFER-SIM comprises a multidisciplinary, synergistic team of researchers in human factors, engineering, computer science, and psychology who will use innovative simulation approaches ranging from microsimulation to human-in-the-loop simulation to promote safety. SAFER-SIM sponsors research, facilitates outreach activities in STEM areas, and aids workforce development efforts in transportation safety.

The universities comprising SAFER-SIM study how road users, roadway infrastructure, and new vehicle technologies interact and interface with each other using microsimulation and state-of-the-art driving, bicycling, and pedestrian simulators.

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Abstract

Advanced driver assistance systems (ADAS) are rapidly being introduced across automobile manufacturer lineups. These technologies have the potential to improve safety, but they also change the driver-vehicle relationship—as well as their respective roles and responsibilities. To maximize safety, it is important to understand how drivers' knowledge and understanding of these technologies—referred to as drivers' mental models—impact performance and safety. This study evaluated the impact of the degree of accuracy (or quality) of drivers' mental models of adaptive cruise control (ACC) on performance using a high-fidelity driving simulator. Participants with varying degrees of ACC experience were recruited and trained such that they had either a strong or weak mental model. Participants then completed a study where they interacted with the ACC system and encountered several edge-case events. In general, participants with strong mental models were faster than those with weak mental models to respond in edge-case situations—defined as cases where the ACC did not detect an approaching object, such as a slow-moving motorcycle. The performance deficits observed for drivers with weak mental models appear to reflect uncertainty surrounding how ACC will behave in edge cases. These results raise several important questions surrounding driver introductions to ADAS and the need for training.

Introduction

New advanced technologies are being integrated into vehicles at an accelerating pace, offering new safety and convenience features to drivers. However, in addition to being complex systems in and of themselves, these technologies stand to change the fundamental nature of the driving task, especially as the systems take on more of the driving responsibilities. Driver knowledge and understanding of advanced driver assistance systems (ADAS)—sometimes referred to as a driver's mental model—are important considerations in the safe and appropriate use of these systems.

A mental model has been defined as a reflection of an operator's knowledge of a system's purpose, its form and function, and its observed and future system states (e.g., Johnson-Laird, 1983; Rouse & Morris, 1986; Seppelt & Victor, 2020). It follows that an operator's mental model can have important implications in determining how they interact with a given system.

There is evidence in the literature that the development of accurate mental models is not necessarily a straightforward process. Some evidence shows that information derived from various sources as well as practice and exposure to the systems help drivers build mental models (Beggiato & Krems, 2013; Singer & Jenness, 2020). However, drivers do not necessarily rely on vehicle owner's manuals, and often their mental models are formed mainly on experience through use (Piccinini, Simões, & Rodrigues, 2012). Importantly, trial-and-error or practice alone seems insufficient for forming well-calibrated mental models, and even experienced users may not understand all capabilities and limitations of a technology (Beggiato & Krems, 2013; McDonald, Carney, & McGehee, 2018; Piccinini, Rodrigues, Leitão, & Simões, 2015). With more sophisticated technologies, we can expect even more complexity and more challenges to the formation of well-calibrated mental models.

There are two central issues related to mental models of vehicle technology. The first is that the driver needs to understand the functions of the ADAS for each possible mode. The driver should also understand the limitations of the system and what conditions and situations the technology is not designed for. To the extent that a mental model is inaccurate or insufficient, drivers might believe that their system can perform actions it cannot, or that it operates properly in conditions that it was not designed for. A study by Dickie and Boyle (2009) placed drivers into three groups based on their awareness of the limitations associated with adaptive cruise control (ACC) (i.e., aware, unaware, and unsure) (Dickie & Boyle, 2009). Drivers who were unaware or unsure engaged more often in potentially hazardous behaviors such as using the ACC on curvy roads compared with those who were aware of the system's limitations. Additionally, a survey of owners of ADAS-equipped vehicles found that some owners expressed a certain willingness to engage in non-driving-related activities, indicating a lack of understanding regarding the limitations of particular technologies, as well as the driver's role and responsibilities while using the technologies (McDonald et al., 2018).

The second issue related to mental models is that the driver needs to recognize the current mode or system status of the ADAS, e.g., knowing whether a single system or multiple systems are engaged and active (versus inactive and/or unavailable). Confusion over the current state of the system (i.e., mode confusion) or insufficient awareness of system status may have detrimental consequences in safety critical situations. Whether this confusion comes from a lack of understanding or insufficient perception is not clear, but it is important to provide the human with enough information to comprehend what the system is doing and why. A driver's mental model likely contributes to the chance of committing mode-confusion errors as well as the probability of detecting such errors when they occur.

Mental models can be assessed in several ways. Indirectly, mental models can be inferred by observing how a user interacts with a system (e.g., Forster, Hergeth, Naujoks, Krems, & Keinath, 2019; Kessel & Wickens, 1982). Observational methods evaluate the accuracy of operation and use of specific cues during system interactions. Mental models can also be evaluated through verbal and written reports (Falzon, 1982). Survey questions can evaluate general and hypothetical information about the technology, such as what the system does and does not do and what situations or driving environments are appropriate (Beggiato, 2014; Singer & Jenness, 2020).

Much research to date has examined how mental models are developed as well as the effect of mental models on trust and acceptance of technology (Beggiato & Krems, 2013; Dickie & Boyle, 2009; Forster et al., 2019; Weinberger, Winner, & Bubb, 2001; Goodrich & Boer, 2003; Seppelt & Lee, 2007; Lee & See, 2004; Xiong, Boyle, Moeckli, Dow, & Brown, 2012; Beggiato, Pereira, Petzoldt, & Krems, 2015). More recent research has helped identify gaps in users' knowledge and understanding of currently available ADAS (McDonald et al., 2018; Jin, Tefft, & Horrey, 2019). However, there is a general lack of research that identifies how these errors and the lack of knowledge will translate to performance and safety impacts. The goal of this project was to map the quality of drivers' mental models of ACC to performance in a driving simulator study.

Method

Drivers with varying levels of experience were recruited for the study. The quality of a potential participant's mental models regarding a typical ACC system was identified using a brief questionnaire and then further established through a training protocol. A final assessment was developed to corroborate the different levels of understanding of the functions and limitations of the ACC system. The quality of mental models was then mapped to driving performance in edge-case situations. This study was completed with approval and oversight by the University of Iowa Institutional Review Board.

Participants

Eighty experienced drivers between the ages of 25 and 65 (*M*=44.0, *SD*=10.7) were recruited via the National Advanced Driving Simulator (NADS) subject registry (Table 1).

Table 1. Number of participants by mental model group, age, and gender

	Strong		Weak	
	Males (N=19)	Females (N=20)	Males (N=18)	Females (N=21)
25-35 years	3	6	5	6
36-45 years	6	6	3	4
46-55 years	5	6	7	4
56-65 years	5	2	1	6

Each potential participant was screened for eligibility. They were required to have a valid drivers' license, have at least three years of driving experience, and drive at least 2,000 miles per year. Potential participants were also asked about any previous experience with ACC, which included ownership of a vehicle with ACC, understanding the difference between ACC and standard cruise control, and experience using ACC. Additionally, their responses to a brief questionnaire enabled researchers to identify, at the onset, evidence of two distinct groups with varying mental models of an ACC system. The questionnaire, shown in Figure 1, was comprised of four multiple-choice questions regarding the functionality and limitations of ACC; one point was given for a correct answer and zero points for an incorrect answer. Participants with a score of 0-1 were placed in the "weak" mental model group, and participants with a score of 3-4 were placed in the "strong" group. Participants with a score of 2 did not meet criteria for either group and were therefore excluded from the study. Of the 231 potential participants who completed the screener 20 scored 0 and 60 scored 1, making them eligible to be enrolled into the "weak" group. There were 49 potential participants who scored 3 and 11 who scored a 4 and who were then eligible to participate as part of the "strong" group. There were 91 who scored a 2 and were ineligible.

These screening questions were originally developed as part of a survey examining the knowledge of owners of ADAS-equipped vehicles regarding the functionality and limitations of particular ACC systems on the market at the time of that survey (McDonald et al., 2018). The questions were not specific to any particular make or brand and participants were made aware that some vehicle makes and models may not refer to this system as ACC but as one of the following: Dynamic Laser Cruise Control ™, Active Cruise Control, Intelligent Cruise Control ™); they were not intended to be specific to the vehicle and system used in the current study.

Adaptive Cruise Control:

- Automatically brakes and accelerates to maintain following gap between your vehicle and the vehicle ahead
- Automatically brakes and accelerates to drive your vehicle at the same speed as the vehicle ahead
- Maintains a set speed but turns off if the system detects a vehicle ahead
- Uses the navigation system to determine the speed limit and automatically drives your vehicle at a speed just under the limit unless the system detects a vehicle ahead
- Prefer not to answer

Adaptive Cruise Control:

- 1: May accelerate if the vehicle ahead moves out of the detection zone
- 2: Brakes the vehicle as it approaches a curve
- 3: Is able to successfully brake the vehicle in any situation as long as the system has detected a vehicle ahead
- 4: May accelerate to match faster vehicles detected ahead
- Both the 1 and 3 are correct
- Prefer not to answer

With Adaptive Cruise Control:

- The driver sets the speed and the system maintains a fixed following gap that cannot be changed
- The driver sets the speed and selects one of several following gaps
- The driver sets the speed and the system determines the following gap based on location and speed
- The system will determine the speed and the following gap based on location and speed
- Prefer not to answer

Adaptive Cruise Control:

- Works well in all weather conditions because it relies on radar
- May not work well to detect vehicles such as motorcycles
- Works well in tight curves and on steep hills
- May not work well if the vehicle ahead is silver due to the reflection off the vehicle
- Works well in traffic conditions that require frequent repeated acceleration and deceleration
- Prefer not to answer

Figure 1. Initial screening questionnaire (correct responses are highlighted)

Simulator and ACC Technology

The study took place at the NADS and used the NADS-1 without motion (Figure 2). The simulator contained a full Toyota Camry cab and 360-degree wraparound display (Figure 3).

Figure 2. The NADS-1 dome exterior

Figure 3. The NADS-1 interior with Toyota Camry cab

The ACC implemented in the simulator was representative of the 2019 Toyota RAV-4 and incorporated realistic features of the ACC user interface, as shown below in Figures 4 and 5. To the extent possible, aspects of system function were designed to match the RAV-4 system (e.g., following gap distances). Table 2 describes the actions necessary for system activation/deactivation, as well as setting the speed and following gap.

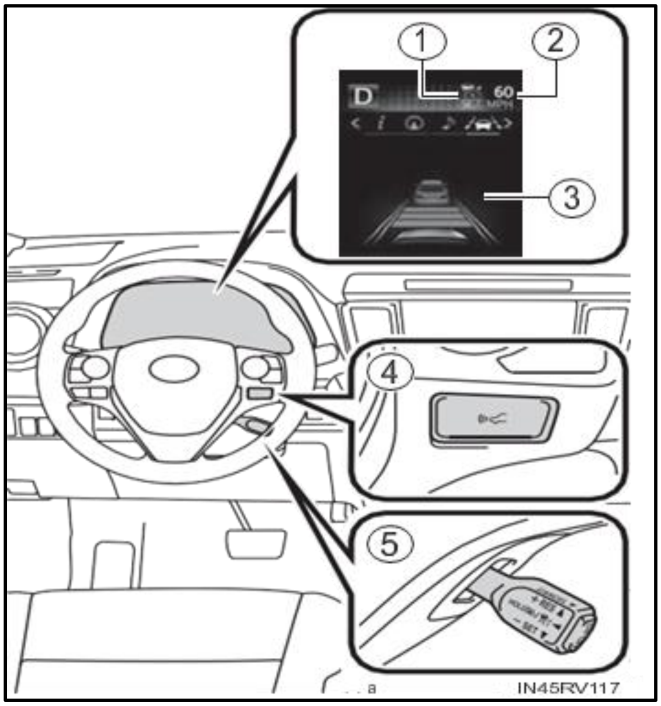


Figure 4. Location of displays and controls: (1) system status on/off, (2) set speed, (3) following gap setting, (4) button for setting following distance gap on the steering wheel, and (5) ACC lever behind and to the right of the steering wheel

Figure 5. Close-up of ACC interface

Table 2. Instructions for ACC system activation/deactivation and settings

Action	Instruction
Turn ACC system on	Press button at end of ACC lever quickly; holding button will activate standard cruise control
Set ACC speed	Once on, press ACC lever down to set speed
Adjust ACC speed	Press ACC lever up/down for 1 mph increments, and hold lever up/down for 5 mph increments
Adjust following gap	Press button on steering wheel to change gap (Long, Medium, Short); Default is Long.
Cancel ACC (standby)	Pull ACC lever toward you or depress brake
Resume ACC (from standby)	Press ACC lever up to resume previous speed
Turn ACC system off	Press button at end of ACC lever

Study Design and Procedure

A between-subjects design was used for this study. The between-subject variable was the mental model classification (weak mental model versus strong mental model) based on responses to the initial screening questionnaire.

Based on the score they received, participants were placed in either the “strong” or “weak” mental model group. Participants were not told which group they belonged to. In order to further ensure that the two groups were distinctly different in terms of the quality of their mental models, each group experienced a slightly different protocol during the session. These are shown in Figure 6 and described further below.

Participants who were assigned to one of the two groups according to their score on the screening survey were scheduled for a study visit. Upon arrival, both groups received a PowerPoint presentation regarding the ACC system that they would be using in the simulator. The two presentations differed in the amount of information provided: the “weak” group received information, mainly in the form of bullet lists, on how to turn the ACC system on, set and adjust the speed, and turn the system off. The “strong” group received figures from the owner’s manual showing controls and procedures for use as well as descriptions and diagrams providing additional detailed information on the ACC’s function and limitations across various situations. The portions of the training presentations related to the ACC system for the “weak” and “strong” groups can be found in Appendices A and B, respectively.

During the training, all participants were informed that they would complete both a practice and a study drive and that these drives would take place on a rural highway during daytime conditions. They were informed that the speed limits would change, but that they were only to change the vehicle speed when they were instructed to do so, even if they were to see a speed limit sign with a different speed. This was done to ensure that events occurred as they were designed for each participant.

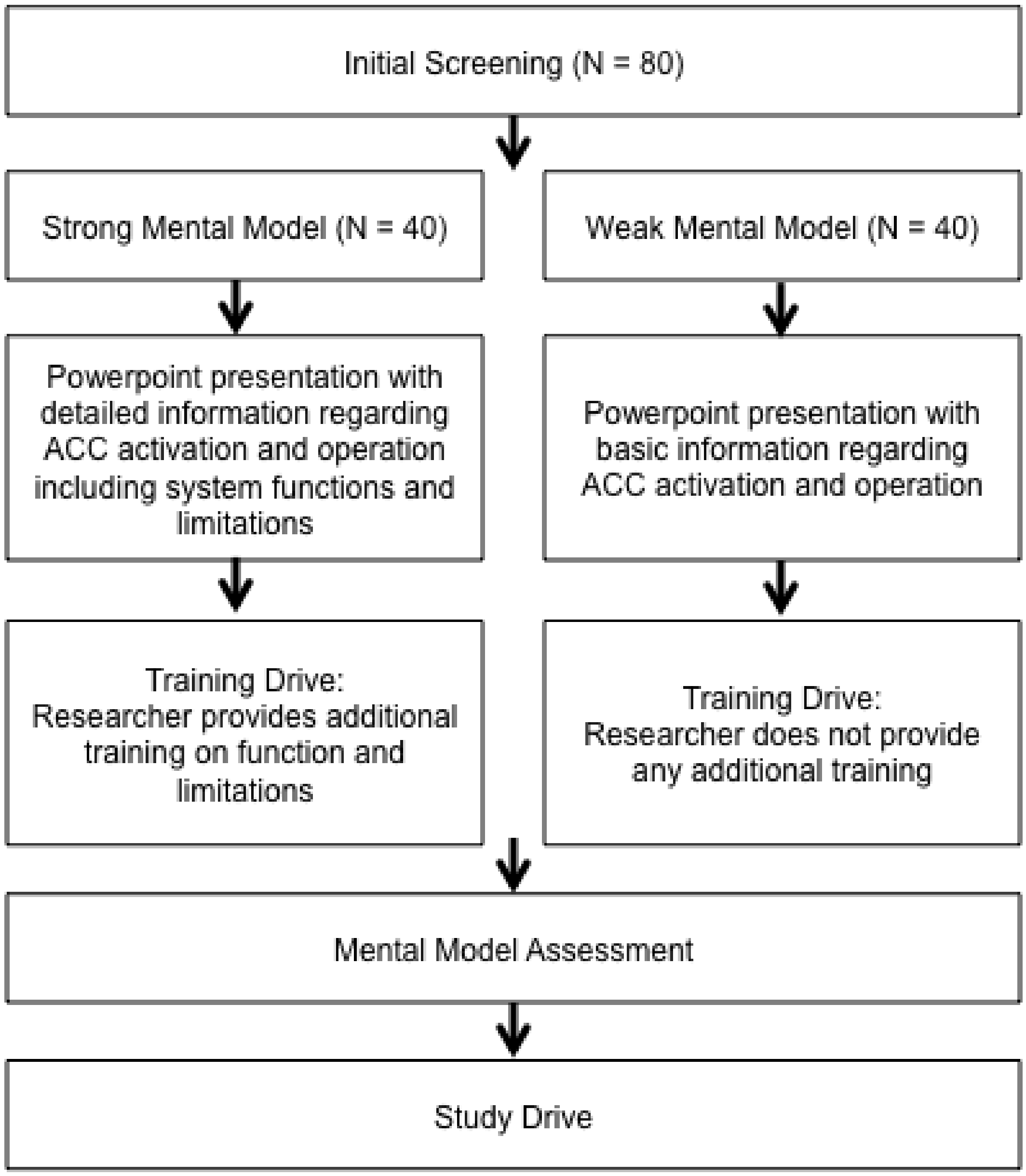


Figure 6. Study procedure

Participants were then escorted to the simulator for the 20-minute training drive. During this drive, participants were acclimated to the simulator and the ACC system. A researcher was present in the simulator to provide instructions about how to turn ACC on, how to set a max speed, and how to adjust both the speed and the following gap. The researcher also answered subjects' questions about the ACC system. Depending on the assigned group, the researcher provided different responses to questions; the "weak" group received minimal, basic, "how to use the system" type answers, whereas the "strong" group received more detailed answers (e.g., "radar will only pick up what is directly in front of it, so vehicles merging on may be picked up late"). For both groups, recorded navigation instructions guided them along the route.

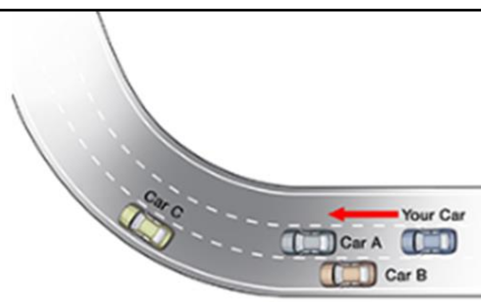
Mental Model Assessment

After the training drive, participants completed the Mental Models Assessment (Appendix C), which asked questions about the participants' understanding of ACC at that point in time. The assessment comprised 20 true or false questions that evaluated a driver's understanding of specific functions and limitations of the system. Examples of these questions are shown in Table 3.

Table 3. Examples of true/false questions in the Mental Model Assessment

Type	Question
Functionality	Maintains the speed that you have set when there are no vehicles detected in the lane ahead
Functionality	Adjusts the speed to match faster vehicles ahead
Functionality	Will provide steering input to keep the vehicle in its lane
Limitation	Will correctly detect motorcycles and other smaller vehicles not driving in the center of the lane
Limitation	May not correctly detect stopped vehicles in your lane
Limitation	Reacts to stationary objects in the road (construction cone, tire, ball)

An additional 14 questions focused on how to interact with the ACC system. For example, "When ACC is active, how do you adjust the speed setting?" or "In how many mph increments does the ACC increase or decrease when the lever is held?" Participants were also presented with three scenarios and asked to describe how they believed the vehicle would respond. Each of these scenarios required that the driver understand a potential limitation of the system. Figure 7 shows an example of one scenario.



How might your ACC system behave in this situation? Why?

Figure 7. Example of scenario questions from Mental Model Assessment

In the example above, the participant was given credit for answers that incorporated some version of the following:

- ACC may detect Car B as it goes around the curve because it is directly ahead of your vehicle.
- My car might lose track of Car A as it goes around the curve. Depending on my set speed, it may slow down or speed up.

Overall, 22 questions dealt with ACC functionality and 15 with the limitations of the system. Following the assessment, participants were escorted back to the simulator to complete the study drive.

The study drive lasted about 40 minutes and required participants to interact with the ACC based on the knowledge of the system they were introduced to. They were instructed that during this drive they would set the ACC, make adjustments to the vehicle speed when instructed to do so, and change the gap if it was necessary or they were instructed to do so. If the driver were to cancel ACC, they were instructed to set the ACC to the posted speed limit when they felt comfortable doing so. Participants were also instructed to stay in the right lane unless instructed otherwise or if they felt that the situation required a lane change. Navigation instructions guided them along their route. The researcher sat in the back seat of the cab monitoring the driver's wellness. The driving environments were designed to mimic the range of operational design domains for ACC. Specific events, described below, were integrated into the drive to measure potential errors stemming from incorrect or incomplete mental models. Throughout the drive, participants were also instructed to change their speed and gap settings to specific values at predetermined locations (see state transitions below), ensuring all participants encountered events in a similar manner.

At the end of the study drive, participants exited the simulator and completed several questionnaires relating to simulator realism and demographics. Participants were then debriefed and given an explanation of the different training methods for each group along with additional resources on ACC.

Experimental Drives

Scenarios and driving tasks were informed by Pradhan et al. (2020), who identified a number of edge-case scenarios based on limitations provided in the owner's manuals, and predicted errors during transitions between different states of a given ACC system.

Database

Simulator drives were completed on the NADS Springfield virtual database. This experiment used a segment of the freeway portion of the database, shown in Figure 8. The roadway consisted of portions of divided highway, with either two or four lanes of traffic traveling in the same direction. Light ambient traffic was present during periods between events. A lead vehicle was present during situations where the participant was asked to change the following gap.

Edge-Case Scenarios

The study drive included six edge-case scenarios (EC1-6) as shown on the map in Figure 8. The edge cases were a subset of possible situations that exceeded the capability of the ACC system. Participants encountered events in the same order. For most of the edge-case scenarios there were 1-2 vehicles in the left lane, making it more difficult for the participant to make a quick, evasive maneuver around the obstacle. Each of the scenarios is described in more detail below.

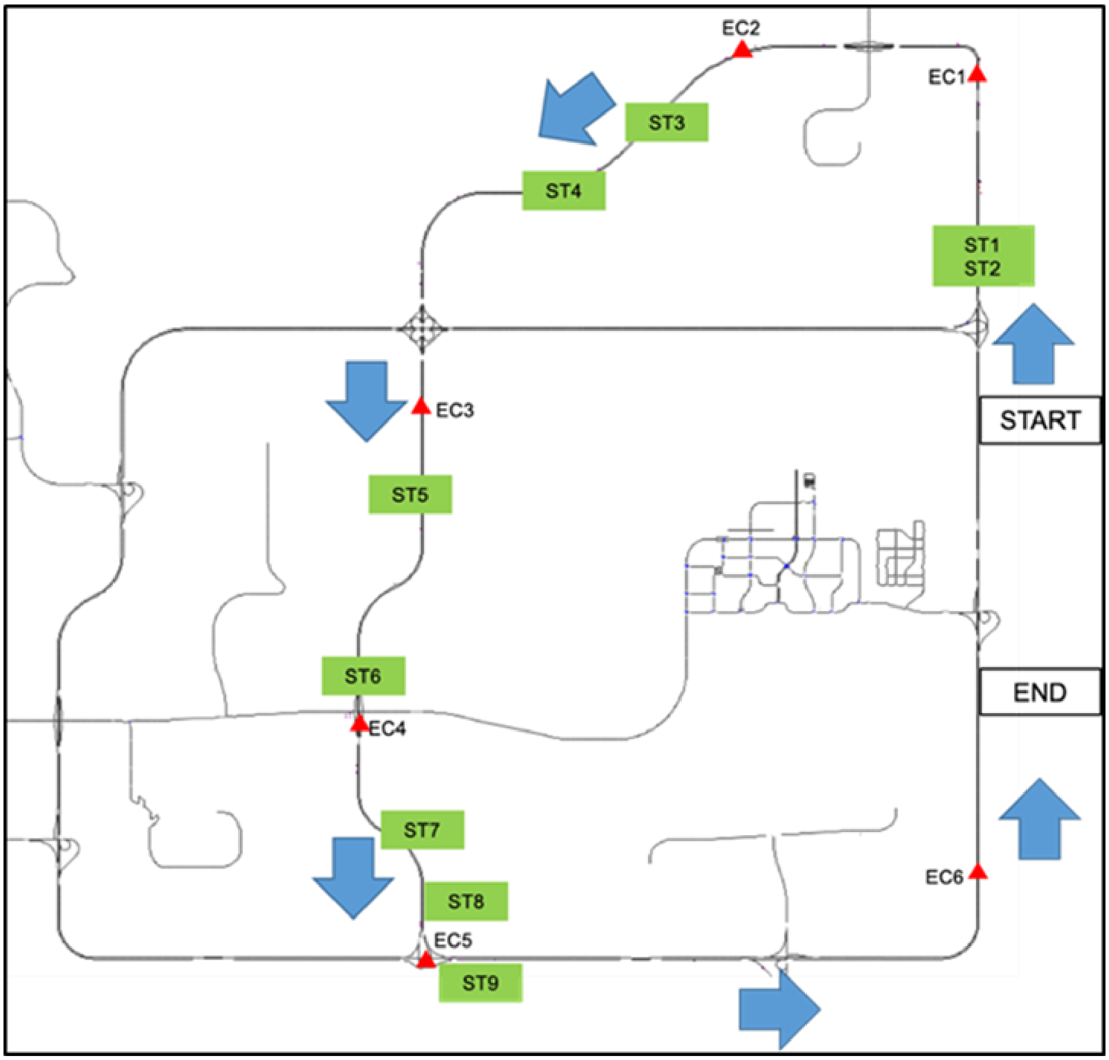


Figure 8. Map of study drive; ST = state transition and EC = edge case

Slow-Moving Vehicle (EC1). The participant vehicle was following the lead vehicle (LV) with the ACC speed set to 70 mph and a long following gap. The LV moved to the left lane to reveal a slow-moving vehicle (30 mph). Although the ACC system detected the slow-moving vehicle, to avoid approaching the slow-moving vehicle at a large and uncomfortable speed differential, the participant had to slow to wait for the left lane to clear to safely pass the slow-moving vehicle.

Slow-Moving Motorcycle (EC2). The participant vehicle was following LV at 65 mph (ACC speed set to 70 mph) when the LV moved to the left lane to reveal a slow-moving motorcycle. As ACC cannot always detect smaller vehicles, the simulation was designed to ignore the presence of the motorcycle, thus accelerating the participant vehicle to its set speed (70 mph). To avoid collision, the participant needed to slow down in order to allow the left lane to clear and safely pass the motorcycle (note that the drive was not stopped for collisions, but the simulator vehicle passed through other objects).

Work Zone (EC3). The participant vehicle was following LV at a set speed of 55 mph (see state transitions section below). The LV moved to the left lane to reveal a work zone in the right lane ahead. The participant needed to slow down to allow the left lane to clear and safely change lanes to avoid the work zone.

Fast-Moving Vehicle Merging On (EC4). The participant vehicle was travelling in the right lane with the ACC speed set at 60 mph and no LV ahead. Another vehicle was merging onto the roadway into the right lane while travelling at a higher speed than the participant vehicle. In this case, the participant did not need to intervene with the ACC system as the merging vehicle was ahead of the participant vehicle.

Slow-Moving Semi-Truck (EC5). This scenario occurred on a curved portion of a highway on-ramp. Prior to taking the on-ramp, the participant was instructed to move to the left lane and adjust the set speed to 45 mph. A slow-moving semi-truck appeared midway through the ramp in the right lane. As ACC cannot always properly detect lead vehicles on hills or curves, the ACC detected the semi-truck as being an LV in the participant vehicle's lane, thus incorrectly reducing the participant vehicle's speed until it had passed the semi-truck.

Offset Lead Vehicle (EC6). The participant vehicle (ACC speed set at 70 mph) followed the LV at 65 mph for about 6 minutes, at which point the LV drifted towards the right-hand shoulder. Similar to the Slow-Moving Motorcycle event (EC2), the simulation was designed to not detect the LV when it was offset in its lane as it was not positioned directly ahead of the participant vehicle. At this point, the participant vehicle's speed returned to 70 mph. The participant had to intervene in order to allow the traffic in the left lane to clear and safely pass the LV.

State Transitions

Five system states that the ACC system could be in were identified and are described in Table 4. Throughout the drive, participants were instructed to perform nine state transitions (ST1-9) as shown in green on the map in Figure 8. These prescribed state transitions are described in Table 5. Additionally, state transitions could arise as a result of driver inputs or reactions to the edge-case scenarios (e.g., to avoid a slow-moving vehicle revealed in the lane ahead). Drivers were not told what action to take in these situations, and in most instances, there were several potential responses (i.e., take no action, brake to put the vehicle in standby mode, use the ACC lever to put the vehicle in standby mode, or turn the system completely off using the ACC lever). Potential state transitions related to the edge cases are described in Table 6.

Table 4. Possible system states

System state	Description
0	ACC is off
1	ACC is on but no speed set (standby mode)
2	ACC is on with a set speed

Table 5. Description of prescribed state transitions during the experimental drive

	Instruction	Required Action	System State / Transition
ST1	Turn on ACC	Press ACC button	0 to 1
ST2	Set ACC speed to 70 mph	Press ACC lever down	1 to 2
ST3	Change following gap to Short	Press gap button on steering wheel twice	2
ST4	Change ACC speed to 55 mph	Press ACC lever down to decrease speed	2
ST5	Change ACC speed to 70 mph	Press ACC lever up to increase speed	2
ST6	Change ACC speed to 60 mph	Press ACC lever down to decrease speed	2
ST7	Change following gap to Long	Press gap button on steering wheel once	2
ST8	Change ACC speed to 45 mph	Press ACC lever down to decrease speed	2
ST9	Change ACC speed to 70 mph	Press ACC lever up to increase speed	2

Table 6. Description of potential state transitions during edge-case scenarios

	Description	Driver Action	System State / Transition
EC1	Slow-Moving Vehicle	Brake (puts system in standby)	2 to 1
		Put system in standby using lever	2 to 1
		Turn off using lever	2 to 0
EC2	Slow-Moving Motorcycle	Brake (puts system in standby)	2 to 1
		Put system in standby using lever	2 to 1
		Turn off using lever	2 to 0
EC3	Work Zone	Brake (puts system in standby)	2 to 1
		Put system in standby using lever	2 to 1
		Turn off using lever	2 to 0
EC4	Fast-Moving Vehicle Merging	No action	2
		Brake (puts system in standby)	2 to 1
		Put system in standby using lever	2 to 1
		Turn off using lever	2 to 0
EC5	Slow-Moving Semi	No action	2
		Brake (puts system in standby)	2 to 1
		Put system in standby using lever	2 to 1
		Turn off using lever	2 to 0
EC6	Offset LV	Brake (puts system in standby)	2 to 1
		Put system in standby using lever	2 to 1
		Turn off using lever	2 to 0

Results

Seventy-eight participants were assigned evenly into “strong” (N=39) and “weak” groups (N=39) based on the scores they received on the four-question screener. The “strong” group had 20 females and 19 males with an average age of 44. They reported an average of 29 years of driving experience. Prior to their participation, 18 had driven a vehicle equipped with ACC. Of those, 11 had owned the vehicle with ACC. When asked if they felt as though their knowledge of the functions and limitations of ACC had improved compared to what it was before their participation, 95% (37 out of 39) responded that it had. The “weak” group comprised 21 females and 18 males with an average age of 45. They also reported an average of 29 years of driving experience. Only three of the participants in the “weak” group reported having driven a vehicle equipped with ACC, and two of those had owned the vehicle. Even though they received limited information, compared to the “strong” group, 92% of participants (36 of 39) reported that they felt their knowledge of the functions and limitations of the ACC system had improved.

Data Reduction and Analysis

The percentage of correct responses on the mental model assessment, given to participants following their group-specific training, was calculated to arrive at an overall score as well as scores on specific items corresponding to the function and limitations of the ACC system. The open-ended questions required respondents to provide key words or ideas in order to receive credit for their answer.

Raw simulator data (sampled at 240 Hz) were reduced using custom MatLab scripts to generate summary statistics (e.g., ACC deactivation response time) for each event. For each driver, individual events were excluded if the setup failed (e.g., driver changed lanes just before the event) or if other aspects of the event functioned incorrectly (e.g., ambient traffic failed to maintain set gaps). Overall, 3% of individual events (10 of 320) were excluded from the analyses for these reasons. Furthermore, the analysis of edge cases excluded the slow-moving semi (EC5) event. Ad hoc review of simulator and video data from this event indicated inconsistent responses by the ACC system to this event, which made it difficult to understand subsequent driver responses.

Data from these events were analyzed using linear mixed effects models with the lme4 package in R (R Core Team, 2016). Linear mixed models have the advantage of adjusting effects for differences in sample size and missing data. Participant and Condition were entered as random effects. To control for differences in event timing, Event was entered as a fixed effect where appropriate. In all cases, p values were obtained by likelihood ratio tests comparing the full mixed model to a partial model without the effect in question (Bates, Maechler, Bolker, & Walker, 2015).

Mental Model Assessment

Figure 9 shows overall scores on the mental model assessment for the two groups. For the strong mental model group (N=38), overall scores ranged from 100% to 81% with an average of 93%. This group had an average score of 94% on the functionality of the ACC system and 92% on the limitations. The weak mental model group (N=39) had scores that ranged from 46% to 86% with an average of 66%. When broken down by knowledge type, the weak group had average scores of 79% about the functionality of the system and 47% on the limitations. These results strongly corroborate the differences between the two groups in terms of their knowledge and understanding of the ACC system.

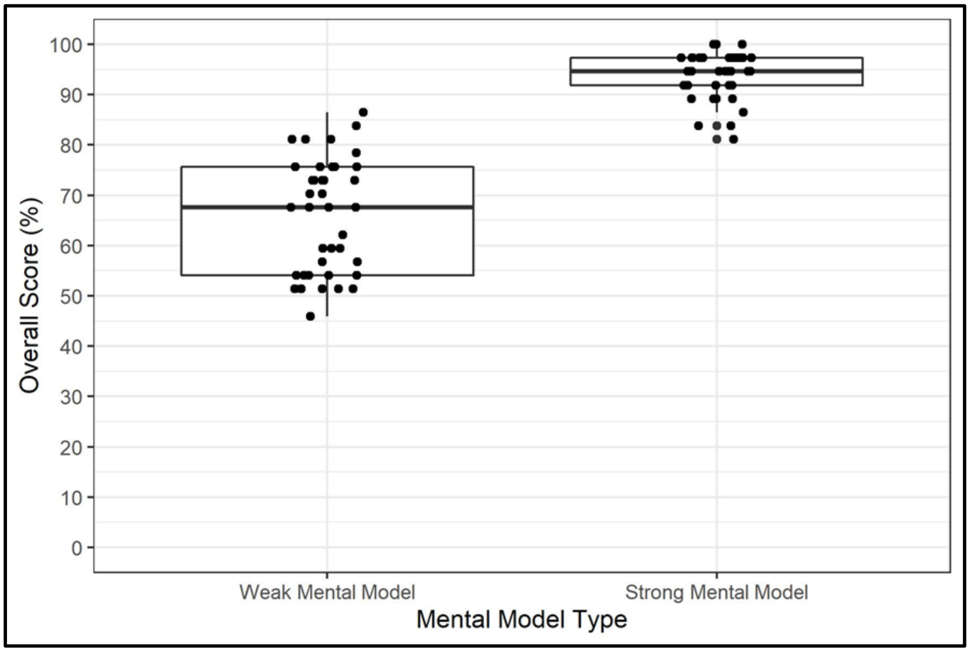


Figure 9. Mental model assessment overall scores

Edge-Case Scenarios

The edge-case events were classified based on whether the ACC was programmed to respond to the target object, such as the lead vehicle or work zone. Events were considered separately because the critical performance metrics differed as a function of how the ACC behaved in those situations. The flowchart in Figure 10 shows the process of identifying key measures (in blue) for different edge-case events and corresponding driver behaviors.

For three events, the ACC did not detect an upcoming object (Figure 10). This set of events included the slow-moving motorcycle, the work zone, and the offset vehicle. In these situations, it was first determined whether the driver had deactivated ACC; deactivation rates were then compared across mental model conditions. For participants who deactivated ACC, the key measure was deactivation time, again compared between the mental model groups. System deactivation was also examined in terms of the minimum approach distance to the target objects (with closer distances representing less safe conditions). For participants who did not deactivate ACC, the critical measure was the time it took to execute a lane change to avoid the edge-case object.

In one edge case, the slow-moving lead vehicle, the ACC system was programmed to be capable of detecting the approaching vehicle and maintaining a gap, albeit at a much-reduced speed from the original velocity (Figure 10). However, as noted, if drivers did not intervene, they approached at a high speed differential where it was unclear (to them) whether the ACC would successfully prevent a collision. System deactivation rates were compared across mental model groups. For participants who deactivated ACC, deactivation times and minimum approach distances were compared. For participants who did not deactivate ACC, the percentage who made a lane change to pass the slow-moving lead vehicle was compared to those who continued following the lead vehicle for the duration of the event.

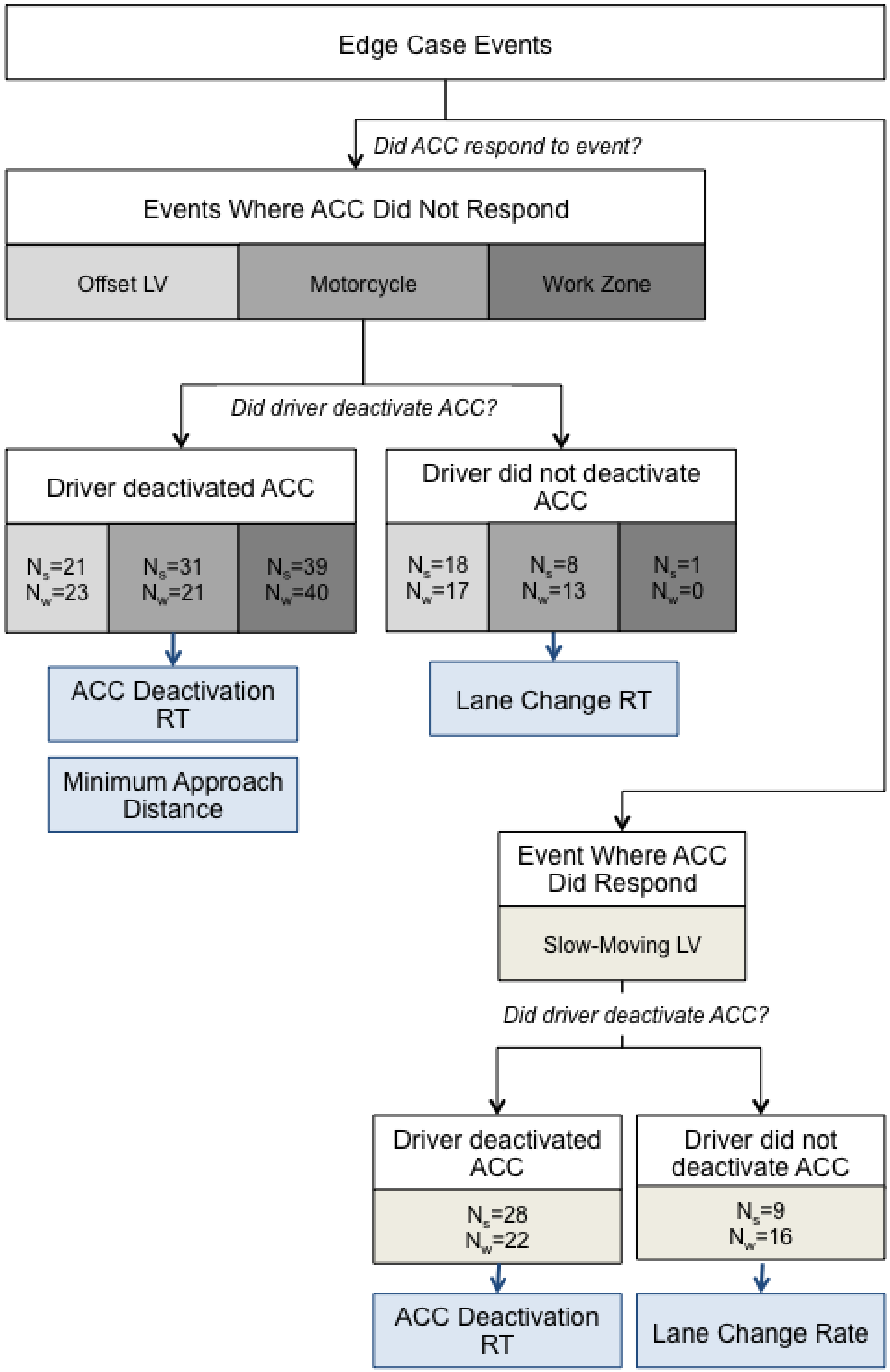


Figure 10. Response categorization and performance metrics (in blue). Values represent number of participants in each category; N_s = strong MM and N_w = weak MM.

Edge Cases where ACC Did Not Respond

Deactivation Rate. Figure 11 shows ACC deactivation rates (percent of participants) across the three events where ACC did not respond to the target object. For both the offset lead vehicle and the work zone event, deactivation rates among participants with strong versus weak mental models were similar to one another. In the slow-moving motorcycle event, participants in the strong mental model group were more likely to deactivate ACC than participants in the weak mental model group. It is also worth noting that deactivation rates were different across events. Nearly all participants deactivated ACC in the work zone event, whereas only 50-75% of participants deactivated ACC in the other two events.

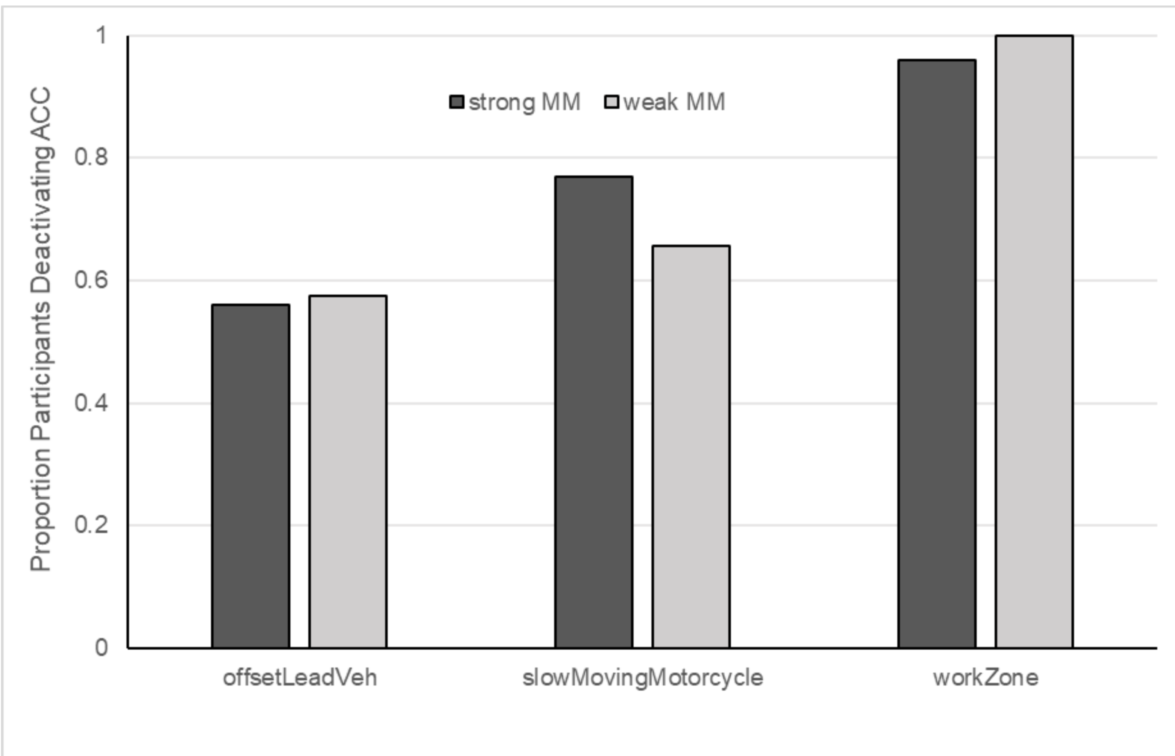


Figure 11. ACC deactivation rates in edge-case events where ACC did not respond

Deactivation Response Time. ACC deactivation response times were computed across these three events. Note that this only includes participants who deactivated ACC. Because the event start locations and time windows varied by event and were somewhat subjective, it is difficult to compare raw response times across events. However, the key question was whether drivers in the strong mental model group deactivated ACC earlier than drivers with weak mental models. As shown in Figure 12, mental model affected ACC deactivation time, $\chi 2(1) = 3.30$, $p = .07$. Participants with weak mental models were slower to deactivate ACC than participants with strong mental models across all three edge-case events. The minimum approach distance to the target object was also computed for each event type (Figure 13). Shorter distances indicate that participants came closer to colliding with the object. As with deactivation time, mental model affected minimum distance, $\chi 2(1) = 4.05$, $p = .04$, such that approach distances were shorter for participants in the weak mental model group than in the strong mental model group. It is also worth noting that collisions with the target object were more frequent for participants in the weak mental model group than in the strong mental model group (although overall few collisions (8) occurred). One participant in the strong mental model group collided with the offset lead vehicle. Five participants in the weak mental model group and two in the strong mental model group collided with the slow-moving motorcycle. No participants collided with the work zone.

Lane Change Response Time. For participants who did not deactivate ACC, we calculated the time until a lane change was executed. Because ACC was active but did not detect the event object, a lane change was necessary to avoid colliding with the offset lead vehicle or slow-moving motorcycle. This analysis excluded the work zone event, where all but one participant deactivated ACC. Lane change times are shown in Figure 14. Lane change time was not significantly affected by mental model group, $\chi 2(1) = 2.56$, $p = .11$; however, nominally, drivers with weak mental models were slower to initiate the lane change.

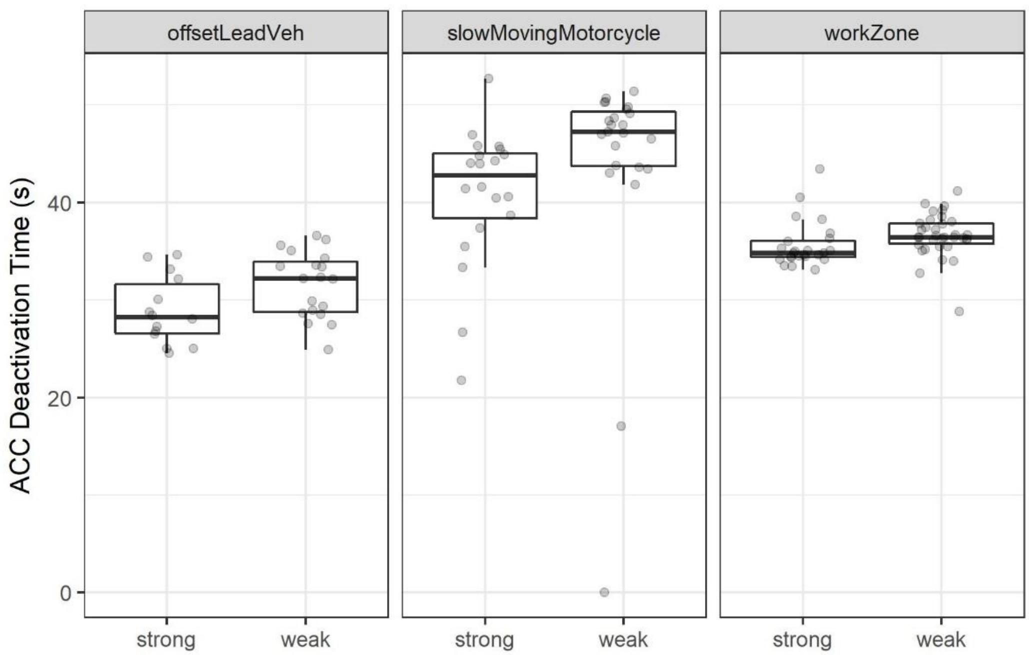


Figure 12. ACC deactivation time for edge-case events where ACC did not respond

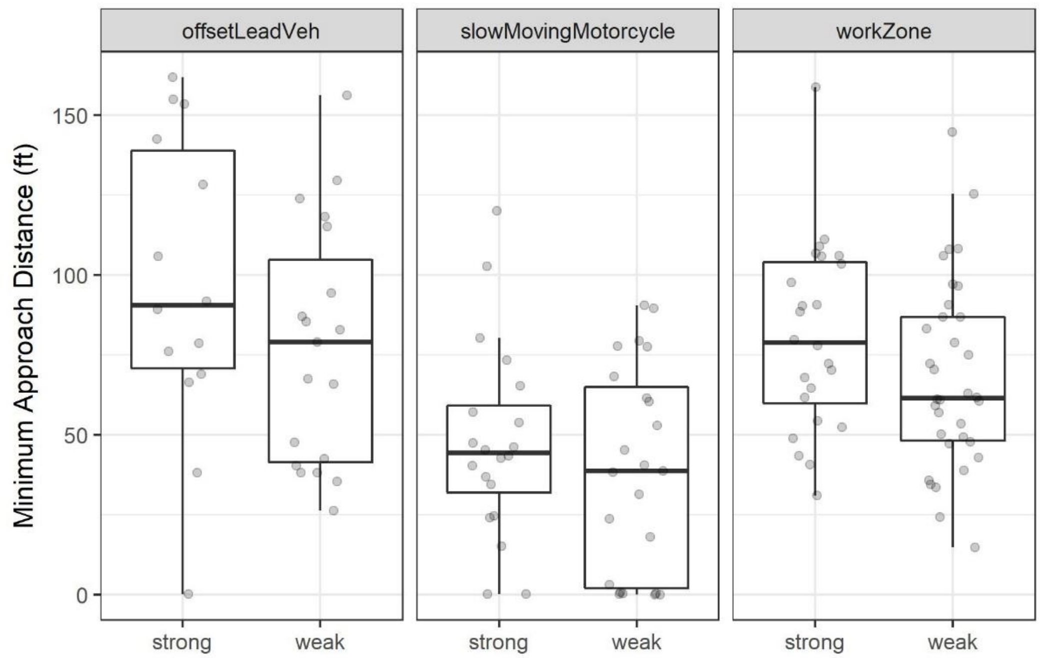


Figure 13. Minimum approach distance for edge-case events where ACC did not respond

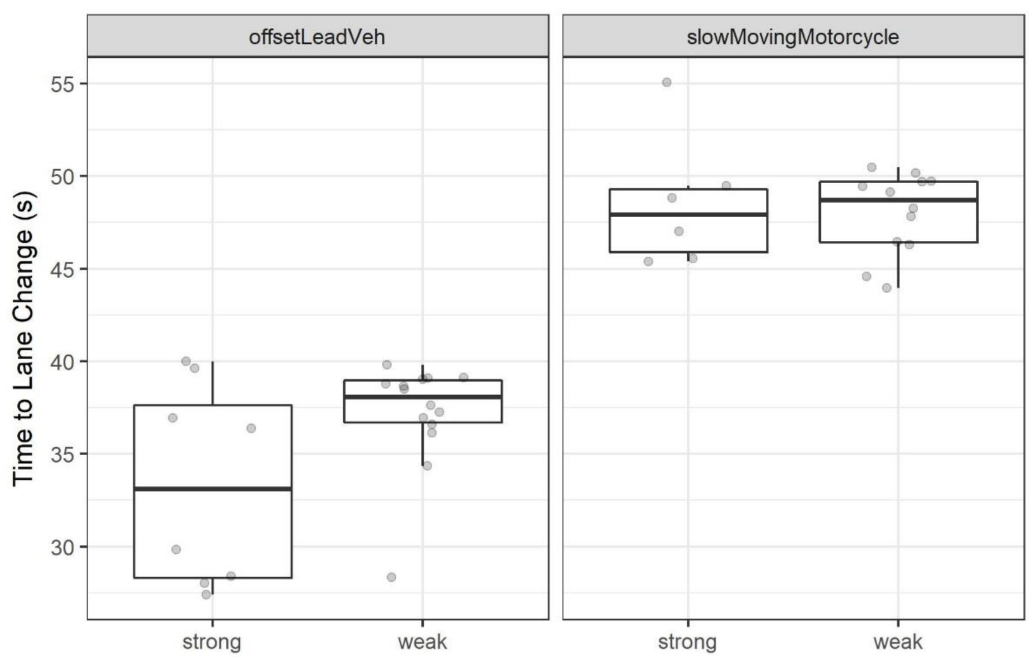


Figure 14. Time to lane change for edge-case events where ACC did not respond

Edge Cases where ACC Responded

Deactivation Rate. Figure 15 shows ACC deactivation rates (percent of participants) for the slow-moving lead vehicle event, in which the ACC did respond to the target vehicle by starting to slow the participant's vehicle. Participants in the weak mental model group were less likely to deactivate ACC during the event than were participants in the strong mental model group.

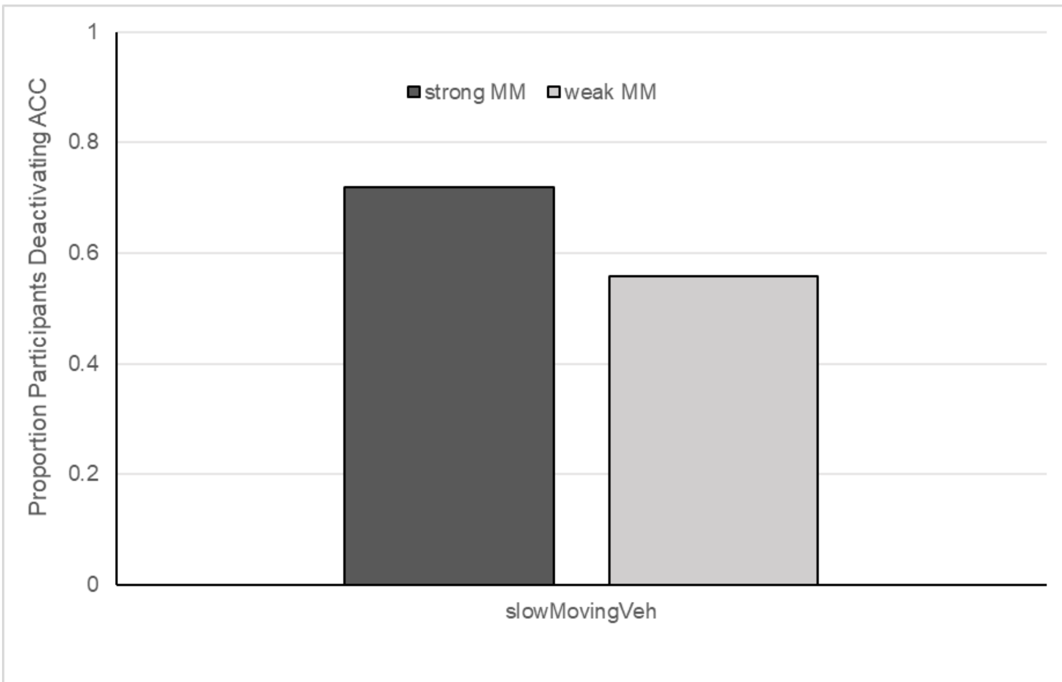


Figure 15. ACC deactivation rates for the edge-case event where ACC responded

Deactivation Response Time. For participants who deactivated ACC, we calculated ACC deactivation times from the start of the event, shown in Figure 16. An independent samples t-test indicated there was not a significant difference in ACC deactivation times between the strong and weak mental model groups, $t(48) = 0.58$, $p = 0.57$.

Lane Change Response Time. Of the 25 participants who did not deactivate ACC (N = 9 strong and 16 weak, respectively), 17 executed a lane change and 8 did not (N = 6 of 9 in the strong mental model group and 11 of 16 in the weak mental model group executed lane changes, respectively). Lane change response times for participants who did not deactivate ACC in the slow-moving lead vehicle event are shown in Figure 17. The difference in lane change response times between participants in the strong and weak mental model groups was not significant, $t(15) = 0.42$, $p = 0.68$.

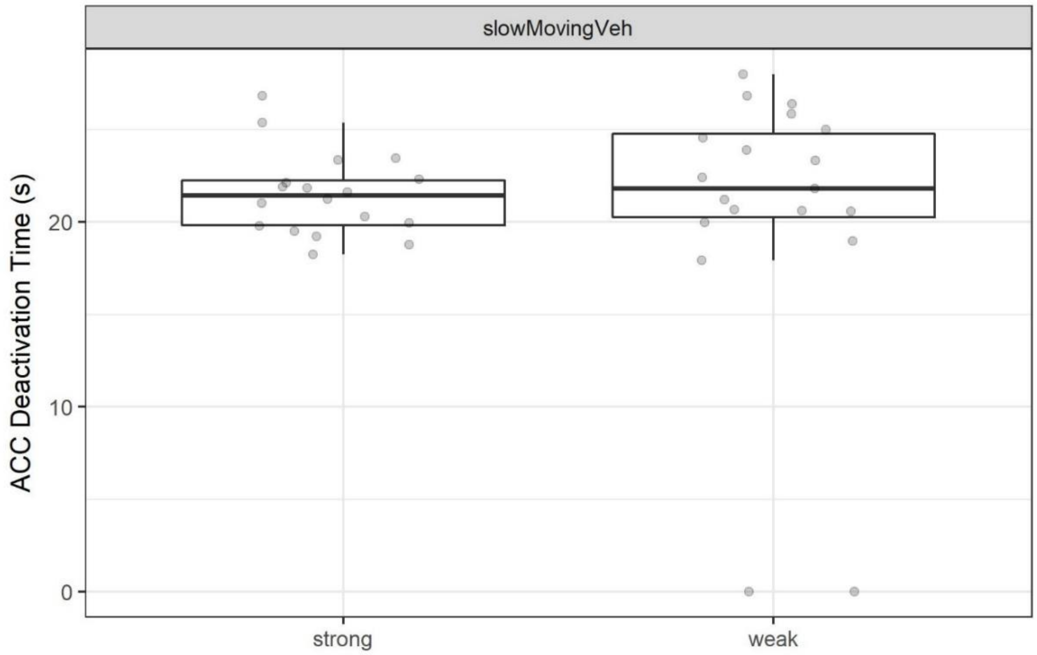


Figure 16. ACC deactivation times for participants who deactivated ACC in the edge-case event where ACC responded

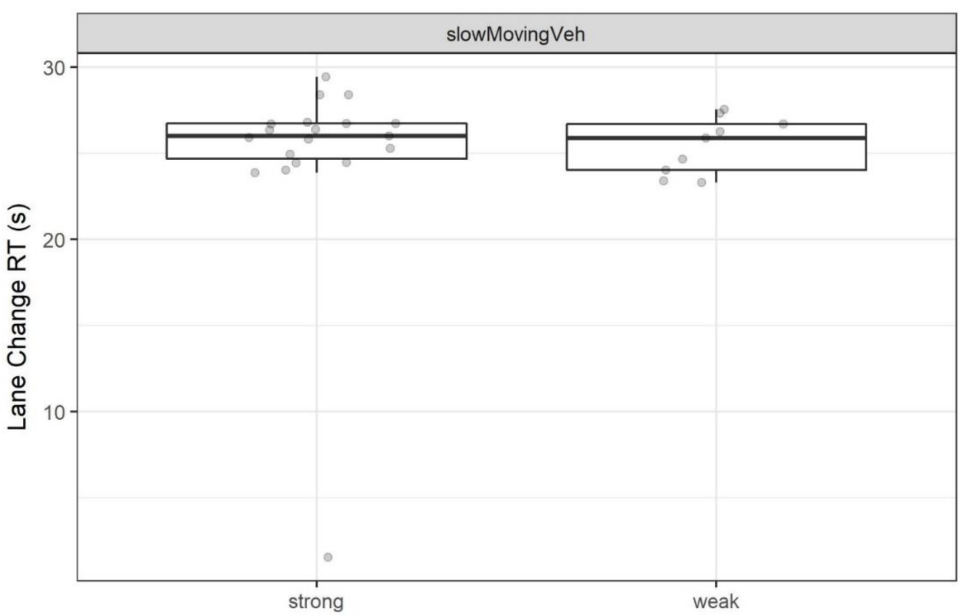


Figure 17. Lane change response times for participants who did not deactivate ACC in the edge-case event where ACC responded

Relationship between Mental Model Assessment and Performance

The mental model assessment was used primarily to measure the differences between the two groups after the manipulation of mental model quality. However, an additional research question was whether performance on the mental model assessment could predict performance in the edge-case events. The correlation between overall mean scores on the questionnaire and ACC deactivation times was computed for each event (only including participants who responded by deactivating ACC).

For edge-case events where the ACC system did not respond, there were significant negative correlations ($r = -0.31$, -0.35, and -0.36 on the offset lead vehicle, motorcycle, and work zone events, respectively) between scores on the questionnaire and ACC deactivation time, shown in Figure 18 (all $p < 0.04$). Higher scores on the mental model assessment were associated with faster ACC deactivation time in the edge-case events. On the other hand, for the slow-moving lead vehicle event where ACC responded, there was not a significant correlation between scores on the questionnaire and ACC deactivation time ($p = 0.91$), as shown in Figure 19.

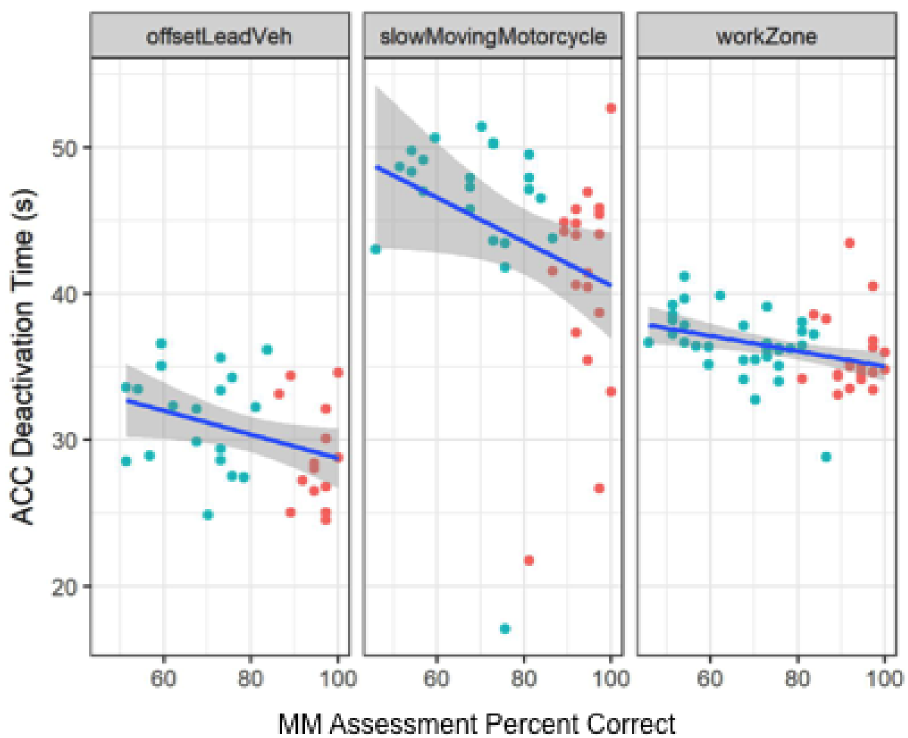


Figure 18. ACC deactivation by questionnaire percent correct for edge-case events where ACC did not respond. Colors indicate MM group (red = strong MM; blue = weak MM).

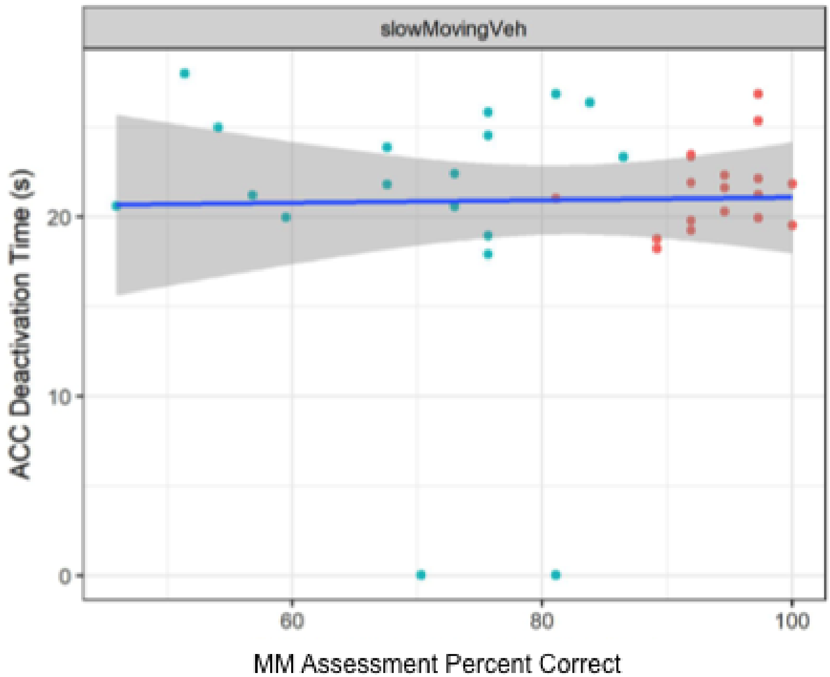


Figure 19. ACC deactivation by questionnaire percent correct for events where ACC responded. Colors indicate MM group (red = strong MM; blue = weak MM).

Discussion

This study was one of the first to explore the relationship between the quality of drivers' mental models of ADAS and objective measures of driving safety and performance. The project used a unique combination of methods to first establish and measure differences in mental models of ACC and then to evaluate the impact of these differences.

Most importantly, differences in mental model quality clearly impacted driving safety and performance. In edge-case situations where the ACC did not respond, among drivers who deactivated ACC, drivers with strong mental models were faster to deactivate ACC and maintained safer gap distances (i.e., minimum approach distance) than drivers with weak mental models. ACC deactivation times for these edge-case events were correlated with scores on the mental model assessment; stronger mental models as indicated by higher questionnaire scores were associated with faster ACC deactivation. Among drivers who did not deactivate ACC in these events, drivers with weak mental models were nominally slower than drivers with strong mental models in changing lanes to avoid the hazard. Thus, whether drivers deactivated ACC or not, a strong mental model conferred performance benefits relative to a weak mental model.

The most likely explanation for these differences in ACC deactivation rates is a difference in expectations between the two mental model groups. It was clear, based on questionnaire results, that participants in the strong mental model group understood at least some of the edge cases for the ACC system. It seems these participants were able to extrapolate this understanding to events in the simulator. On the other hand, participants with weak mental models had a poor understanding of how the ACC system would behave in these situations and were therefore slower to recognize that the ACC system was not responding to the edge-case event. Consequently, drivers with weak mental models were slower to take the actions needed to maintain safety (e.g., deactivating the ACC or steering). Such delayed responses forced these participants into less safe situations, as reflected by the closer approach distances compared to those of the strong mental model group.

Similar effects have been observed in studies of driver interaction with automation and linked to differences in driver expectation. Victor and colleagues (2018) found that some drivers of a more highly automated vehicle simply did not respond to an object in the road despite actually looking at the object several seconds prior to the collision (Victor, Tivesten, Gustavsson, Johansson, Sangberg, & Ljung Aust, 2018). The authors attribute this effect to uncertainty around whether the automated driving system will respond (i.e., a weak mental model).

It is worth noting that these performance differences were not as apparent in the edge-case situation where the ACC did respond to a slow-moving vehicle. The differences in both ACC activation times and lane change response times were not significant. Participants with strong mental models were, however, more likely to deactivate ACC than participants with weak mental models. If participants did not deactivate ACC, the vehicle maintained a gap but traveled at a much slower speed than surrounding traffic. It could be argued that following at this increased speed differential could create an unsafe situation. However, it is worth reiterating that the lack of a deactivation response or lane change was not safety-critical in the slow-moving vehicle event, and therefore it is difficult to say that one response was safer than another.

Another key contribution of this research is the development of the Mental Model Assessment to classify the quality of a driver's mental model of ACC. The questionnaire includes two critical components of mental models: knowledge of the function and the limitations of an advanced vehicle system. This questionnaire method builds on existing research that used survey instruments to evaluate drivers' mental models. One component of these methods that seems particularly important is the inclusion of hypothetical situations (e.g., Beggiato, 2014). Participants are asked how the system is likely to behave in particular situations and why. Such items appear efficacious in determining understanding of how the ADAS will behave in edge-case situations. Similar questionnaire methods could be used to measure mental models "in the wild," as drivers develop mental models of real-world systems. Indeed, the next stage of this research will use this method to track mental models of new vehicle owners over the first six months of interaction with ACC and other advanced features.

One unanswered question that is important in light of the present results is how drivers typically form mental models and when mental models go from weak to strong. Although most drivers learn predominantly through experience, trial and error alone is insufficient for forming robust mental models (Beggiato & Krems, 2013; McDonald et al., 2018; Piccinini et al., 2015). This suggests that many drivers, although they have significant ADAS experience, may actually have impoverished mental models that could pose risks to safety, particularly in rare edge-case events. If additional training on ADAS technology is necessary, how comprehensive does training need to be, and what form should the training take to yield sufficiently strong mental models? It is worth noting that a modest amount of information provided in the current study concerning the function and limitations of ACC was sufficient to incur large group differences in mental model and, subsequently, performance (although there were also some a priori differences that cannot be disentangled).

Another set of questions revolves around the methods for training driver mental models of ADAS. The training provided in this study consisted of several points and formats (presentations, in-vehicle training), and additional research is needed to understand the unique contribution of each of these components to the quality of resulting mental models (cf. AAAFTS 2018; 2019; 2020). The answer to this question could help inform where and how training is provided to new vehicle owners. Additionally, future research could determine the impact of this type of training for drivers with varying mental models coming into training. Randomly assigning participants to mental model conditions and determining how training shifts existing mental models could address this question.

Several limitations are worth mentioning. One unanswered question is how much of the mental model was brought into the lab compared to how much was altered by the training. More research is needed to understand the impact of different facets of the training protocol and to understand how incoming mental models influenced the results. The study also included only a subset of potential edge-case situations. Future research should expand the range of edge cases to fully understand the impact of mental models on performance. Furthermore, additional analyses using this and similar datasets could help researchers understand how drivers interact with ADAS technology during nominal driving situations and how mental models might influence these interactions.

This study provides an important first step in linking the quality of mental models to driving performance in realistic driving scenarios. While much research is needed to elucidate the processes involved in mental model development and best practices for efficiently setting mental models, these results provide insight into how driver understanding of advanced vehicle technology can manifest in important behavioral differences during a variety of safety-critical events. These challenges will become more prominent as vehicle automation technology continues to evolve and increase in complexity.

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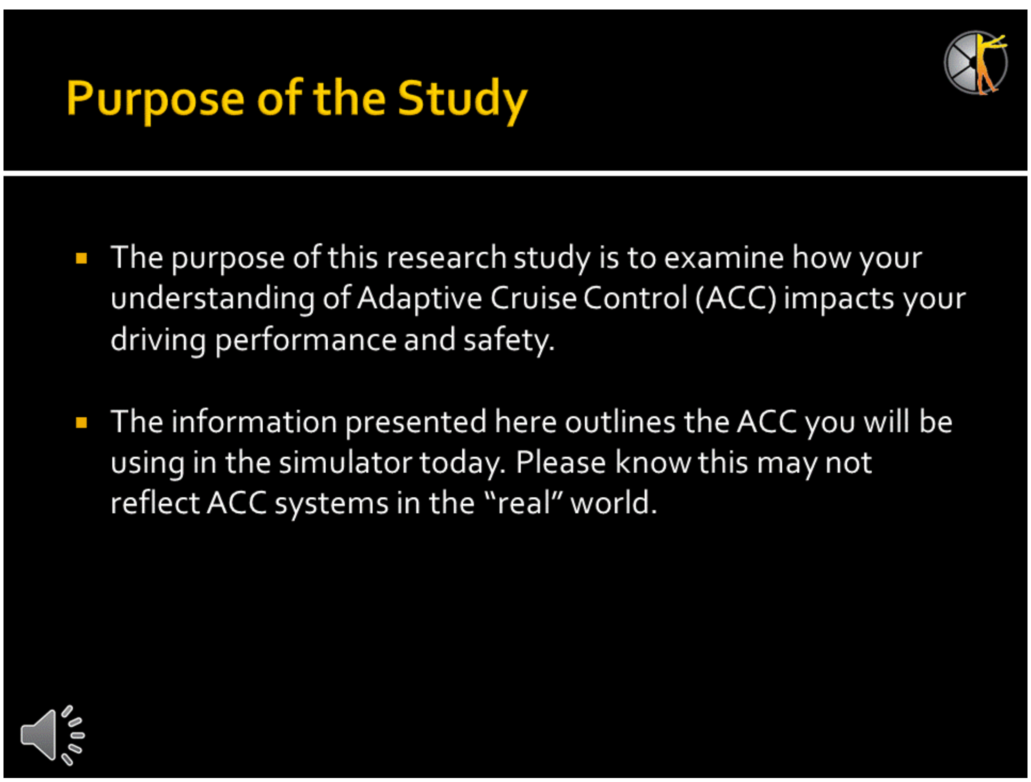
Appendix A

Training Presentation for Weak Group



Adaptive Cruise Control (ACC)

- Assists the driver with maintaining a set speed and a set gap from the vehicle in front of them.
- If no vehicle is detected, the system works like conventional cruise control and maintains a set speed. If you, the driver, encounter a vehicle travelling slower, the ACC will reduce your vehicle's speed and maintain the fixed gap between your vehicle and the vehicle ahead. When the slower moving vehicle is no longer in front of you, the system will accelerate your vehicle in order to resume the set speed.

Steps to Activate ACC

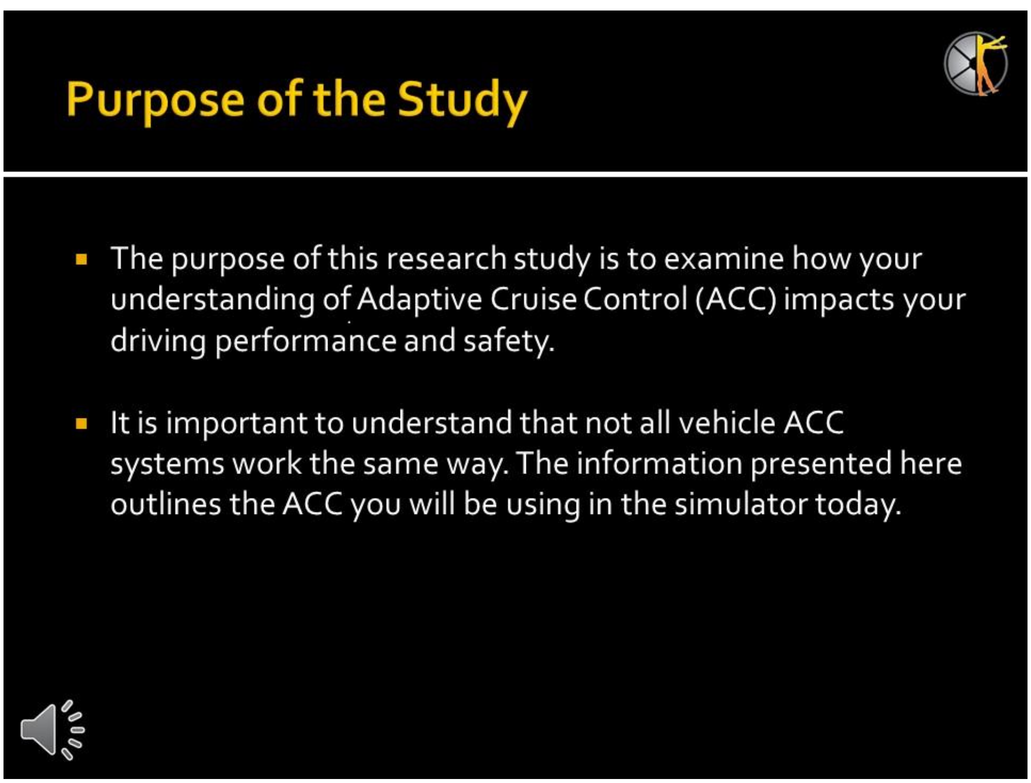
1. Press the 'On-Off' button on the end of the lever to turn ACC 'On'.
2. Press the ACC lever down to set the ACC speed (ACC activated).
3. To adjust speed, press lever up or down in direction needed.
4. To adjust following gap, press the button on the steering wheel.

Steps to Cancel & Resume ACC

- To cancel ACC (no longer active): 3 methods
  - Pull the ACC lever toward you
  - Press the brake
  - Press the ACC 'On-Off' button
    - To resume from the 'Off' state, you will need to push the 'on-off' button, then set speed and following gap.
- To place ACC in 'Standby' rather than 'Off':
  - Pull the ACC lever toward you or press the brake pedal
  - To resume ACC from the standby state, push the ACC lever up

Appendix B

Training Presentation for Strong Group



Adaptive Cruise Control (ACC)

- Assists the driver with maintaining a set speed and a set gap from the vehicle in front of them.
- If no vehicle is detected, the system works like conventional cruise control and maintains a set speed. If you, the driver, encounter a vehicle travelling slower, the ACC will reduce your vehicle's speed and maintain the fixed gap between your vehicle and the vehicle ahead. When the slower moving vehicle is no longer in front of you, the system will accelerate your vehicle in order to resume the set speed.

Adaptive Cruise Control (ACC)

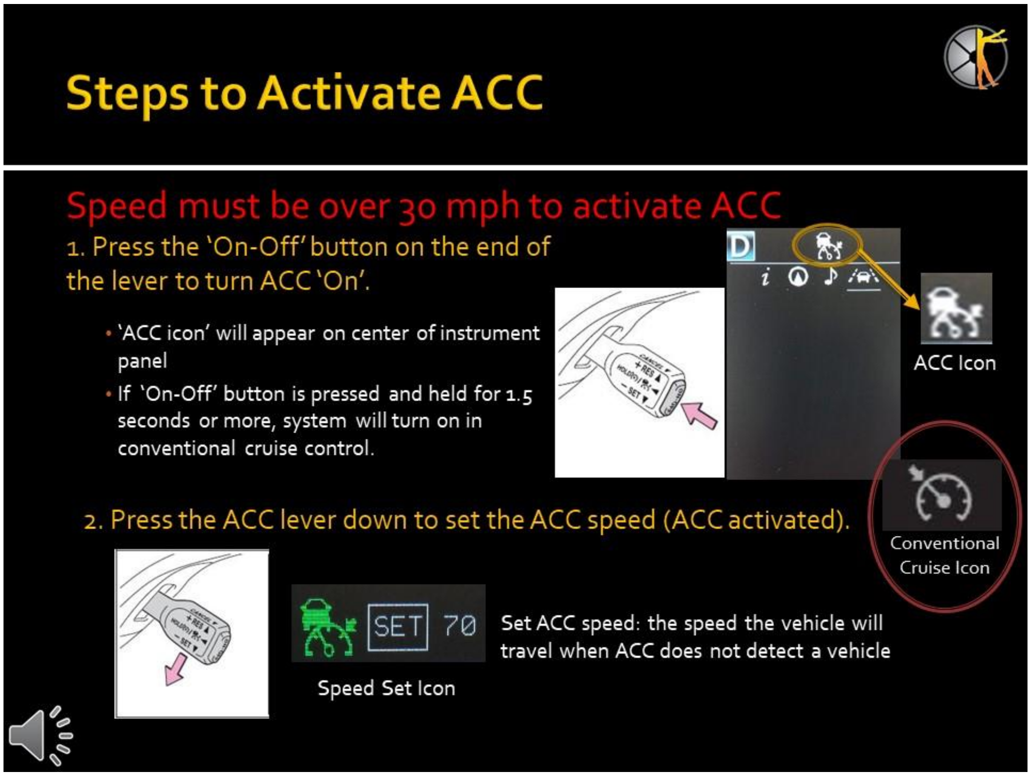
- The driver selects the following gap and can adjust it whenever ACC is activated.
- ACC can be activated at speeds of 30 mph and above.
- If the accelerator is pressed when ACC is activated (set speed), it will not be able to brake to keep you within the desired set following gap.
- ACC is primarily intended for driving on dry, straight roads, such as highways and freeways. It should <u>not</u> be used on city streets or when traffic is constantly changing.

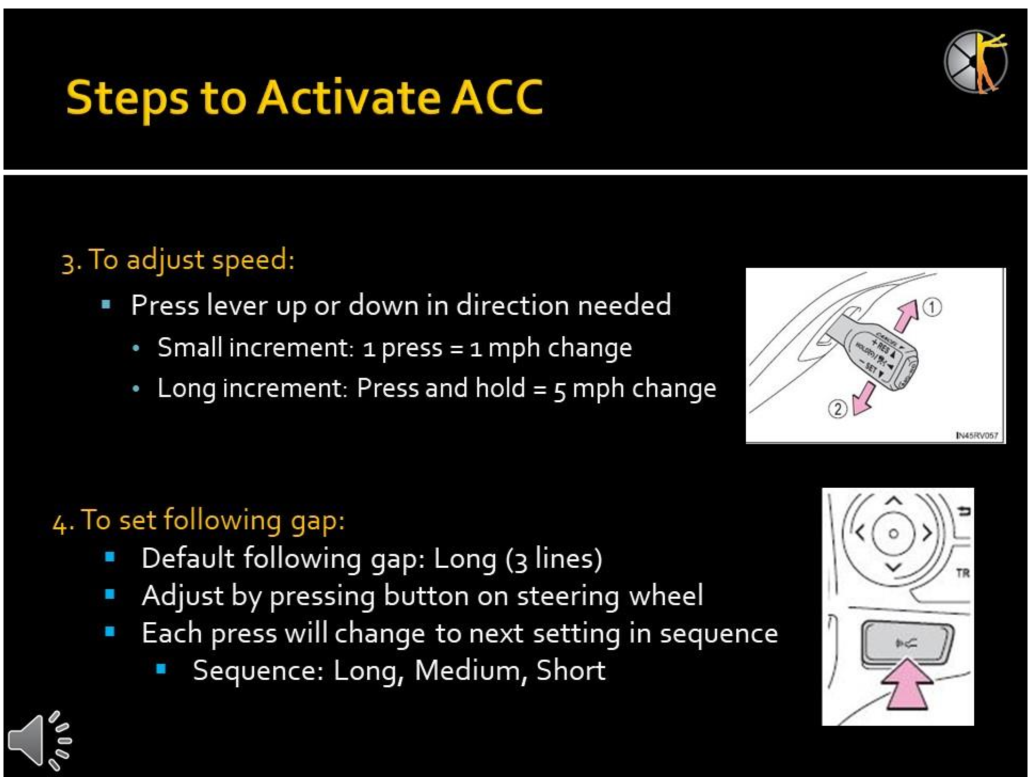
Adaptive Cruise Control (ACC)

- ACC typically uses radar to detect vehicles in front of you and to estimate the following gap.
- ACC may not detect a vehicle even when a vehicle is present in the lane ahead:
    - Roadway elevation changes
    - Turning vehicles
    - Smaller vehicles like motorcycles
    - Vehicles not in the center of the lane ahead

Adaptive Cruise Control (ACC)

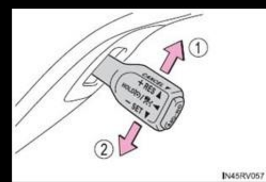
- ACC may not work effectively if the sensors or camera become blocked by dirt, moisture, or other material.
- ACC can only provide a limited amount of braking. The driver must apply the brakes in situations that require immediate braking or harder braking than the system can provide.


Steps to Activate ACC
Speed must be over 30 mph to activate ACC
1. Press the 'On-Off' button on the end of the lever to turn ACC 'On'.
• 'ACC icon' will appear on center of instrument panel
• If 'On-Off' button is pressed and held for 1.5 seconds or more, system will turn on in conventional cruise control.
ACC Icon
Conventional Cruise Icon
2. Press the ACC lever down to set the ACC speed (ACC activated).
SET 70
Speed Set Icon
Set ACC speed: the speed the vehicle will travel when ACC does not detect a vehicle


Steps to Activate ACC
3. To adjust speed:
▪ Press lever up or down in direction needed
• Small increment: 1 press = 1 mph change
• Long increment: Press and hold = 5 mph change
4. To set following gap:
▪ Default following gap: Long (3 lines)
▪ Adjust by pressing button on steering wheel
▪ Each press will change to next setting in sequence
▪ Sequence: Long, Medium, Short

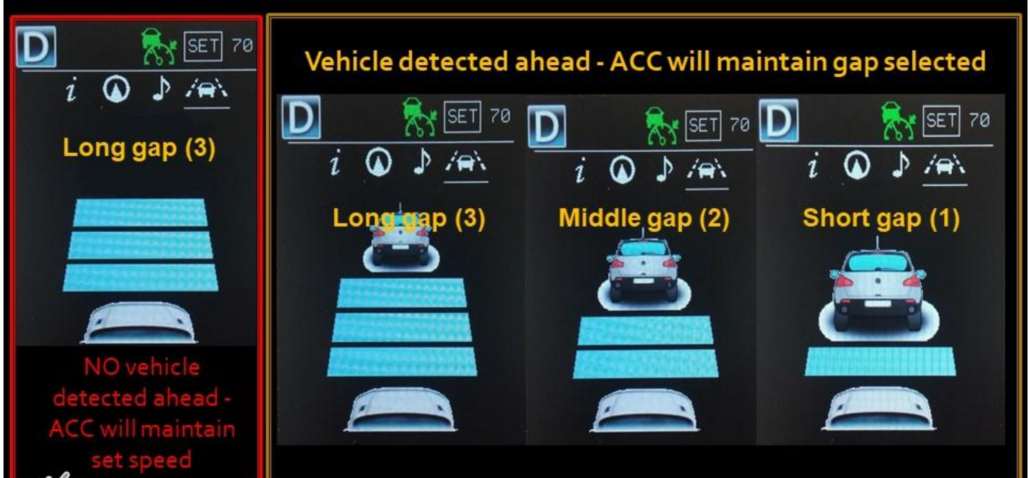
Steps to Activate ACC

3. To adjust speed:
   - Press lever up or down in direction needed
     - Small increment: 1 press = 1 mph change
     - Long increment: Press and hold = 5 mph change



4. To set following gap:
   - Default following gap: Long (3 lines)
   - Adjust by pressing button on steering wheel
   - Each press will change to next setting in sequence
     - Sequence: Long, Medium, Short

Instrument Panel: Following Gap Setting



Steps to Cancel & Resume ACC

- Three ways to cancel ACC: ACC lever, brake press, or ACC 'On-Off' button

- ACC to 'Standby'
  - Pull the ACC lever toward you or press the brake pedal

  ** To RESUME previous ACC settings, push the ACC lever UP**

- ACC to 'Off'
  - Press ACC 'On-Off' button

  ** To reactivate ACC: push the ACC 'On-Off' button, set the speed by pressing the lever DOWN, press the gap button to adjust following gap from default long gap if desired**

ACC Summary

Speed must be over 30 mph to activate ACC

<u>Steps to Activate ACC</u>

1. Turn ACC 'On-Off': Press button on end of ACC lever
2. Set max ACC speed: Press ACC lever DOWN
3. Adjustments to speed: Press ACC lever up or down in direction needed
4. Set following gap: Press button on steering wheel (default gap: long)

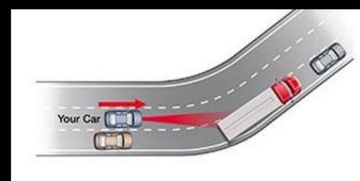
<u>Cancel & Resume ACC</u>

ACC to 'Standby': RESUME previous ACC settings = Press ACC lever UP

ACC to 'Off': Reactivate ACC = Need to RESET the ACC settings using the 4 steps listed above

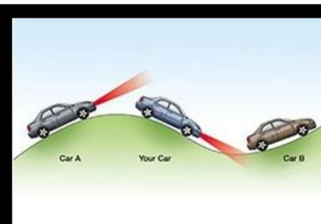
ACC Limitations

ACC uses a radar system to detect vehicles directly in front of you. Radar may identify traffic in another lane and may **NOT** always be able to detect vehicles in your lane. This occurs because vehicles may or may not be in the radar's field of view.



ACC behavior may respond differently in these and other situations:

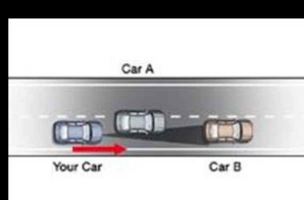
- Sharp curves
- Turning vehicles
- Roadway elevation changes/hills
- Extremely slow moving vehicles

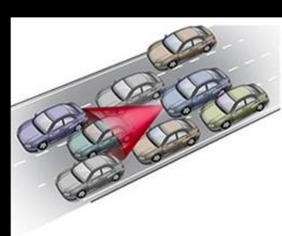


ACC Limitations

ACC behavior may respond differently in these and other situations:

- Merging vehicles
- Smaller vehicles like motorcycles
- Vehicles not in the center of the lane ahead
- Heavy traffic with frequent repeated acceleration & deceleration
- Stopped vehicles or objects in the road (construction cone, tire, ball)
- Poor weather conditions (e.g., fog, snow, rain, ice) = covered sensors





Appendix C

Mental Model Assessment

The following questions will ask you about your current understanding of Adaptive Cruise Control (ACC). You may have previous experience with ACC systems, but it is important that you focus on the information provided and drives experienced today to answer these questions. For each question, please indicate whether the statement is "True" or "False". Please answer the following questions regarding ACC.

The statement about ACC is…	True	False
Maintains the speed that you have set when there are no vehicles detected in the lane ahead	❍	❍
Brakes and accelerates to maintain a following gap from the vehicle ahead	❍	❍
Adjusts the speed to match faster vehicles ahead	❍	❍
Will accelerate if a slower vehicle ahead moves out of the detection zone	❍	❍
Will provide steering input to keep the vehicle in its lane	❍	❍
Will correctly detect motorcycles and other smaller vehicles not driving in the center of the lane	❍	❍
Is meant to be used on highways and interstates	❍	❍
May not correctly detect stopped vehicles in your lane	❍	❍
Reacts to stationary objects on the road (construction cone, tire, ball)	❍	❍
Works well on curvy roads and hills	❍	❍
Is meant to be used in slow and heavy traffic	❍	❍
Adjusts the speed when there are slower moving vehicles detected ahead	❍	❍
Will react immediately to vehicles merging onto the road in front of you	❍	❍
Reacts to oncoming traffic	❍	❍
Adjusts the vehicle speed when approaching tight curves	❍	❍
Is meant to be used on rural roads	❍	❍
May not correctly detect vehicles ahead travelling at much slower speeds	❍	❍
Works even when the radar sensor is dirty	❍	❍
Can be activated at a standstill	❍	❍
Can handle operating in all weather conditions	❍	❍

The following questions ask about how to operate the ACC system in the simulator. It is important that you focus on the information we have provided and the drives you have experienced today to answer these questions. Please type your response in the space provided.

How do you activate ACC when it is "Off"?

____

When ACC is active, how do you adjust the speed setting?

____

In how many mph increments does the ACC increase or decrease when the lever is held?

____

How do you change the following gap setting for the ACC?

____

From the "Off" state, when ACC is activated by setting the speed, what is the default following gap setting?

____

How many following gap settings are available and what are they called?

____

What two ways can you interrupt/cancel ACC and put it into "Standby" mode?

____

When ACC is in "Standby", what one step allows you to resume the previously set max speed and gap immediately?

____

Below is an example of the ACC display seen in the simulator today. Use this to answer the following questions.

Is the ACC activated?

- ◯ Yes
- ◯ No

What is the following gap set to?

____

Is there a vehicle detected in front of you?

____

Is the speed set?

- ◯ Yes
- ◯ No

What is the speed?

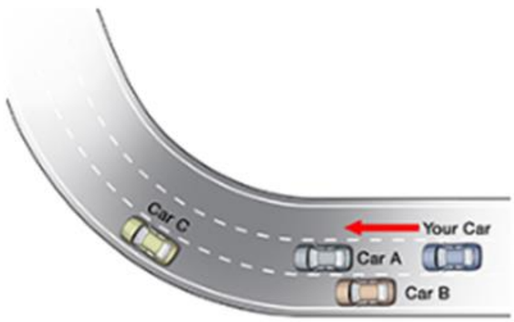
____

What does the icon below indicate?

____

You will now be presented with three potential situations while driving with ACC activated (set speed and following gap). Please look at the illustration provided and think about how the ACC system will behave in the situation and explain why it will behave that way. Each scenario will be presented on a separate page and you will not be able to go back to a previous page. If you are unsure of your response, please feel free to type "I do not know" in the space provided.

Imagine yourself driving the blue vehicle, labeled "Your Car". Use this to answer the questions shown below.



How might your ACC system behave in this situation? Why?

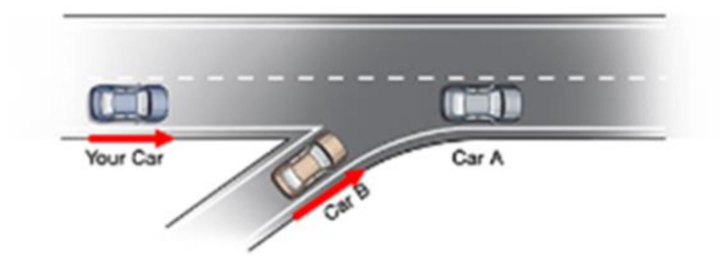
____

Look at the scenario in the image below. Imagine yourself driving the blue vehicle, labeled "Your Car". Use this to answer the questions shown below.

How might your ACC system behave in this situation? Why?

____

Look at the scenario in the image below. Imagine yourself driving the blue vehicle, labeled "Your Car". Use this to answer the questions shown below.



How might your ACC system behave in this situation? Why?

____