Quantifying Drivers' Use of In-Vehicle Systems: Implications for Long-term Behavior

Huimin Xiong

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Reading Committee:

Linda Ng Boyle, Chair

Zelda B. Zabinsky

Christina M. Mastrangelo

Quizi (Cynthia) Chen

Program Authorized to Offer Degree:

Industrial and Systems Engineering

University of Washington

Abstract

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Huimin Xiong

Chair of the Supervisory Committee:

Associate Professor Linda Ng Boyle

Industrial & Systems Engineering, Civil & Environmental Engineering

The modern day vehicles encompass many in-vehicle Intelligent Transportation Systems (ITS), which can provide continuous feedback to drivers but do require an understanding of the driver, system, and vehicle interactions. A conceptual model of adaptive behavior was developed and used as a framework for the analysis of operators' responses to one such ITS: Adaptive Cruise Control (ACC). Data from both observed (i.e., real world setting) and controlled (i.e., driving simulator) studies was used to examine drivers' adaptation to ACC (novice and experienced users) based on their experience gained and the effectiveness of the system algorithm. The overall goal was to use a systems approach to identify how adaptation to and functionality of the system might affect driving performance and overall safety. The findings of this dissertation revealed several underlying environmental (roadway type) and driver factors (selected settings, speed, and age) that influence drivers' responses. The drivers were further segmented based on their use of the ACC: risky, moderately risky, and conservative. System effectiveness was evaluated by quantifying attention placed on controllers (ACC and drivers) to hazardous situations from internal and external factors. The combined outcomes provided insights on driver differences and system effectiveness that should be considered by designers, engineers, and policy makers.

TABLE OF CONTENTS

List of Figures

List of Tables

Dedication

To my parents, who have been there for me from day one. Thank you for all of the love, support, encouragement and dedication.

To my husband, who has been there for me for the last nine years. Thank you for all of your love and support.

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Introduction

Behavioral adapation, when defined by transportation psychologists, describes the collection of behaviours that occurs following a change to the road traffic system (OECD, 1990; Rudin-Brown & Noy, 2002). The modern day vehicle consists of a great deal of in-vehicle Intelligent Transportation Systems (ITS). Many of these technological innovations are designed to improve safety by reducing crash risk, and making travel easier and more enjoyable. Behavioral adaptation is acknowledged in the use of these new technologies, but little has been established regarding underlying explanatory factors and processes (Rudin-Brown & Noy, 2002; Saad, 2004). Because adaptive behavior can have a great impact on overall system performance, developing approaches to understand and model this effect is crucial. Llaneras (2006) indicated that behavioral adaptation extends beyond changes in driver performance to also include drivers' attitudes and feelings, as well as their mental models of how the system operates, capabilities and limitations, utility and effectiveness, and its impact on driving style. However, capturing all these components is a complex task.

Adaptive Cruise Control (ACC) is one example of ITS, and has been available in the U.S. since 2001 (Gee, 1997; Llaneras, 2006). As of 2013, there were approximately 100 vehicle models with ACC as a standard or optional feature. Therefore, with the growing prevalence of ACC, understanding the affect of behavioral adaptation on overall system use is critical. ACC is an enhanced version of conventional cruise control and allows a driver to follow another vehicle at a preset time headway and speed by automatically controlling both the engine and braking capability (Szuszman, 2005). As shown in Figure 1, ACC uses sensors and rule-based algorithms to immediately detect a leading vehicle. If a vehicle is detected, ACC will either assist the driver or take full control of the vehicle (Bishop, 2000). Studies on drivers' use of ACC have shown

that it can improve driving comfort and enhance traffic flow (Bose & Ioannou, 2001; Hoedemaeker, 2000; Kesting, Treiber, Schönhof, & Helbing, 2008; C. Liang & Peng, 2000). However, the benefits of ACC for safety are not as clear.

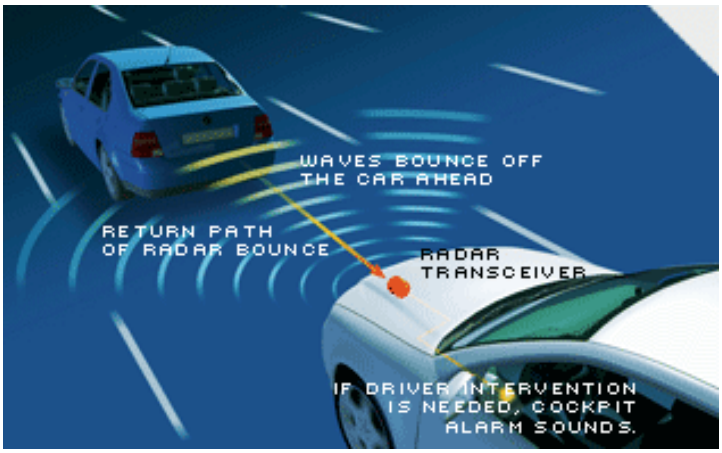


Figure 1. ACC control system
(http://www.popsci.com/cars/article/2003-02/adaptive-cruise-control-meet-your-new-co-pilot)

1 Research Objective

ACC systems are human-automation systems, which include driver, system, and vehicle interactions. A system view of factors that influence the safety outcomes based on use of in-vehicle technology is proposed in Figure 2. These include driver factors (e.g. mental model of ACC, trust in ACC, driving styles etc.), ACC system factors (e.g. speed control, gap setting control, alert algorithm), and vehicle dynamics. Both the driver and the ACC system share control of the vehicle at the same time, and both receive feedback from the vehicle for subsequent control. The ACC system can also alert the driver when a safety critical event occurs such that the driver can override it as needed. According to this control model, each controller in the loop (the driver and ACC system) will exhibit different responsibilities or driving tasks. The driver, as a higher-level controller, needs to supervise the ACC system and even override as necessary in addition to monitoring road environments. The driver's mental model of ACC

(attitudes, feelings, and knowledge), trust in ACC (Rajaonah, Anceaux, & Vienne, 2006), and driving styles have effects on maintaining these driving tasks and will further affect driving safety. These variables are, therefore, considered as inputs to the driver. When the ACC automation is engaged, it will detect the lead vehicle and maintain headway distance and speed, as well as provide feedback to the driver. The gap and speed setting inputs will regulate the ACC system and further affect safety. Task effectiveness of an ACC system depends on appropriate time to automatically brake or alert the driver to manually brake the vehicle. Therefore, it is crucial to identify when the system should automatically brake and when it should alert the driver to manually intervene for a lead vehicle braking. The actions from the driver, the ACC system, and the cooperation between them have an overall influence on driving safety. The safety consequences could be either performance measures such as adjust minimum time to collision, minimum time headway, and drivers' response time to driving critical events, or driving conflict states based on severity of crash likelihood.

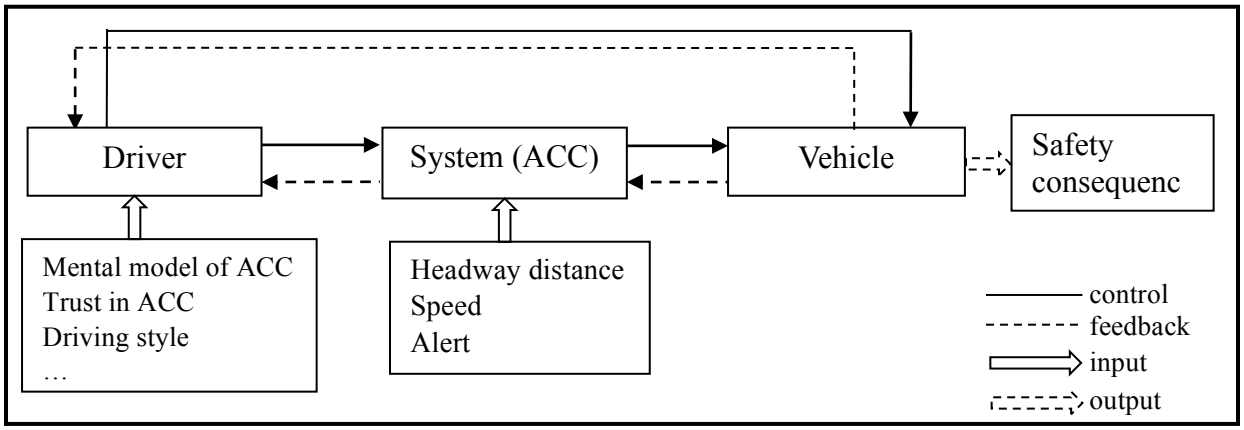


Figure 2. Driver-system-vehicle model

The overall goals of this dissertation are to (1) understand how driver adaptation and (2) system functionality might influence driving performance and overall safety, and (3) to examine this from a system-wide perspective. The proposed system approach using a control theory

perspective to examine underlying explanatory factors and processes that influence driver safety from a modular (individual component) and holistic (interactions between components) view, which is different from other studies that mainly focused on the outcomes (driving performance measures) rather than the underlying constructs that generated the outcomes. A control theory approach is useful because many of these intelligent systems can provide continuous feedback to drivers, which require an understanding of the driver, system, and vehicle interactions.

There are other system approaches that could have been considered. The system could have been examined by capturing multiple components within a system simultaneously using analytical models such as structural equation modeling, which can also provide causal relationships for the system. The systems approach can be based on the decomposition of the subsystems, which accounts for the different focuses at each level. In the control theoretical perspective, the relationships among the driver, system, vehicle, and roadway will be established using a three part approach where any associations will first be identified, followed by an exploration of the latent structures, and lastly, establishing the directionality (causal) and magnitude using a repeatable, controlled study.

This dissertation work will first decompose the system into two components (driver and ACC system) using data from an on-road field operational test, which will provide insights on novice ACC users. Data from controlled (i.e., driving simulator) studies will provide insights on any latent groupings within novice and experienced ACC users. The factors that generate changes in driver performance will be examined based on these groupings, as well as other road, vehicle, and system factors. This three-part approach provides a more holistic, systems approach to observe overall safety within our transportation network. One outcome of this dissertation related to differences in behaviors among non-ACC, novice and experienced ACC users that

subsequently safety consequences are associated with their behaviors. Another outcome of this dissertation related to algorithm effectiveness by considering different control parameters.

2 Specific Aims

AIM 1: *Determine the factors that will influence drivers' behaviors for novice ACC users.* A previous field operational test (FOT) on an advanced collision avoidance system from 2003-2004 is used to examine this specific aim. This dataset is applicable for this aim because it is one of the first studies conducted on some of the first users of an ACC system in a naturalistic driving environment. During this naturalistic driving, 66 drivers used ACC for three weeks. Drivers' adaptation (i.e. response to the automatic braking control feature available on ACC systems) was examined. A conceptual framework for drivers' adaptation has been established and factors that have significant impacts on drivers' responses have been identified.

AIM 2*: Evaluate ACC system effectiveness on automatic braking capabilities.* As part of the FOT study, the events were categorized into four different driving conflict states by using Range (distance between the host vehicle and lead vehicle) and Range Rate (speed difference between the host vehicle and lead vehicle). System automatic braking capabilities under different driving conflict states were examined. ACC responses differed under different driving conflict states. A more reliable algorithm design was proposed.

AIM 3*: Identify ACC use patterns for experienced users (those who have used an ACC system in their own vehicles).* A survey study conducted in 2008 on experienced ACC users by Dickie and Boyle (2009) showed that drivers' understanding of ACC limitations were different among ACC users. Different awareness of the systems' capabilities or limitations may cause

different driving behaviors and can impact driver safety. Following this preliminary result, a driving simulator study was conducted at the University of Iowa to examine experienced ACC users. ACC use patterns for experienced users have been examined and the safety consequences associated with different use patterns were analyzed. Subgroups of ACC users based on use patterns were found from this study and each group exhibited different safety consequences.

AIM 4*: Examine braking behaviors of non-ACC, novice and experienced ACC users.* As part of a simulator study conducted at the University of Washington (UW), the participants encountered several leading vehicle braking events (non-critical events, critical events, vehicle cut-in). A between-subjects design was used to compare non-ACC, novice and experienced ACC users. Drivers' reaction to these braking events from different user groups was examined. Differences on speed and headway distance control were observed among these user groups. Different braking behaviors also existed between novice and experienced ACC users.

Chapter 1 contains a review of the relevant literature related to ACC, drivers' adaptation, and their influence on driving performance. Chapter 2 demonstrates the results of a naturalistic study conducted to evaluate novice ACC users' behaviors (Aim 1). Chapter 3 describes the system algorithm effectiveness on automatic braking capabilities (Aim 2). Chapter 4 shows the results of a simulator study conducted to examine experienced ACC use patterns (Aim 3). Chapter 5 contains the results of a simulator study conducted to examine differences among non-ACC, novice and experienced ACC users (Aim 4). Chapter 6 describes the general conclusions based on this research, the general and scientific contributions of this research, and future research directions.

Chapter I: Background

This chapter contains an overview of related literature to this dissertation. Drivers may adapt to new in-vehicle technology by changing their driving tasks and willingness to take on perceived risks. Hence, a good understanding of how drivers' adaptation and ACC system effectiveness impact driving safety is an essential task for this dissertation. This chapter contains the literature related to these observations and ends with a discussion of the research gap that this dissertation will address.

1.1 Behavioral Adaptation

Typically, researchers are most interested in those adaptations that negatively impact safety (Rudin-Brown & Parker, 2004). Therefore, adaptive behavior is defined, in the context of current research, as the behavior exhibited when one adapts in unintended ways to systems that are designed to improve safe operation. Studies have shown that adaptation greatly influenced a driver's response to safety-based systems. For example, Evans and Gerrish (1996) showed that ABS (which is designed to improve brake performance) significantly reduced front impacts, however an unintended consequence was an increase number of rear impacts. Similarly, ACC may not be appropriate for dense driving conditions where driver assistance is most needed. Additionally, drivers who become dependent on the feedback provided by ACC may actually become complacent and have a decreased awareness of their surroundings, leading to an unintended mishap or crash. Furthermore, how effective the system algorithm is may also have great impacts on safety.

Many studies examine driving performance with ACC in terms of behavioural adaptation. Nilsson (1995) found that drivers with ACC spent more time in the left lane than drivers without ACC in a simulator study. Ward, Fairclough, and Humphreys (1995) found that drivers set the

ACC at higher speed and shorter headways, and had poor control over lane position compared to drivers without ACC through a field trail with a prototype ACC. Hoedemaeker and Brookhuis (1998) conducted a driving simulator study by dividing participants into four different groups based on their driving styles (Speed: driving fast or slow; Focus: the ability to ignore distractions high or low) and showed that higher speeds, smaller minimum time headways and larger braking forces were associated with ACC driving, with little differences among groups. Rudin-Brown and Parker (2004) demeonstrated that using ACC resulted in more engagement in secondary tasks, significantly more lane position variability and increasing trust in ACC after using the system. Pauwelussen and Feenstra (2010) studied driving performance during ACC activation and deactivation using a FOT. The gap with the lead vehicle was decreased after the participants deactivated the ACC by pressing the brake pedal. Compared to an overruled ACC or the ACC turned off, a larger gap was shown when resuming the ACC by activationg the system or by releasing the throttle.

The aforementioned studies examine driving performance caused by behavioral adapation, but none emphasized the factors that influence drivers' initial adaptive behavior. Some of the studies do take into into account driving styles and trust in ACC, but a systematic overview of factors that infuence operators' initial adaptive behavior is still lacking.

1.2 Adaptive Cruise Control

Like a conventional cruise control system, ACC automatically maintains the driver's preset speed. Moreover, ACC will also respond to a lead vehicle that is too close by automatically decelerating to maintain a preset headway and alerting the driver (either visually or auditory) when hard decelerations are needed, thereby should reduce the likelihood of a front-end collision.

Numerous studies related to ACC systems have examined their impacts on comfort, highway capacity and safety. The goal of ACC is to relieve the driver from the routine of spacing adjustments at cruise speeds. Therefore it is marketed as a convenience system. Studies showed that ACC implemented a smoothing effect to decrease the variance between the acceleration and deceleration (Bose & Ioannou, 2001), and reduced speed variability (Hoedemaeker, 2000) compared with manually operated vehicles.

Moreover, ACC has also been incorporated into collision avoidance and brake assist systems as part of integrated advanced safety systems. Some of the benefits of ACC systems described in the literature have included less headway variations (Heino, Rothengatter, & Van der Hulst, 1995; Ward, 2000) with thresholds typically ranging from 0.9 to 2.5 s (Kesting, Treiber, Schönhof, & Helbing, 2007), lower maximum speeds, less speed variations (Bjørkli & Jenssen, 2003; Suzuki & Nakatsuji, 2003; Törnros, Nilsson, Östlund, & Kircher, 2002), and reduced necessity to monitor the external surroundings or manually accelerate or brake (Young & Stanton, 2004). The reduction in required mental and physical resources makes driving less effortful and reduces driver stress and human errors (Hoedemaeker & Brookhuis, 1998; Stanton & Marsden, 1996). However, if the reduction becomes too high, it may actually affect the ability of the driver to maintain awareness of situations. Less safe behavior using ACC was also observed with more frequent off-road glances (Thompson, Tönnis, Lange, Bubb, & Klinker, 2006) and harder braking (Bjørkli & Jenssen, 2003).

These studies have examined ACC safety consequences by comparing drivers that use ACC with those that have never used ACC. However, examination of risk compensation (homeostasis) theory (Trimpop & Wilde, 1994) requires understanding the user's own level of acceptable risk, and changes in behavior over time as previously examined in drivers that use antilock braking

systems (Aschenbrenner & Biehl, 1994; Grant & Smiley, 1993; Sagberg, Fosser, & Saetermo, 1997; Winston, Maheshri, & Mannering, 2006), variable speed limit information (Boyle & Mannering, 2004; Jackson & Blackman, 1994), and airbags (Sagberg, Fosser et al., 1997; Winston, Maheshri et al., 2006). Therefore, more research is needed to examine ACC use for more experienced users, which can then provide insights on long-term use.

The effectiveness of these systems is based on the timeliness of the automatic braking feature and whether it appropriately alerts the driver when to manually intervene. This aspect of system effectiveness (based on a braking lead vehicle) has not been extensively examined in the literature. Appropriate responses to the external and continually changing environments are crucial to maintain safe vehicle control. Lee, Young & Regan (2008) have proposed that distraction-related mishaps can be explained by the overlap in attention placed on the driver from the external environment (which the authors call roadway demand) and those centered on the driver. This theory can be extended to examine the effectiveness of driver-related longitudinal control assistance systems, such as ACC.

Task effectiveness of an ACC system depends on appropriate time to automatically brake or alert the driver to brake manually. A good design should therefore consider both the external environment (situation severity) and the capability of the controllers (driver and system). ACC can perform well under many circumstances, particularly when traffic flow is stable, predictable, and demands on drivers' attention are low. However, there are also situations where the lead vehicle may brake unexpectedly or too abruptly given road construction or other unexpected events (Bato & Boyle, 2011; Dickie & Boyle, 2009). Therefore, whether ACC can result in safer traffic patterns is still an open question and safety implications related to behavioral adaptation and system effectiveness need to be examined comprehensively. This dissertation proposes a

conceptual model for adaptive behaviors. Portions of this model are quantified using a predictive model of drivers' likelihood to intervene (i.e., manually brake) whenever ACC begins braking or slowing down the vehicle (Ch2 in detail). This dissertation also proposes a quantitative method for evaluating ACC automatic braking capability, which provides insights on ACC algorithm design (Ch3 in detail).

1.3 ACC Limitations and Use

Advanced technologies have propelled efforts to automate vehicles, and since its implementation over a decade ago, ACC has continued to evolve. Many studies on ACC have focused on the potential innovations of the system such as full start-stop control or the overall effect it may have on traffic systems, which include road users, vehicles, roadways, and controls (Naranjo, Sotelo, Gonzalez, Garcia, & Pedro, 2007; Venhovens, Naab, & Adiprasito, 2000). However, it is still a semi-automated system (a share control system) and drivers' cooperation control (use) plays an important role on driving safety. ACC uses laser range finders or radar to detect the vehicle directly in front of it. It can accommodate some of the demands for the driver but there is limited braking authority. ACC systems do have maximum deceleration rates and do not regulate speeds based on stationary vehicles or objects (Naranjo, Sotelo et al., 2007). In addition, ACC cannot function properly when a lead vehicle enters a curved road (Rudin-Brown & Parker, 2004). That is, the ACC radar may not detect a lead vehicle given the angle of curvature even when in close proximity to a lead vehicle. In this situation, the ACC vehicle will accelerate back to the original cruise speed even though there is a vehicle in front.

Given the system limitations, examining drivers' acceptance and use becomes essential. Even though ACC was available starting in 2001 in the U.S., the number of active users is still relatively small. However, those who used ACC when it was first marketed to general consumers

(henceforth called early adopters) can provide initial insights on safety as well as adaptive behavior. Previous field operational tests and simulator studies have provided some insights on novice ACC users' performance, behavioral changes, and safety among early adopters of ACC (Hoedemaeker & Brookhuis, 1998; Hoedemaeker & Kopf, 2001; Sayer, Fancher, Bareket, & Johnson, 1995; Stanton, Young, & McCaulder, 1997). Long-term adaptation has also been implied in surveys, and responses suggest that over the course of months or years, changes in performance and reliance can occur (Jenness, Lerner, Mazor, Osberg, & Tefft, 2008; Llaneras, 2006). These studies showed that ACC was well received among early adopters, based primarily on its perceived convenience and improved safety. However, relatively few respondents fully understood how the system operated. More importantly, respondents were unaware of the systems' limitations and overestimated the effectiveness in situations where ACC does not work appropriately. A survey study conducted by Dickie and Boyle (2009) found that some experienced ACC users were not aware of ACC limitations and they were more willing to use ACC when tired or on curvy roads. Both automation overreliance and a lack of system understanding may cause misuse of the system. In situations where limits are exceeded, these may further result in more critical "near misses" or collisions. Therefore, examining ACC use patterns for experienced users will provide another aspect of understanding drivers' adaptive behavior and safety.

1.4 Gaps in Literature

There are many studies that examine driving performance and safety with ACC and other studies that focus on drivers' adaptation to this technology. However, there have been few studies that focus on the bridge between these two. As a shared and cooperative control system (Flemisch, Kelsch, Loper, Schieben, & Schindler, 2007), safety consequence has not been

examined under a systematic view (driver, ACC, vehicle). The proposed model, "Systematic view of the factors that impact safety consequence for an ACC (Figure 2)", will provide a new aspect to evaluate safety implications for similar safety-based systems.

Numerous studies on drivers' adaptation to ACC showed the outcomes of adaptation rather than the underlying reasons. The studies associated with ACC have focused on the potential innovations of the system rather than system effectiveness. This dissertation applies a system approach from control aspect to examine the underlying factors that influence drivers' adaptation, system effectiveness based on ACC's ability to respond to external demands, and interactions between drivers and system, which can provide greater insights on how best to assess automation algorithm designs.

The findings associated with ACC have also centered on novice users, but research on experienced users' behavior is equally important and has larger implications toward safety. The proposed model, "Factors that influence operators' adaptive behavior (Figure 3)", will help fill this gap by addressing factors that have a significant impact on adaptive behaviors and differences between novice and experienced ACC users' adaptations.

Drivers adapt to new systems in ways that designers may not always anticipate. This can have implications for safety because this adaptation may either enhance or compromise the potential benefits of the system. Given the growth of in-vehicle technology, there is a high likelihood that some systems may actually make drivers less aware of their surroundings, which would negatively impact safety. ACC provides a good example for examining behavior because it is one such technology that was novel 10 years ago and hence, initial data is available (through a field operational test) to capture novice users' adaption. Moreover, ACC is continually evolving and the adaptation associated with its use for experienced users is still unclear. The

results of this dissertation will quantitatively add to the knowledge in this area. The results gained from this research should provide insights on drivers' adaptive behaviors, and system design and lead to beneficial changes in the ACC system and other new in-vehicle systems as well. People's behavior evolves changes based on their gained experience and this can only be captured with parametric statistical methods that can be used so that the results of these analyses can be viewed from a scientific aspect and fully incorporate into this knowledge base.

Chapter 2: Novice ACC Users' Adaptive Behaviors (Aim 1)

In this chapter, a naturalistic study is used to examine the study hypothesis. It begins with a conceptual framework for adaptive behavior. This is followed by an overview of the field operation test (FOT) and results related to this study. Lastly, the statistical methods used for this chapter and results are described. The work described in this chapter has been published in *IEEE Transaction on Intelligent Transportation Systems (Xiong & Boyle, 2012)*.

2.1 Conceptual Framework for Adaptive Behaviors

The goal of this chapter is to quantify the factors that influence how drivers initially adapt to the ACC system and to gain insights for the design of future in-vehicle systems. Based on previous studies (Boyle & Mannering, 2004; Fuller, 2005; Hedlund, 2000; Michon, 1989), a model of drivers' adaptive behaviors was developed that includes the relationship between initiating and mediating factors and the influences of each toward the operator's behavior (Figure 3).

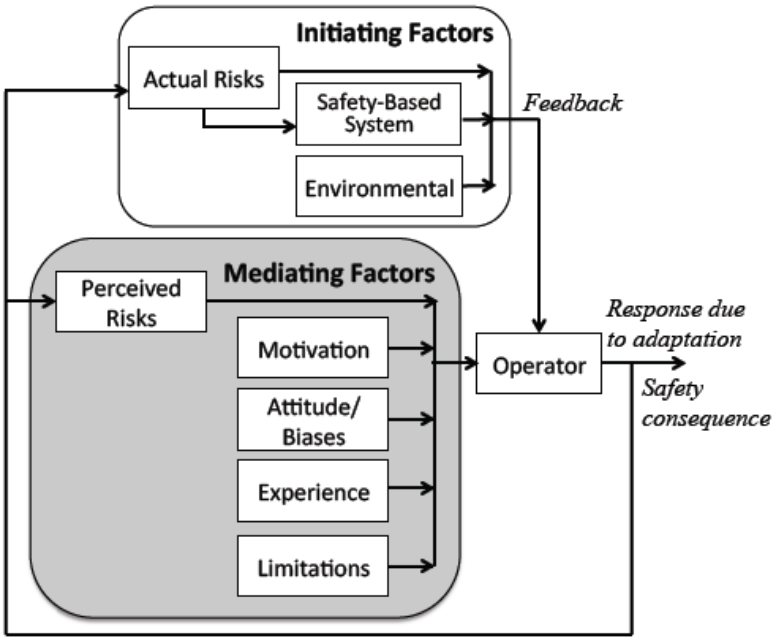


Figure 3. Factors that influence operators' adaptive behavior

Initiating factors are based on the driver's direct interaction with the system, the environmental cues, and the actual risk at the moment of ACC use. For example, an actual risk can relate to the following distance of the ACC vehicle, which becomes shorter as a lead vehicle brakes. Coupling the response of a safety-based system (ACC) with environmental conditions (i.e., roadway, weather, traffic) provide feedback that drivers can use to respond to the next safety-critical situation. These factors have immediate adapting effects on the driver.

Mediating factors are more subjective, but may actually have a greater influence on the operators' long-term behavior. These factors emerge from exposure to a system in conjunction with perceived risks (e.g. gap setting, speed setting); motivational factors (e.g. willingness to use ACC); attitudes/biases (e.g. driving styles, trust in ACC, overall system use); experiences (e.g. exposure to ACC), and user limitations (e.g. physical, cognitive, medical). The interaction of these factors will influence the final response of the operator in ways that may not have been incorporated into the system design. Therefore, the first step in assessing driver adaptation is to understand the influence of initiating and mediating factors on drivers' response during first exposure to ACC.

2.2 Field Operation Test

A FOT was conducted from 2003 to 2004 on an advanced collision avoidance system by the University of Michigan Transportation Research Institute (UMTRI) (Ervin, Sayer et al., 2005). The system was composed of two components: adaptive cruise control and forward collision warning. This FOT provided a useful dataset for this study because it was one of the first studies conducted on early users of an ACC system and included naturalistic driving. The original study included 96 drivers and 10 vehicles. Of this original study sample, 66 drivers used ACC and were included in the sample of this analysis. There were three age groups with equal number of

males and females: younger-aged (20 to 30 years old), middle-aged (40 to 50 years old), and older-aged (60 to 70 years old) drivers.

The details of the original UMTRI study can be found in (Najm, Stearns, Howarth, Koopmann, & Hitz, 2006). However, some of the interesting results that are relevant to this study are presented here. The results indicated that ACC was widely accepted by drivers. Possible benefits observed during ACC driving include a significant reduction in short (less than one second) time headways and reduced overtaking behavior.

Drivers in this study were able to select a gap setting (time headway) from six intervals. The six intervals ranged from 1 to 2 seconds (s) with 0.2-s increments (e.g., gap setting 1 would correspond to 1-s headway, and setting 2 corresponds to a 1.2-s headway). The ACC was capable of providing warnings for braking events with a maximum value of 0.3 g. Because the likelihood of a collision is rare within a study period, a potential surrogate measure (or proxy) for safety, with respect to ACC, is a "closing" event. A closing event is defined as the moment that the ACC's automatic braking control is activated until any braking (or deceleration) ceases, regardless of whether a driver intervenes or not. Therefore, this study focuses on drivers' adaptive responses to ACC during "closing" events. There were a total of 3924 "closing" events extracted from the 64 drivers (two drivers were excluded as they did not have any "closing" events) with an average of 61 events per driver (SD=68.83).

For each driving event, information was recorded on drivers' response, range, weather condition, road type, lighting condition, traffic condition, speed, and gap-setting. Traffic conditions were predefined by UMTRI as heavy, moderate, or light congestion based on a combination of vehicle speed for the roadway type and the density of traffic on the roadway;

specific definitions for each is available in (Najm, Stearns et al., 2006). This database also included drivers' demographic information that was also used in the analysis.

2.3 Statistical Analysis

2.3.1 Preliminary analysis

The numbers of "closing" events was greatest for the older drivers (1603 events), followed by younger (1327 events) and middle-aged drivers (994 events). There were more events for males (n=2410, 61.4%) than females (n=1514, 38.6%). Of the six gap settings, there were not as many observations for gap setting 2 (1.2 s headway), 4 (1.6 s), and 5 (1.8 s) (Table 1). Hence, the data was recoded into three groups of gap settings and used as the explanatory variable in the forthcoming logistic regression model: short (gap setting 1 and 2), medium (gap setting 3 and 4), and long (gap setting 5 and 6). There were 1574, 1296, and 1054 observations for gap settings short, medium, and long, respectively. The results showed a significant association between gap settings and drivers' responses. There were more occurrences of drivers' intervention in the longer gap setting ($\chi^2(2)=19.6$, $p<0.001$) (Table 1), which was counterintuitive.

Table 1. Driver response based on gap settings

Gap Setting		Manual brake press		Automatic by ACC	
Original	Recoded	Original events	Total recoded (%)	Original events	Total recoded (%)
1	Short	111	147 (9.3%)	1081	1427 (90.7%)
2	Short	36		346	
3	Medium	97	154 (11.9%)	775	1142 (88.1%)
4	Medium	57		367	
5	Long	32	158 (15.0%)	131	896 (85.0%)
6	Long	126		765	
	Total	459		3465	

However, as observed in Figure 4, the road types had an impact on gap selection. Drivers were more likely to use the longer gap setting in non-highway situations and the shorter gap setting on highways. The mean speed for short, medium, and long gap-settings was 30.5m/s, 27.9m/s, and 25 m/s, respectively. Given the preferences that long gap-settings were associated with non-highway (when ACC is most likely to be disengaged), more occurrences of drivers' intervention in the longer gap-setting were reasonable.

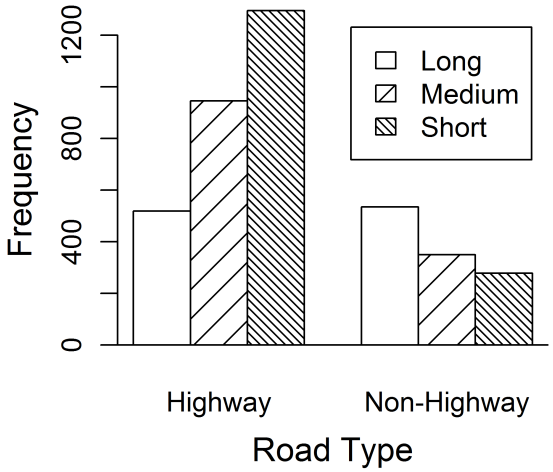


Figure 4. Frequency of events by gap-setting and road type

Traffic conditions may exhibit differences in different road types. The relationship among traffic congestion level, road type, and drivers' response was further explored with respect to number of closing events. There were 73 events (out of 3871 observations) or 1.89% of ACC "closing" events triggered in heavy congestion, 1682 (43.4%) in light and 2116 (54.7%) events in moderate congestion. There were 53 events recorded as unknown traffic condition. Controlling for the traffic condition level, a significantly higher frequency of drivers' intervening in non-highway situations was observed when compared to highway ($\chi^2(4)=227.1$, $p<0.001$). Controlling for road type, more drivers intervened in heavy congestion when compared to the other congestion levels ($\chi^2(6)=27.0$, $p<0.001$) (Table 2).

Table 2. Driver response based on traffic conditions and road type

Road type	Traffic congestion	Manual brake press	Automatic by ACC
Non-highway	Light	151	488
	Moderate	113	314
	Heavy	16	28
Highway	Light	69	974
	Moderate	106	1583
	Heavy	3	26

2.3.2 Generalized estimating equations

In the FOT study, drivers' responses were recorded at multiple points in time and were, therefore, correlated. The most widely used approach for fitting marginal generalized linear models to longitudinal data and repeated measures is the generalized estimating equations (GEE) method, which has been applied in many domains (Kenward, Lesaffre, & Molenberghs, 1994; Lipsitz, Kim, & Zhao, 1994). The GEE approach focuses on models for the mean of the correlated observations within clusters without fully specifying the joint distribution of the observations.

Liang and Zeger (1986) introduced the GEE approach for the regression analysis of correlated observations. This approach generalized the estimation method of quasi-likelihood of Wedderburn (1974) to correlated data.

Consider a sample of $i = 1, \cdots, K$ independent multivariate observations $Y_i = (Y_{i1}, \ldots, Y_{it}, \ldots, Y_{in_i})$. Here i may represent a cluster with n_i observations. The expectations $E(Y_{it}) = \mu_{it}$ are related to the p dimensional regressor vector x_{it} by the mean-link function g

$$g(\mu_{it}) = x_{it}^T \beta \tag{1}$$

Let

$$VAR(Y_{it}) = \phi a_{it} \tag{2}$$

where ϕ is a common scale parameter and $a_{it} = a(\mu_{it})$ is a known variance function. Let $R_i(\alpha)$ be a working correlation matrix completely described by the parameter vector α of length m. Let

$$V_i = \phi A_i^{1/2} R_i(\alpha) A_i^{1/2} \tag{3}$$

be the corresponding working covariance matrix of Y_i, where A_i is the diagonal matrix with entries a_{it}. For given estimates $(\hat{\phi}, \hat{\alpha})$ of (ϕ, α) the estimate $\hat{\beta}$ is the solution of the equation

$$\sum_{i=1}^{K} \frac{\partial \mu_i^T}{\partial \beta} V_i^{-1} (Y_i - \mu_i) = 0 \tag{4}$$

Liang and Zeger (1986) suggest to use consistent moment estimates for ϕ and α. This yields an iterative scheme which switches between estimating β for fixed values of $\hat{\phi}$ and $\hat{\alpha}$ and estimating (ϕ, α) for fixed values of $\hat{\beta}$. This scheme yields a consistent estimate for β. Moreover, $K^{1/2}(\hat{\beta} - \beta)$ is asymptotically multivariate normally distributed with zero mean and covariance matrix $\Sigma = \lim_{K \to \infty} K \Sigma_0^{-1} \Sigma_1 \Sigma_0^{-1}$ where

$$\Sigma_0 = \sum_{i=1}^{K} \frac{\partial \mu_i^T}{\partial \beta} V_i^{-1} \frac{\partial \mu_i}{\partial \beta^T}, \quad \Sigma_1 = \sum_{i=1}^{K} \frac{\partial \mu_i^T}{\partial \beta} V_i^{-1} COV(Y_i) V_i^{-1} \frac{\partial \mu_i}{\partial \beta^T} \tag{5}$$

Replacing β, ϕ and α by consistent estimates and the covariance matrix $COV(Y_i)$ by $(Y_i - \mu_i)(Y_i - \mu_i)^T$ in (5) yields a sandwich estimate, $\hat{\Sigma}$ of Σ. The estimate $\hat{\Sigma}$ is a consistent

estimate of Σ even if the working correlation matrices $R_i(\alpha)$ are misspecified (Halekoh, Højsgaard, & Yan, 2006).

Given the random effect for each driver, let y_{it} be the measure for driver i at occasion t, GEE with working covariance matrix $\text{cov}(y_{it}, y_{it'})$ was used to fit the model. The GEE models were fitted using function geeglm in package geepack (Halekoh, Højsgaard et al., 2006; Parsons, Costa, Achten, & Stallard, 2009), in R statistical software. Stepwise method was used to select the model.

2.3.3 Prediction model for drivers' adaptation

Based on the model of adaptive behavior (Figure 3), the initiating factors, or those factors that directly impact the immediate decision, are defined in this study as the distance to the lead vehicle (range). This factor is also used as a measure of the actual risk. Other factors such as weather condition, road type (highway or non-highway), lighting condition (day or night), and traffic condition (heavy, moderate, and light congestion) are used to describe the environment. The combination of the environment, actual risk, and ACC response then provides feedback to the driver, which influences the drivers' response for the next safety critical situation. These initiating factors are then considered along with (or adjusted for) the mediating factors that measure perceived risk (the selected gap-setting and vehicle speed), experience defined as the number of sequential "closing" events (which range from 1 to 408 events), and user factors (age and gender) (Table 3).

Table 3. Predictor variables to identify driver adaptation

Factors that influence adaptation
Initiating Factors
Actual risks: Distance to the lead vehicle (range)
Environment: Weather, road type (*), lighting condition, traffic condition
Mediating Factors
Perceived Risk: Selected gap-settings (*), vehicle speed (*)
Experience: Number of sequential closing events
User Factors: Age (*), gender

Note: * means that these factors are significant in the later analysis

When a "closing" event occurs, there are several decisions that can be chosen by the driver: to allow ACC to automatically brake, to manually brake for vehicles in front, to move to another lane, or even to accelerate. The driver's response related to the "closing" event is used as an indicator of how drivers behave and initially adapt to the ACC system. In this dataset, there were no situations in which the drivers accelerated (whether inadvertently or intentionally is not known) or move to another lane. The drivers responded by either manually braking or allowing ACC to automatically brake. There are times when the ACC begins to brake automatically but is immediately followed by the driver also braking manually – these events are coded as a manual braking event since the driver does intervene. Therefore, these responses can be considered a binary outcome and a logistic regression model is used. For the binary response variable, we first consider linear logistic regression model with the form:

$$\log\left(\frac{\Pr(Y=1\mid x)}{1-\Pr(Y=1\mid x)}\right)=x^{T}\beta \tag{6}$$

Two working correlation structures, independence ($cor(y_{it},y_{it'})=0$) and exchangeable ($cor(y_{it},y_{it'})=\alpha$) were considered in the model fitting. Results showed that the estimated

correlation under exchangeable structure is very small, 0.0038, and the differences between $\hat{\beta}$ are less than 0.1 for the two models. Therefore, the random effect was not considered in the following analysis and result interpretation.

The outcomes of the logistic regression model with independent correlation structures (Table 4) showed that the regression coefficient for highway roads is -0.94. The negative estimate indicates that drivers are less likely to intervene on highways. More specifically, they are 2.6 times less likely to intervene on the highway when compared to the non-highway condition. The higher the vehicle speed, the less likely the driver is to intervene. The interaction between these two factors was not significant. Given hard braking does not occur very often on highway conditions, ACC system can accommodate most situations. Therefore, it is reasonable to see that drivers are less likely to intervene on highway conditions. As noted earlier, both of these factors impacted gap selection. Hence, when these factors are included in the model (i.e., their effect is accounted for in the regression model), drivers are shown to intervene more with short gap settings (or shorter time headway settings) than with medium and long gap settings. The relative likelihood of intervention for short gap setting is 1.4 times higher than that of long gap setting. Additionally middle-aged drivers are 1.5 times more likely to intervene compared to younger-aged drivers.

Table 4. Likelihood that drivers would intervene given a close event

Variables		Estimate	Stand Error	Wald-statistics	P-value
Intercept		0.27	0.36	0.59	0.44
Road (highway)		-0.94	0.19	24.73	<0.001
Speed		-0.07	0.02	21.11	<0.001
Gap setting					
	Medium vs. Short	-0.11	0.14	0.61	ns
	Long vs. Short	-0.33	0.16	4.41	0.04
	Medium vs. Long	-0.22	0.16	2.3	ns
Age					
	Middle-aged vs younger	0.41	0.18	5.17	0.02
	Older vs. younger	0.21	0.19	1.24	ns
	Middle vs. older	-0.2	0.15	1.76	ns
Number of observations				3943	
Number of clusters				64	
Maximum cluster size				408	

Note: ns is non-significant

2.3.4 Measure of model predictive accuracy

Since recent data is unavailable, it is very important to test the logit model's predictive accuracy with a confusion matrix. Suppose the response is categorical, with $Y \in \{0,1,\ldots,K-1\}$. In the situation where a class label is assigned, the loss function is a $k \times k$ matrix L with element $L(j,k)$ representing the loss incurred when the truth is $C = j$, and the classification is $g(X) = k$, with $j,k \in \{0,1,\ldots,K-1\}$, where $g(X)$ is a class predictor and the loss function is

$$L(j,k) = \begin{cases} 0, j = k \\ \geq 0, j \neq k \end{cases} \quad (7)$$

Therefore, the expected loss is:

$$E_{X,Y}[L(Y,g(X))] = E_X\{E_{Y|X}[L(Y,g(x))\,|\,X=x]\}$$
$$= E_X\{\sum_{k=0}^{K-1} L(Y=k,g(x))\Pr(Y=k\,|\,x]\} \quad (8)$$

Table 5 shows the confusion matrix with loss function for $K = 2$ case.

Table 5. Loss table for a binary decision problem

		Predicted Class	
		g(x)=0	g(x)=1
TRUE	Y=0	0	L(0,1)
Class	Y=1	L(1,0)	0

Given the loss functions, models were selected by using the test error:

$$E = \frac{1}{m}\sum_{i=1}^{K} L(y_i, \hat{g}(x_i)) \quad (9)$$

where m is the number of observations and K is the number of classes. The confusion matrix for this model was shown in Table 6, the test error is 27.1%.

Table 6. Confusion matrix for the logistic model

		Predicted Class	
		g(x)=0	g(x)=1
TRUE	Y=0	2584	881
Class	Y=1	181	278

2.4 Summary

The goal of this chapter is to examine any initial adaptive behavior among novice ACC users, and to understand the underlying driver constructs within the system, using a conceptual model of adaptive behavior developed and examined quantitatively using logistic regression techniques. The findings showed that drivers would do one of two things: either allow ACC to take control, or override ACC by manually braking. Several initiating and mediating factors (road type, gap-setting, speed, and age) were observed to influence drivers' initial adaption to the

ACC system. Drivers were less likely to intervene on roads that typically have higher posted speeds (when ACC is most likely to be engaged). Although this may be expected given that hard braking does not occur often in highway situations, a negative safety consequence may result in safety critical situations since drivers may not response quickly enough when hard braking presents. In this case, system effectiveness (ACC system component of the system approach) plays an important role on driving safety. Hence, future research will need to consider the ACC system effectiveness.

Chapter 3: System Effectiveness Based on ACC Automatic Braking Capabilities (Aim 2)

The goal of this chapter is to examine the ACC automatic braking capabilities based on factors from the external environment. Data from the same FOT study (as in Chapter 2) was used to achieve this goal. This chapter begins with a driver distraction mishap model based on factors external to the driver, as well as within the vehicle. This is followed by a discussion of interested measure of external demand, which will be used to quantify the model. Lastly, the statistical methods used for this chapter and results are described. This work will be submitted to *Accident Analysis and Prevention*.

3.1 Extended Mishaps Model

3.1.1 Driver-distraction mishaps model

Appropriate allocation of drivers' attention is crucial to maintain safe vehicle control in a dynamic roadway environment that includes varying levels of traffic. Studies on driver distraction have focused on the type and degree of distraction (Lee & Kantowitz, 2005; Walker, Stanton, & Young, 2001), but rarely on the context of the distraction. Lee, Young & Regan (2008) have proposed that distraction-related mishaps can be explained by the overlap in attention placed on the driver from the external environment (which the authors call roadway demand) and those centered on the driver (Figure 5). This theory can be extended to examine the effectiveness of driver-related longitudinal control assistance systems, such as ACC system.

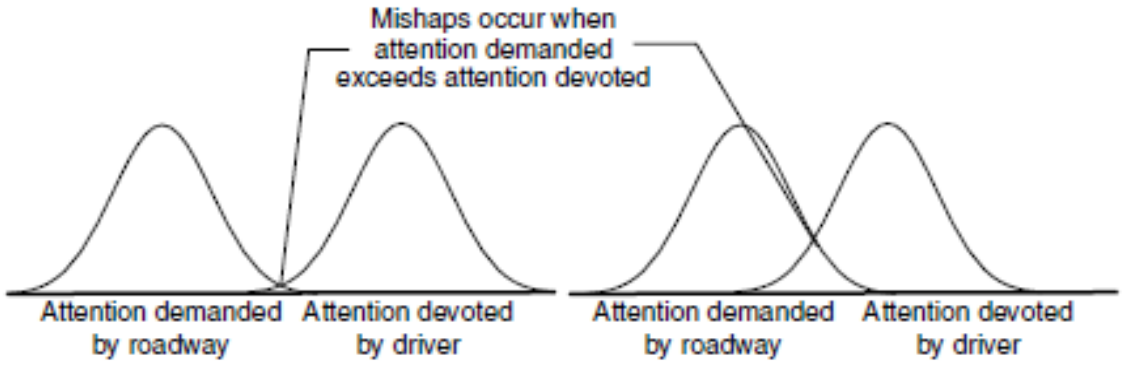


Figure 5. Driver distraction mishaps model [from Lee, Young, Regan (2008), Ch3]

ACC uses laser range finders or radar to detect the vehicle directly in front of it. It can accommodate some of the demands for the driver but there is limited braking authority. As a human-automation interaction design, task effectiveness of an ACC system depends on appropriate time to automatically brake or to alert the driver to manually brake. Therefore, a challenge for designers of ACC is to identify when the system should automatically brake and when it should alert the driver to manually intervene for a lead vehicle that is braking. A good design should therefore consider both the external environment (situation severity) and the capability of the controllers (driver and system). ACC can perform well under many circumstances, particularly when traffic flow is stable, predictable, and demands on drivers' attention are low. However, there are also situations where the lead vehicle may brake unexpectedly or too abruptly given road construction or other unexpected events (Bato & Boyle, 2011; Dickie & Boyle, 2009). Identifying the corresponding response from the controller for each situation (based on the interaction with external factors) can provide insights on the design of these in-vehicle systems.

The driver and external demands associated with ACC use can be quantified in terms of longitudinal control, such as with deceleration of the lead vehicle, relative speed, and relative

distance over time between the host and lead vehicle (Francher & Bareket, 2007; Godbole & Lygeros, 1994). Quantifying attention demanded by the road is a challenging problem. Zhang, Smith, and Witt (2008) examined the demands of driving by using data from both subjective ratings (1 [low]-7 [high] scale) and in-vehicle sensors that included the distance between the lead and host vehicle (range), relative speed (range rate), and angle. In their study, these demands were represented categorically (high, medium, and low) and not as a continuous distribution, making the outcomes difficult to generalize to many situations.

3.1.2 Measure of external demand

One potential measure associated with external demand is the deceleration of the lead vehicle, which the driver cannot control. The magnitude and duration of the deceleration are two metrics that can characterize the lead vehicle situation. These two metrics depend on the status of the lead vehicle and typically reflect the dynamic nature of a lead vehicle-braking event. However, they might also vary greatly depending on the context and are therefore not very predictable. In a lead vehicle-braking situation, the driver needs to control the vehicle using full braking capabilities if no automation exists to assist the driver. Lead vehicle deceleration, as a measure of external demand may be useful to examine drivers' attention given the variability in the environmental. From the driver's perspective, attention devoted by the driver could be examined by how quickly he or she notices or responds to the lead vehicle braking (response time to lead vehicle brake). From the ACC perspective, where there is limited automatic braking authority, the system functions based on the onset of lead vehicle braking. However, this may lead to ineffectiveness given the unpredictability of the deceleration of the lead vehicle.

Another measure of external demand is the relative position between the host and lead vehicle, which can be measured with range (relative distance) and range rate (relative speed).

The ratio of these two measures defines time-to-collision (TTC), and the formal definition is "the time required for two vehicles to collide if they continue at their present speeds and on the same path" (Hayward, 1972). Some of the algorithms associated with forward collision warning systems use the inverse of TTC to trigger alerts (Smith, Witt, Bakowski, Leblanc, & Lee, 2008). In general, these measures take into account the interaction between the host and lead vehicle, and can be used to characterize the situation severity. Test track studies conducted by the General Motors-Ford Crash Avoidance Metrics Partnership (CAMP) characterized drivers' last-second braking and steering performance in car following scenarios (Najm & Smith, 2004; Najm, Smith, & Glassco, 2002). In terms of event severity, CAMP defined four categories of events as low risk (no prompt intervention is needed to avoid a crash), conflict (last-second normal intensity maneuvers), near crash (last-second hard intensity maneuvers), and crash events. Events were also identified for situations when range and range rate between the host vehicle and a lead vehicle exceeded these defined levels. This crash prevention boundary method provided an analytical technique to quantify external demand for complex and dynamic conditions. The boundary showed that the ratios of range and range rate for each category are quite consistent.

Conflict events are onset of risk situations and the controllers need to respond whenever conflict events occur. Therefore, the TTC for the onset of a conflict event instead of the lead vehicle braking is used as an indicator for external demand. From the controller's perspective, response time to conflict events could be used as an indicator for the controllers' attention and is a common measure to examine driving safety. It has also been used to evaluate the efficacy of rear-end collision avoidance systems, where drivers' attention has been shown to change when an alert system was available in the vehicle.

3.2 Method

3.2.1 Data set

A sample of "closing" event was used to examine novice ACC users' behavior. These events were classified into three risky levels: low-risk, conflict, and near-crash events. The classification of these events was predefined by UMTRI based on test track studies conducted by the General Motors-Ford Crash Avoidance Metrics Partnership (CAMP) used to characterize drivers' last-second braking and steering performance and video data validation. The classifications were determined by identifying situations where the ACC vehicle exceeded defined levels based on range and range rate with a lead vehicle. For example, a "closing" event is classified as a near crash whenever it crosses the near crash boundary regardless of the starting or ending point (Figure 6 [right]). Conflict and near-crash events are used in this chapter to examine controllers' response to lead-vehicle braking events and external demand.

There are several assumptions associated with external demand. Given the categories of event severity, conflict events are defined as the onset of severe situations (when range and range rate between the host and lead vehicle first exceeded defined boundary level), and these events can provide insights on safety. Lead vehicle braking is the most common situation for abrupt increases based on demands from the external environment. Therefore, events categorized as conflict events with a lead vehicle braking will be considered in this study.

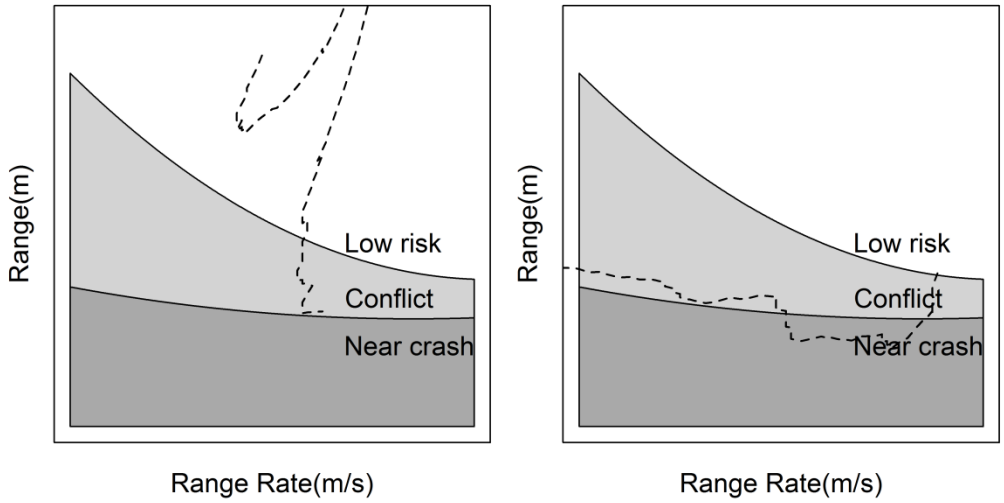


Figure 6. Examples of closing events [represented as the dotted line] for a conflict [left] and a near crash [right] (based on Ervin et al, 2005)

A total of 449 events (conflict and near crash) were extracted from the dataset. All events started as a conflict event with 188 of these events becoming progressively more severe to a near crash event. When any event occurs, appropriate responses are needed from the ACC, the driver, or both for continued safe driving. Therefore, conflict events were used as an indicator to describe severity of roadway environment in this study. Among these events, very few (n=40) were acted upon directly by the driver (i.e. no automatically braking) and as such; the sample size was not large enough to generate a distribution. Therefore, they were not included in further analysis. The majority of the events (n=409) were responded either by ACC alone or a combination of ACC and driver intervention (Table 7).

Table 7. Driver and ACC response based on criticality of events

Braking Response	**Criticality of closing events**		**Total**
	Near-crash	Conflict	
ACC + Driver	80	92	172
ACC only	84	153	237

3.2.2 Measure of interest

3.2.2.1 Deceleration of lead vehicle

Deceleration of lead vehicle can be described with two dimensions: magnitude (how hard) and duration (how fast). The average deceleration (magnitude) of the lead vehicle is an important measure of longitudinal control, which capture how hard for each deceleration. It was measured as:

$$a = \frac{S_1 - S_2}{t_2 - t_1} \quad (10)$$

where a is the average deceleration, S_2 is the lead vehicle speed at time t_2 (end time of lead vehicle brake), and S_1 is the speed at time t_1 (start time of lead vehicle brake).

The trajectories of events reveal that the lead vehicle speed decreased steadily over time with some fluctuation for only a few events (4.8%). For the events that become classified as a near crash, no differences in the average deceleration were observed between events that were based on ACC and those that included ACC+Driver (Kolmogorov-Smirnov [KS] Test, p=0.68). All near crash events were therefore grouped together and the resulting distribution was normal (mean = 0.18 g, SD = 0.07 g) with a maximum value of 0.66 g.

For the events that remained classified as a conflict, no differences in the average deceleration between the ACC and ACC+Driver events were observed (KS Test, p=0.16) and these conflict events were also grouped together. The resulting distribution (conflict) was not normal (median = 0.15, skewness=0.79) with a maximum value of 0.48 g. The deceleration magnitude of the lead vehicle for near crash events was significantly larger than that of conflict events (KS Test, p<0.001) [Figure 7(a)].

Deceleration time is a measure of how quickly the lead vehicle is decelerating. There were no significant differences in duration of deceleration for events with ACC automatic braking

only, regardless of whether the event became a near crash or stayed as a conflict (KS Test, p=0.28). All automatic braking events were therefore combined, but it is noted that the distribution (for ACC only) was not normal (median=2.5 s, skewness=1.46) with a maximum value of 13.1 s. This distribution of automatic braking was significantly different from distributions of events that included manual braking [Figure 7(b)]. That is, the harder the lead vehicle braked, the riskier the situation. Likewise, the longer it took for the lead vehicle to brake, the more likely the driver was to manually intervene. The joint distributions of magnitude and duration of lead vehicle deceleration also underscore the differences among the four event situations (Figure 8).

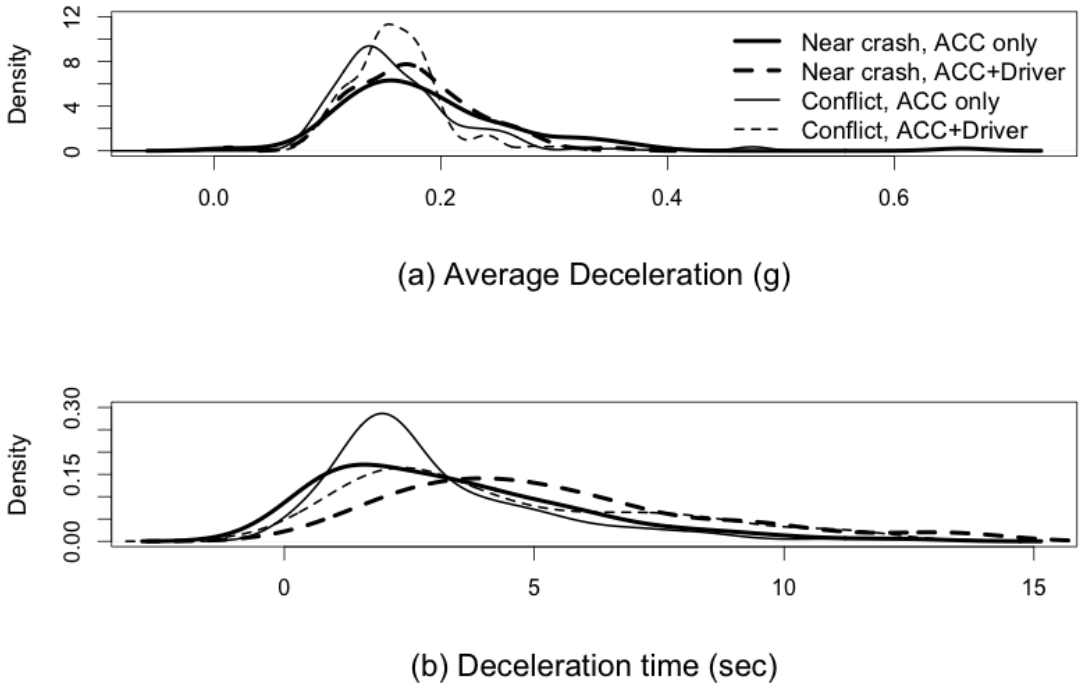


Figure 7. Distributions of average deceleration (a) and time (b)

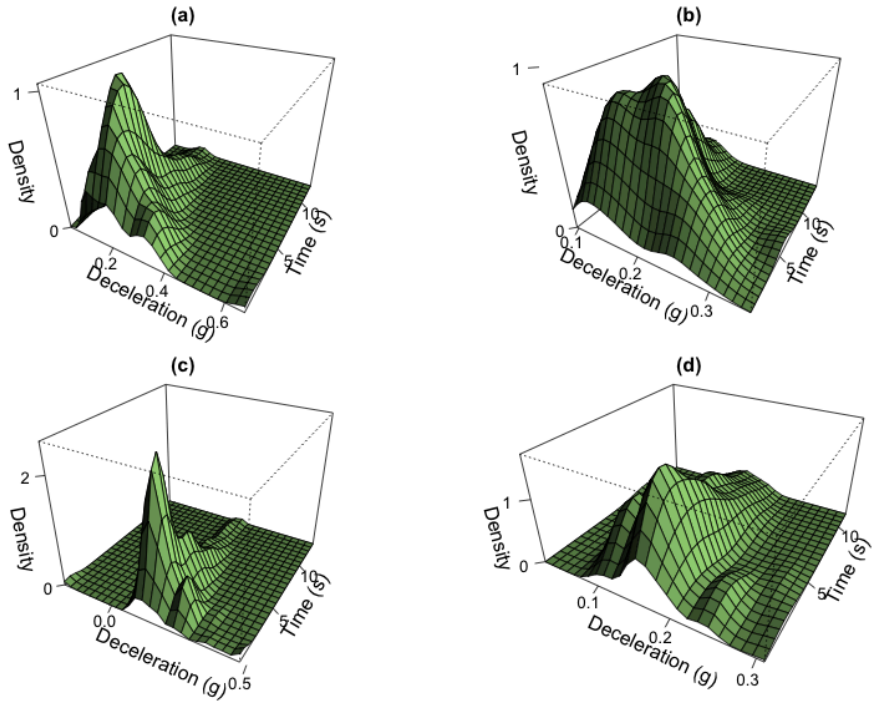


Figure 8. Density plots of duration and magnitude of lead vehicle deceleration for (a) near crash – ACC only, (b) near crash – ACC+Driver, (c) conflict – ACC only, (d) conflict – ACC+Driver

The response time of the controller (ACC) to a lead vehicle braking was examined and no significant differences were observed among the four conditions (Figure 9). Examples of controllers (ACC and Driver) responded to a lead vehicle braking under conflict and near crash events showed that less and shorter deceleration of the lead vehicle was occurred under a conflict event (Figure 10a) compared with a near crash event (Figure 10b). However, the ACC response times to the lead vehicle brake were the same (0.6 seconds, 0 indicated the onset of the lead vehicle brake). This indicates that the ACC automatic brake algorithm might be based on the onset of the lead vehicle decelerating. It is reasonable since the main functionality of the algorithm is to maintain constant time headway distance. Whenever the lead vehicle brakes, the headway distance will decrease. Therefore, ACC auto-brake will be triggered. Given the

variations of the deceleration rate, the algorithm design could be improved by accounting for changes in relative position.

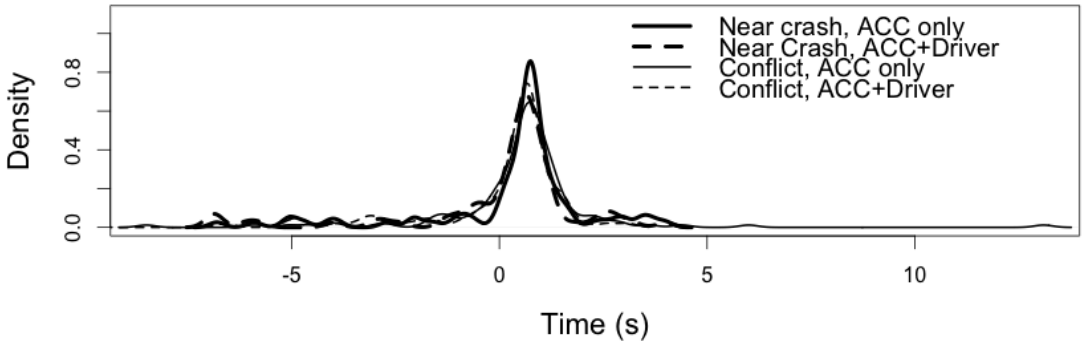


Figure 9. Distribution of response time to lead vehicle brake

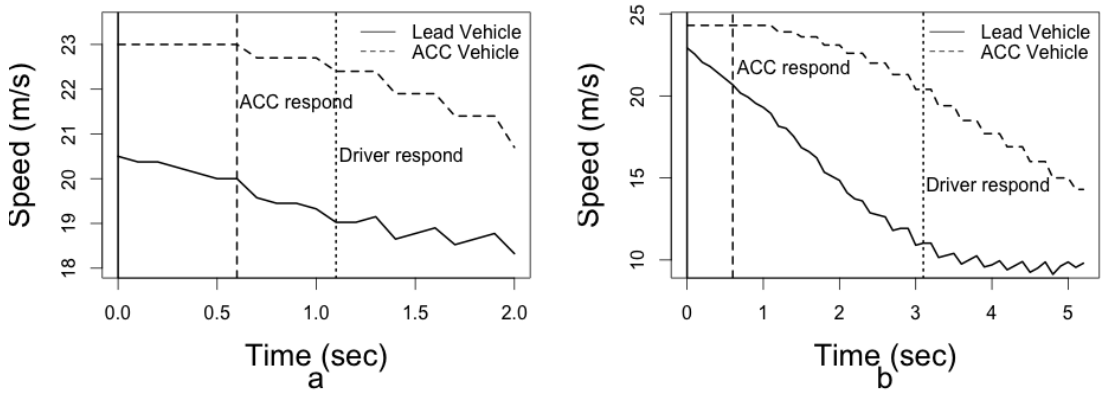
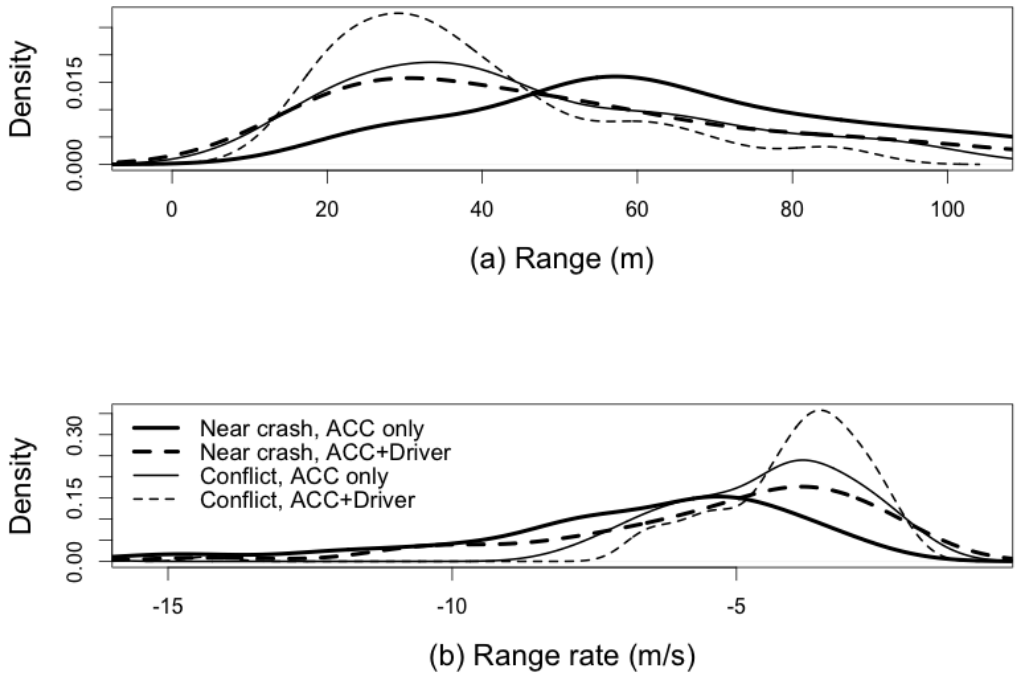


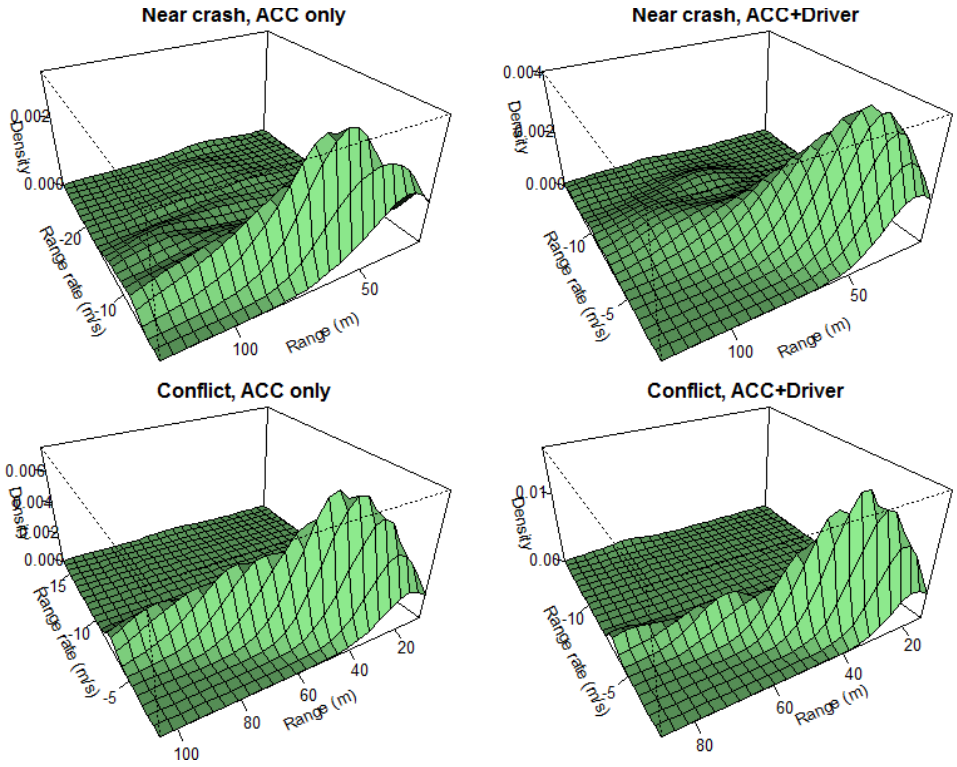
Figure 10. Response to lead vehicle brake under conflict event (a) and near crash event (b)

3.2.2.2 Range and range rate

Range and range rate are two measures of longitudinal control that rely on both the host and lead vehicle. The distributions of range and range rate differ according to the response situations [Figure 11 (a)]. The range and absolute values of range rate were smaller for events that remain at conflict level when compared to those events that became progressively more severe to a near crash level. But the 2-D plot [Figure 11 (b)] showed similar pattern of range and range rate for four different conditions. Taking the ratio of range and range rate could even out these differences, and that is the same as TTC. Therefore, TTC was used as the measure of external demand.



(a) One-dimension distributions of range and range rate



(b) Joint distribution of range and range rate

Figure 11. Distribution of range and range rate

3.2.2.3 TTC

In terms of event severity, CAMP defined four categories of events as low risk (no prompt intervention is needed to avoid a crash), conflict (last-second normal intensity maneuvers), near crash (last-second hard intensity maneuvers), and crash events. Events were also identified for situations when range and range rate between the host vehicle and a lead vehicle exceeded these defined levels. This crash prevention boundary method provided an analytical technique to quantify external demand for complex and dynamic conditions. The boundary showed that the ratios of range and range rate for each category are quite homeostasis. Conflict events are onset of risk situations and the controllers need to respond whenever conflict events occur. Therefore, the TTC for the onset of a conflict event is used as an indicator for external demand. The TTCs then decrease as the events progress.

3.3 ACC Braking Capability Analysis

The distributions of TTC under different response situations for events that begin as conflict events are shown in Figure 12. For the events that progressed to a near crash, no differences were observed between the ACC only and ACC+Driver events (Kolmogorov-Smirnov [KS] Test, $p=0.30$). They were therefore combined for subsequent analysis. Differences were observed for the conflict only events between ACC only and ACC+Driver so they were not combined (KS Test, $p=0.01$). The comparison of the combined near crash events (ACC only, ACC+Driver) to the conflict only events in the ACC+Driver condition was not significantly different (KS Test, $p=0.23$). In other words, TTC did not differ based on the time the conflict began, regardless of whether the event became a near crash or stayed a conflict in the ACC+Driver event. Henceforth, these three events were combined into one distribution [labeled Dist A in Figure 12 (b)]. This confirmed our assumption of non-significant TTC variations at the start point of conflict events.

Hence, TTC provided greater homeostasis and predictability of the external environment when compared to using only lead vehicle deceleration.

Dist A appears to be normally distributed with mean 9.17 s and sd 2.14 s (KS Test, p=0.17) and is therefore modeled as such for this point on. This distribution appears to be a good indicator of TTC and may be useful for examining attention demanded from external environment. However, there were significant differences between Dist A and the distribution of events that remained at as conflict events with ACC automatically braking only (Dist B) (KS Test, p=0.04). Dist B appears to be normally distributed with mean 9.75 s and sd 1.86 s (KS Test, p=0.89) and Dist B has a larger mean (9.75 s) than Dist A (mean=9.17 s) indicating that Dist B appears safer.

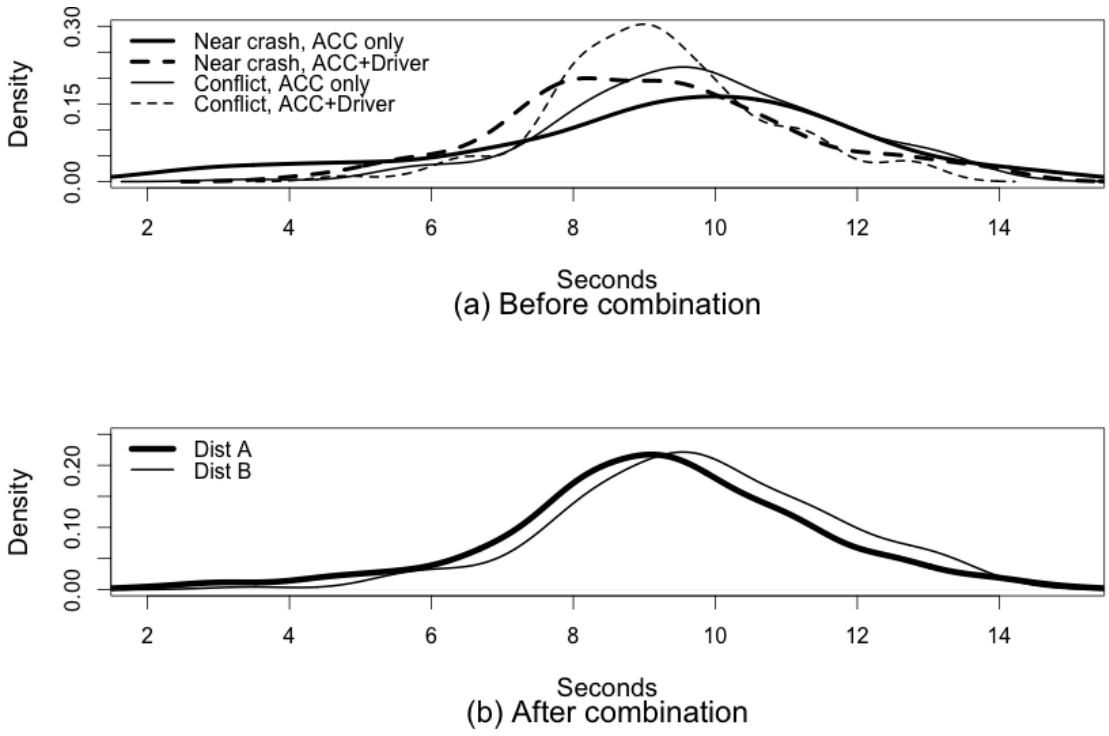


Figure 12. Distributions of time-to-collision under conflict events before (a) and after (b) combination [for distribution A (combination of autobrake in near crash, auto+manual brake in near crash, and auto+manual braking in conflict events) and distribution B (autobrake in conflict events only)]

As stated earlier, Dist A has similar severity at the start, but the severity of the events did change later. Some events became more severe to near crash, and others stayed in the conflict level or disappeared altogether. Drivers' interventions also differed with some drivers intervening while others allowed ACC to automatically brake. The differences can be observed by examining the initial response of ACC during the conflicts events, which can be used as an indicator of attention devoted by the driver and vehicle controllers. There were significant variations in the ACC response time to conflict events given varying situations (

Figure 13. and Table 8).

Table 8. Comparison of response time to conflict events given varying situations

Condition 1	**Compared to Condition 2**	**P-Value**
Near Crash, ACC only	Near Crash, ACC+Driver	$p<0.001$
Near Crash, ACC only	Conflict, ACC+Driver	$p<0.001$
Near Crash, ACC+Driver	Conflict, ACC+Driver	$p<0.01$

If ACC responded quickly to conflict events (indicated by the thinner line), the severity levels of the event would remain in conflict stage. On the other hand, if ACC responded slowly, the event severity levels moved to a higher, near crash level. This also suggests that the ACC algorithm used in this study were not designed based on TTC as an indicator of conflicts.

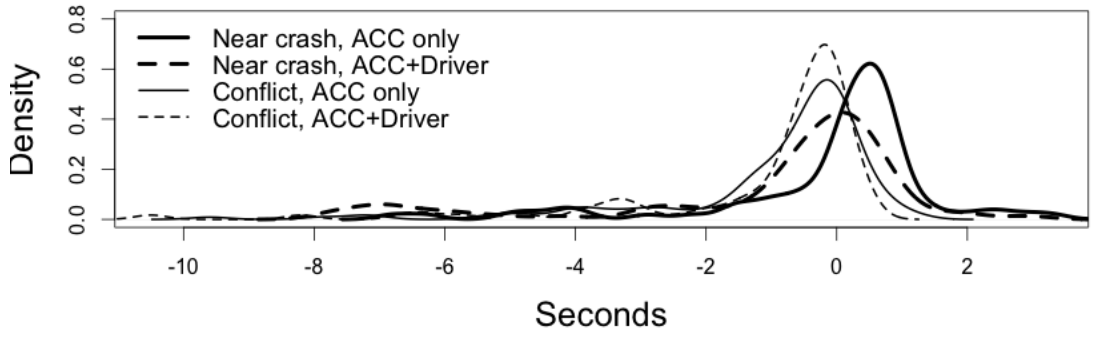


Figure 13. ACC response time to conflict events

As noted earlier, TTC can be used an indicator of the attention demanded from the external environment. If that is the case, ACC response time to conflicts can be used as an indicator of attention devoted by the ACC system. Hence, drivers' response time to conflict events is needed to also identify the attention needed by drivers. The relationships of these two attention distributions under varying situations can provide insights on the design of safety systems. Since all response time distributions have long left tails, median is used as a more robust measure than the mean. The distributions of ACC response time under conflict only events are very similar with each other and have similar median (m=-0.4 s [conflict, ACC+Driver], m=-0.3 [conflict, ACC only]). However, the medians of ACC response time under near crash events were different (m=-0.15[near crash, ACC+Driver], m=0.35 [near crash, ACC only]).

Figure 14 shows the empirical distributions of TTC and response time to conflict events for four situations: ACC auto brake and combine ACC auto + driver manually intervening for near crash events, and the same two scenarios for conflict events. Figure 14 (a) shows the events that became more severe (i.e., near crash events) in the auto-braking condition. The overlap in the two distributions represents the area that the drivers' attention demanded by the roadway exceeds the attention devoted by the ACC system and driver. Hence, there is a higher likelihood of a crash (4.82%, empirical results). Figure 14 (b) shows the events that became more severe to near crash events later but unlike Figure 14(a), the driver does intervene. In these situations, the two distributions have very little overlap. Figure 14 (b) shows that the ACC system responded slightly earlier to events when compared to Figure 14 (a). Because ACC responded slightly earlier, the drivers also had more time to intervene, which resulted in safer driving situation (only one observation overlapped between the two distribution). There was a 1.25% likelihood of a crash. Figure 14 (c and d) shows events remained at as conflict events. The two distributions

were far from each other, indicating that ACC system responded to the events very early and a safer driving condition maintained by the ACC system (no overlap was observed in this dataset).

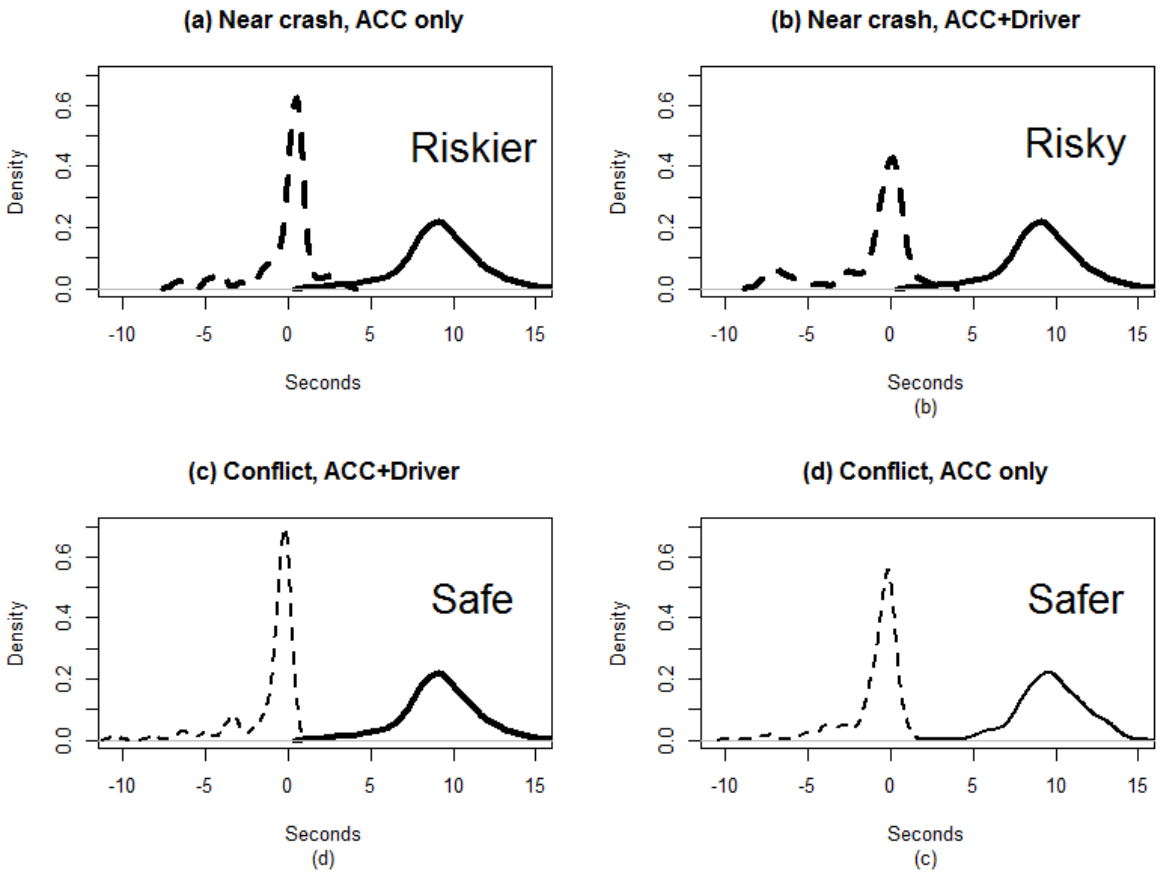


Figure 14. Empirical distributions of TTC and ACC response time to conflict events

Since TTC did differ slightly under varying situations, further examination of the mean and median (i.e., location differences) between the TTC and ACC response time might provide additional insights on system design. Empirical data shows that TTC values appear to be normally distributed. However, the ACC response time were highly skewed. Given that this data is from one sample, a bootstrap resampling method was used with the recorded data to predict the outcomes for multiple samples. There was minimal variations between bootstrapping results and empirical results. The small standard deviations in the simulated data showed fairly

consistant results. Differences in means and medians between distributions greater than 9.55 s indicate a minimal likelihood of a crash. Differences on the order of 9.55 s indicate that any conflict situations can be removed with driver intervention. When the difference is greater than 10.15 s, the conflict situation will disappear with ACC auto braking. When the difference decreases to 9.35 s, the crash likelihood will increase by 0.82%. When the difference decreases further to 8.81 s, the crash likelihood will increase to 3.5% (Table 9). These findings can be beneficial for an ACC auto braking algorithm design.

Table 9. Likelihood of crash between the distributions of TTC and ACC response time for mean and median values

Conditions	**Empirical results**		**Simulated results**	
	Difference (TTC mean- response time median)	**Crash likelihood**	**Difference (SD)**	**Crash likelihood**
Near Crash, Auto	8.82	4.76%	8.82 (0.17)	3.48%
Near Crash, Auto+Manual	9.32	1.25%	9.35 (0.20)	0.83%
Conflict, Auto+Manual	9.47	0%	9.55 (0.18)	0%
Conflict, Auto	10.15	0%	10.10 (0.17)	0%

3.4 Summary

The objective of this chapter was to examine system effectiveness based on demands that can occur based on situations that cannot be controlled by the driver, and the attention devoted by the controller (driver and ACC). This objective was accomplished using data from a subset of "closing" events from the FOT conducted at UMTRI. The data lends itself well for calculating distributions of external demand and controllers' attention because it contains an extensive data set recorded over time under severe situations with lead vehicle braking events.

The distributions of the lead vehicle deceleration rates show that larger lead vehicle deceleration rates and longer duration were associated with more severe situations. If the automatic brake algorithm is designed to trigger based on the response time to the onset of the lead vehicle braking but not the degree of lead vehicle deceleration, it will not be useful in all crash situations. Lead vehicle braking is a dynamic process (the deceleration magnitude will change over time). Hence, if the auto-braking algorithm is based only on the onset of the lead vehicle braking, any changes in external demand will not be appropriately accounted for by the ACC system. This chapter showed that the likelihood of a safety critical event is highly affected by the system response to TTC at the onset of conflict events, which can also capture situation severity. Therefore, accounting for lead vehicle braking events as well as TTC is important for developing guidelines for the timing of system-set braking.

This chapter provided an initial framework for designing automation algorithm that can be used for other driver assistance safety systems. This chapter showed that those who encountered greater lead vehicle deceleration rates have a higher probability of being in a near crash when compared to the conflict state. Previous studies have demonstrated that driver performance (e.g., speeding, acceleration, braking) can have an impact on safety (Lajunen & Summala, 1997; Xiong & Boyle, 2012b). This chapter extends previous studies by also examining response time to changing environments (i.e., roadway demands). The findings underscore that the profile of system response and driving behavior can have an impact on crash risk.

The naturalistic study provided a way to identify the association between safety and various road factors. The framework to examine drivers' behavior and ACC system effectiveness was established through the previous and current chapter. This system decomposition method provided a means to examine a system by focusing on individual components in detail while still

accounting for the complexity of the system. The findings from the on-road study provide insights that will be examined further in the forthcoming chapters. More specifically, the next two chapters will examine the causal effects and magnitude of the driver-system interactions.

Chapter 4: Experienced ACC Use Patterns (Aim 3)

The goal of this chapter is to examine the ACC use patterns of experienced ACC users. Data from a driving simulator study is used to achieve this goal. This chapter begins with an overview of the simulator study conducted in Iowa City, IA, followed by the analysis tools (cluster analysis and bootstrapping methods) that are used to examine differences in ACC user groups. The work described in this chapter has been published in *Human Factors (Xiong, Boyle, Moeckli, Dow, & Brown, 2012)*

4.1 Driving Simulator Study

Participants

There were 24 participants with a registered Toyota or Lexus solicited from a motor vehicle database from the Iowa Department of Transportation (Dickie & Boyle, 2009). This Institutional Review Board approved (No. 200809771) database included a list of Iowa-registered vehicles that could be equipped with ACC, by make, model, and year. All participants were screened for some ACC experience and drove at least 4,830 km per year. The mean age was 55.8 years (sd=13.7, min=31, max=77). There were 14 males with a mean age of 60.4 years (sd=14.2) and nine females with a mean age of 48.8 years (sd=9.9). Participants' median self-reported driving distance with ACC was 60,800 km (range=2,414 to 125,370). One driver was excluded due to the low percentage of ACC use during the study drive.

Apparatus

The driving simulator: The University of Iowa's motion-based simulator (National Advanced Driving Simulator) was used in this study (see Figure 15). It consisted of a 13-degrees-of-freedom motion base with a 24-foot-diameter dome in which the cab of a passenger vehicle was mounted. The dome could rotate about its vertical axis by 330 degrees in each

direction and moved independently along the X-axis and Y-axis in a 64-foot-by-64-foot bay. The visual system consisted of eight liquid crystal display projectors that projected a 360-degree photo-realistic virtual environment.

Figure 15. NADS-1 simulator

The ACC system: The ACC system was based on the Toyota Dynamic Laser Cruise Control system and could only be engaged within speed ranges of 40.3 to 141.5 km/h. ACC controls and display features were also designed similarly to this vehicle (see Figure 16). Two types of alerts may also appear as needed. The ACC will automatically disengage and send an audio alert of termination with a speed of 40.3 km/h or lower. As the leading vehicle brakes hard and the required deceleration rate exceeds the ACC maximum rate (0.3g), an audio alert of deceleration limit exceedance will also be sent.

Figure 16. ACC controls (left) and display (right) in the motion-based simulator

Real world testing on a 2010 Toyota Avalon was conducted in a variety of roadway and traffic environments to validate the realism and performance of the ACC model. The data from the accelerometer was collected at 10 Hz and included longitudinal acceleration, lateral acceleration, and engine revolutions per minute (RPM). A laptop data acquisition system was also connected to the car's on-board diagnostic system port and used to collect engine RPM, engine load, throttle input, and velocity. Finally, a video camera and digital voice recorder were used to record the icons and alerts generated by the car, and assist in deducing any unknown model parameter values. The model included built-in lag for detecting vehicles, adaptive limits on deceleration and jerk, and adaptive sensor object detection on curves.

Driving Environment and Task

The simulated driving environment controlled for the road geometry (straight and curve) and road type (rural, interstate, and residential). The radius of the curved roads ranged from 91 m to 1173 m. The distance of rural, interstate, and residential road segments is 22 km, 21 km, and 3 km, respectively. The main study scenarios consisted of 14 events and had an estimated drive time of about 30 minutes (i.e., each event appears approximately two minutes apart). Of the 14 events, three were critical events, three were non-critical events and eight were other types.

Critical events were designed to elicit crash-avoidance maneuvers from the driver (e.g., braking or steering) and included a braking lead vehicle with a high deceleration rate (exceeding the ACC maximum deceleration rate of 0.3g) on both curved and straight roads (Figure 17). Non-critical events did not require crash-avoidance maneuvers from the driver and the ACC system could safely respond to the events. The non-critical events included a lead vehicle brake with a low deceleration rate (not exceeding the ACC maximum deceleration rate) on both curved and straight roads (Figure 18). Other events may or may not have required crash-avoidance maneuvers from the driver and these include encounters with a slow moving vehicle, a stopped vehicle, vehicle cut in, and entering or exiting an interstate ramp. These were not considered critical or non-critical because the deceleration rates were not controlled but were included to add realism to the experiment.

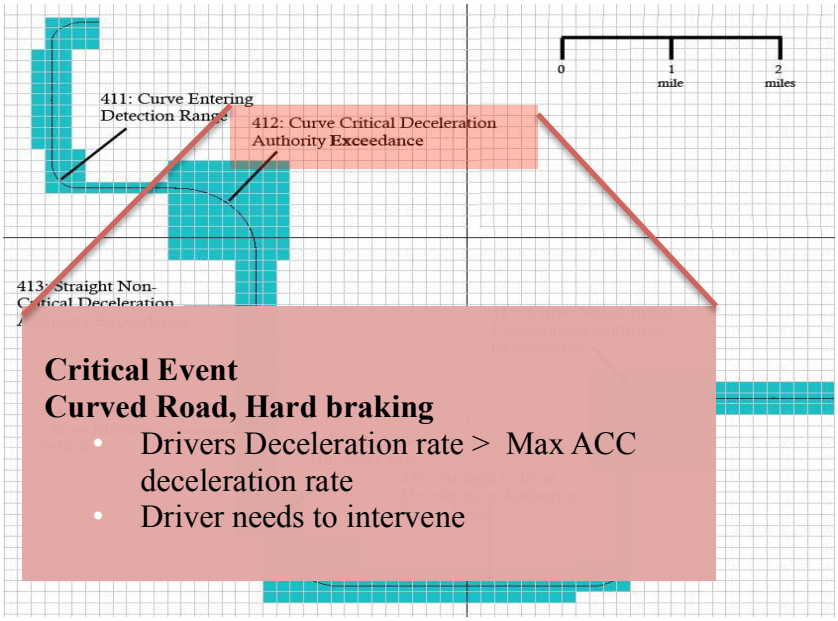


Figure 17. An example of critical events occurred in curve road

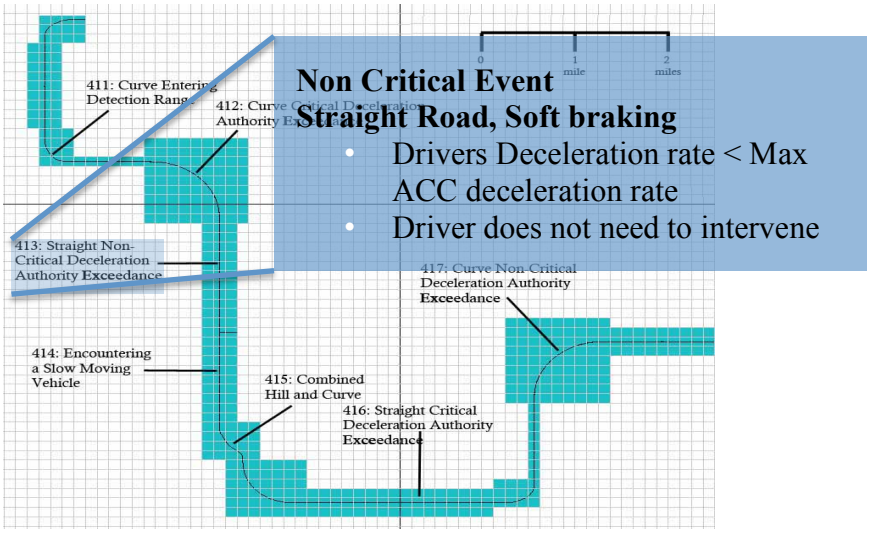


Figure 18. An example of non-critical events occurred in curve road

Seven events occurred in the rural environment, six events appeared in the interstate environment, and the stop vehicle event happened in the residential environment. There were two different main study drives administered between subjects to control for any order effect associated with the sequence of events. The order of the matched critical/non-critical events and the location of the curve entering detection events were balanced between these two study scenarios. The lead vehicle decelerating events occurred in identical (paired) straight and curve segments in the rural environment, and in identical straight segments in the interstate environment. A preliminary analysis showed no significant differences between the two study-drives. Therefore, they were not separated out in the final data analysis.

Procedure

Upon arrival to the testing facility, participants completed an informed consent form and surveys covering general questions about their driving style and background, previous experience with ACC, health history, and trust in ACC. After that, participants were provided with an overview presentation of the simulator cab and drive, and the ACC system to be used on

their drive. Immediately afterward, they completed an estimated 5-minute practice drive in the interstate environment to become familiar with the simulator and the ACC system. The main study began after participants reported they were comfortable in the simulator and understood the task. Participants were instructed to drive with ACC engaged as much as they were comfortable doing so, but also to drive as they would normally. After the drive, participants completed a questionnaire to assess the realism of the simulator and a post drive questionnaire asking questions about three video clips which reflected key events in the drive (e.g., critical driving event, stationary vehicle).

4.2 Statistical Analysis

4.2.1 Cluster analysis

Studies suggest that there are subgroups of ACC users based on age, experience, and drivers' awareness of ACC system limitations (Dickie & Boyle, 2009; Jenness, Lerner et al., 2008; Rajaonah, Anceaux et al., 2006). The subgroups in Dickie & Boyle's study were determined based on cluster analysis, a method proven useful in other studies that have examined technology use among different driver groups (Conquest, Spyridakis, Haselkorn, & Barfield, 1993; Deery & Fildes, 1999; Donmez, Boyle, & Lee, 2010; Lee, McGehee, Brown, & Reyes, 2002). This same methodology was used in this study to cluster drivers based on ACC use patterns to gain insights on potential safety consequences.

Cluster analysis is typically used to make inferences about groupings that may exist in a given population of data. It can be used to create classifications essentially based on measures of similarity. Ward's distance measure is used to measure of variance within each of the clusters. Unlike other hierarchical methods, this method seeks to minimize the error sum of squares

between two clusters added over all the variables. As opposed to maximizing differences between clusters with other methods, Ward's distance instead makes the entities within each cluster more similar to each other (Punj & Stewart, 1983). Moreover, it is most appropriate for quantitative variables and thus was chosen in this study. The number of clusters was determined from the Pseudo F statistics, a common measure of clustering fit (Pedersen, 2005). It is a measure of between-cluster variation divided by within-cluster variation and can capture the "tightness" of clusters.

4.2.2 Clusters of experienced ACC users

Drivers' adaptive behavior can be measured by their use of ACC (driver-system), and is demonstrated in this study by the drivers' preferred selections of headway and speed and their intervention preference with ACC. The measures included total number of times ACC was disengaged, percentage of time the short, medium, or long gap settings were selected, the total number of warnings issued, and the difference between average set speed and speed limit. These measures were collected across the entire drive for each participant and were therefore used as the clustering variables.

The Pseudo F (PSF) statistics suggested that three clusters (PSF=9.23) was appropriate (compared to 2 [PSF=10.3] and 4 clusters [PSF=15.5]). These clusters were classified as: Conservative (C), Moderately risky (M), and Risky (R). Drivers in the Conservative group selected lower set speed and longer gap settings, and had fewer numbers of warnings. Therefore this cluster was considered as the lowest risk group. Drivers in the Moderately risky group set higher speed and shorter gap settings, but they drove moderately safe as demonstrated with the least number of warnings. Drivers in the Risky group had the most number of warnings and the least number of ACC disengaged events (Table 10). As shown in Figure 19, Conservative and

Moderately risky drivers had significantly fewer warnings than Risky drivers (Δ_{C-R} 1=-2.82, CI: -3.33, -2.33 and Δ_{M-R}=-2.95, CI:-3.50, -2.43).

Table 10. Mean values for ACC use pattern by cluster group

Clusters (sample size)	**Numbers of ACC disengaged**	**Number of warnings**	**D Speed (Set - posted [m/s])**	**% of gap setting**		
				Short	Medium	Long
C (n=12)	13.83	0.42	-1.27	1.6%	4.9%	93.5%
M (n=7)	15.86	0.29	0.20	32.6%	54.1%	13.3%
R (n=4)	9.50	3.25	0.15	0.0%	2.9%	97.1%

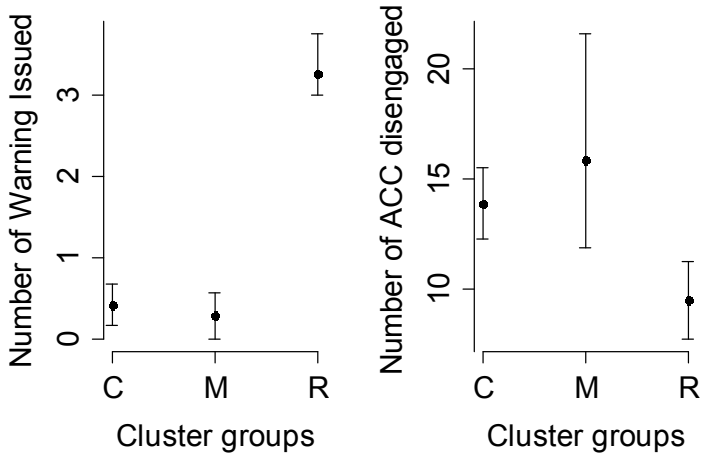


Figure 19. The different use patterns between cluster groups: conservative (C), moderately risky (M), and risky (R)

4.2.3 Characteristic of clusters

4.2.3.1 Subjective measure analysis

Statistical differences of subjective variables among the cluster groups were assessed using a bootstrapping sampling technique. Bootstrapping is a computer-intensive approach to statistical inference that constructs a number of resamples of the observed dataset by random sampling with replacement from the original dataset (Efron, 1979; Efron & Tibshirani, 1994).

[1] C-R is the mean difference between Conservative (C) and Risky (R) clusters; M-R is the mean difference between Moderately risky (M) and Risky (R), and so forth.

Bootstrapping procedures can be used when the theoretical distribution of a statistic is complicated or unknown, the sample size is insufficient for straightforward statistical inference (Adèr, Mellenbergh, & Hand, 2008). The 95% confidence interval (CI) was examined and statistical significance was assessed if the pair-wise test did not include zero.

Studies have shown that trust may affect the use of automatic controllers (Dzindolet, Peterson, Pomranky, Pierce, & Beck, 2003; Lee & See, 2004; Parasuraman & Riley, 1997). There were 12 questions related to trust in ACC reflecting drivers' attitude to ACC operation, the extent that ACC performed properly, and the driver's self-confidence in manually intervening. Each question used a scale that was based on the degree that they trusted ACC from 0 (Not at all) to 100 (Extremely high) (Muir & Moray, 1996).

There were significant differences among five of the 12 trust questions. Drivers in the Conservative group were more likely to count on the ACC system to do its job when compared with drivers in the Moderately risky group (Δ_{C-M} =19.61, CI: 5.23, 34.66). Compared to the other two groups (Δ_{R-C} =-13.42, CI: -22.75, -4.66; Δ_{R-M} =-11.93, CI:-22.79, -0.78), drivers in the Risky group were less likely to trust ACC to work the same for similar circumstances at different time periods. Drivers in the Moderately risky group had less trust in the ACC system's display than drivers in the other two groups (Δ_{M-C} =-18.88, CI: -39.62, -1.12; Δ_{M-R} =-21.64, CI:-42.73, -3.21). Drivers in the Conservative group had higher overall trust in the ACC system when compared with drivers in the Moderately risky group (Δ_{C-M}=22.04, CI: 0.79, 45.66). Drivers in the Conservative group were more likely to trust their cooperation with ACC system compared to drivers in the Moderately risky group (Δ_{C-M} =20.55, CI: 0.39, 40.29).

There were three questions related to knowledge of ACC. Each question was on a 5-point Likert scale ranging from (1) "Not at all (indicating aware)" to (5) "Very much (indicating

unaware)", and 6 as "not know (towards unaware)". Drivers in the Conservative group were more likely to know the ACC doesn't function with a stationary vehicle compared with the Moderately risky group (Δ_{C-M} =-1.33, CI: -2.62, -0.02). Drivers in the Conservative group were more likely to know the ACC doesn't function well when a leading vehicle brakes hard compared with the Risky group (Δ_{C-R} =-1.50, CI: -2.75,-0.17).

Driving style may also influence the use of automatic controllers and 15 responses were solicited using a driving style questionnaire (West, Elander, & French, 1992). Each question was on a 6-point Likert scale ranging from (0) "Never or very infrequently" to (5) "Very Frequently or Always". Drivers in the Moderately risky group were more likely to plan long trips in advance when compared with drivers in the other two groups (Δ_{M-C} =1.29, CI: 0.07, 2.48; Δ_{M-R} =1.63, CI: 0.29, 2.79). Drivers in the Conservative group were more likely to like people giving them advice about their driving compared to drivers in the Risky group (Δ_{C-R} =-1.08, CI: -1.75, -0.50). Drivers in the Moderately risky group ignored distractions more easily while driving than drivers in the Risky group (Δ_{M-R} =0.82, CI: 0.29, 1.46). Drivers in the Moderately risky group were more likely to drive faster than drivers in the other two groups (Δ_{M-C} =1.19, CI: 0.12, 2.25; Δ_{M-R} =1.57, CI: 0.36, 2.64). Drivers in the Risky group passed vehicles more frequently on a four lane roadway if they had the opportunity than drivers in the Conservative group (Δ_{R-C}=0.92, CI: 0.08, 1.83).

4.2.3.2 Safety performance analysis

Three measures were used to examine driving performance. These included the vehicle's relative position to a lead vehicle (minimum time headway), the minimum allowed reaction time from the controller (adjusted minimum time to collision), and driver's reaction time to critical events. The minimum time headway (MTH), defined as the minimum time it would take the

participant's vehicle to travel the distance from the participant to the lead vehicle given the participant vehicle's current velocity, has previously been used to study behavioral adaptation (Hoedemaeker & Brookhuis, 1998). The adjusted minimum time to collision (AMTTC) was defined as the amount of spare time the controller (either the driver or ACC system) has available based on the avoidance response chosen. This measure differs from the traditional minimum time to collision by accounting for the change in velocity as well as change in deceleration rate, which allows a more accurate and robust approach to examine crash scenarios (Brown, 2005). The driver's reaction time was defined as the elapsed time from the initiation of the event, e.g. when the lead vehicle began to decelerate (indicated by the lead car brake lights come on), to the driver's initial steering wheel or braking response, and has been used in studies related to a new in-vehicle technology and driver distractions (Consiglio, Driscoll, Witte, & Berg, 2003; Srinivasan & Jovanis, 1997).

Non-critical events. In terms of the ACC system, auto-brake control is an essential factor that may affect safety consequence. Non-critical events were designed to allow ACC to safely respond to the event without any intervention from the driver. There were 69 non-critical events (or three per driver) in this study, and drivers responded to 21.7% of these non-critical events (Table 11). Both AMTTC and MTH were evaluated between cluster groups by using linear mixed-effects model.

Table 11. Response frequency to non-critical events among cluster groups

	Non-Response Number (percent)	Response Number (percent)
C(n=12)	28 (77.8%)	8 (22.2%)
M(n=7)	14 (66.7%)	7 (33.3%)
R(n=4)	12 (100.0%)	0 (0.0%)
Total	54 (78.3%)	15 (21.7%)

Drivers in the Moderately risky group responded to non-critical events more often than drivers in the other two groups and drivers in the Risky group did not respond to any non-critical event. Significant differences in response frequency were shown between drivers in the Moderately risky and Risky groups ($p=0.03$, Fisher's exact test). Drivers in the Moderately risky group also showed significantly shorter AMTTC (M vs. C, $p=0.004$; M vs. R, $p=0.01$) and MTH (M vs. C, $p<0.001$; M vs. R, $p<0.001$) compared with drivers in the other two groups, but there were no significant differences between drivers in the Conservative and Risky groups (Figure 20).

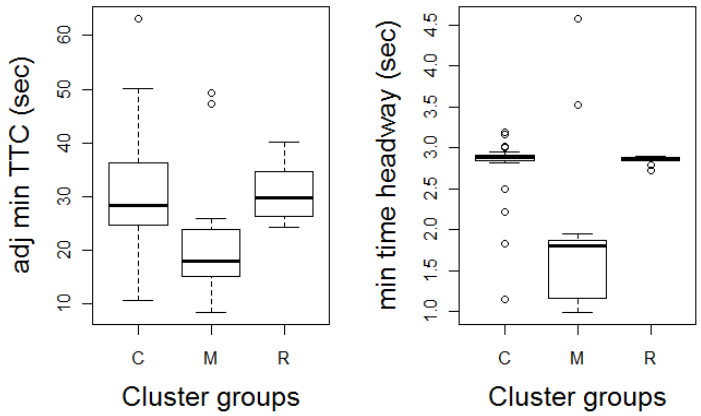


Figure 20. Performance during non-critical events

Critical events. Critical events were designed to elicit crash-avoidance maneuvers from the driver. There were 68 critical events (one event value was not recorded) with drivers responding to 97% of these events. Two non-responses did occur: one from the Conservative group and the other from the Risky group. There were no significant differences for AMTTC among the three groups for critical events. Drivers in the Conservative group had a significantly longer MTH compared with drivers in the Moderately risky group ($p=0.008$). Drivers in the Risky group showed a significantly longer reaction time (R vs. C, $p<0.001$; R vs. M, $p=0.01$) compared with drivers in the other two groups (Figure 21).

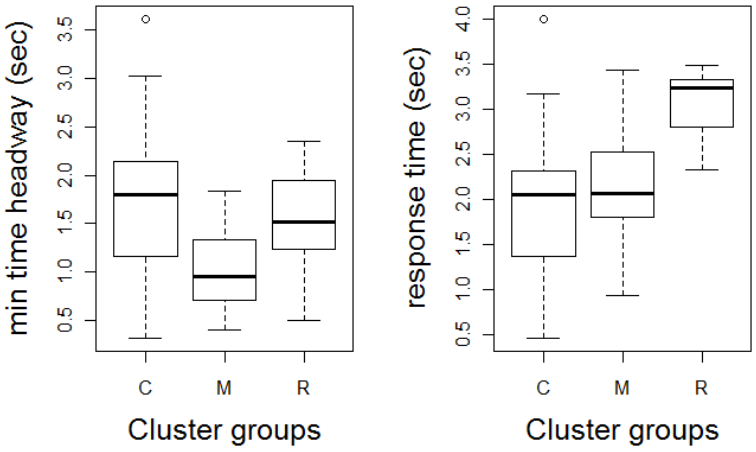


Figure 21. Performance during critical events

The Conservative (and lowest risk) group selected longer gap settings and lower speeds when using ACC and had fewer numbers of warnings issued compared to the Risky group. Drivers have been shown to be more aware of ACC limitations with prolonged use and the drivers in the Conservative group also demonstrated this. They had the most experience with ACC and awareness of ACC limitations compared with the other two groups. This group also showed more cautious use pattern (lower speed setting and longer gap-setting).

Drivers in the Moderately risky cluster used shorter gap settings and higher set speeds, and would intervene more frequently. These Moderately risky drivers appear to be very confident in their driving skills (as revealed by the driving style questionnaire) and also received fewer warnings compared to the Risky group. In contrast, the Risky group never used the short gap setting, had the most warnings, and lowest number of disengaged ACC when compared to the other two groups.

The Moderately risky group were more likely to report driving faster and expected ACC to work even in situations when it would not, such as approaching a stationary vehicle. In other words, this group was not as aware of the limitations of ACC as other groups and may actually

misuse the system. Interestingly, this misuse may relate to the reported low levels of trust in ACC. Moderately risky drivers were also more likely to intervene when compared to the other two groups. Muir (1994) had observed similar behavior in operators intervening when trust in the automation fell below a certain threshold. Moderately risky drivers also reported being more likely to plan long trips and can more easily ignore distractions than drivers in the Risky group. These behavioral characteristics are consistent with the mental model that is intrinsic within each driver as described by Rudin-Brown and Noy (2002). That is, some drivers are Internals and believe their behavior is guided by their personal decisions and efforts; while externals believe their behavior is guided by external circumstances. These beliefs, in turn, guide what kinds of attitudes and behaviors people adapt. In this respect, the Moderately risky group appears to be internals and the Risky group appears to be externals. Recognizing the connection between behavioral adaptation and the psychological characteristics can provide further insights on how drivers adapt to ACC.

The Risky drivers exhibited relatively high trust in ACC and displayed the most ACC usage in the simulator. However, they also had the most warnings. This phenomenon, known as automation complacency (Parasuraman, Molloy, & Singh, 1993) can exist if the operator trusts the automation too much. As a result they may fail to override the system when its operational limits are exceeded or if the system fails (Parasuraman, 2000). Hence, the Risky drivers' use of ACC may be more related to misaligned trust in the automation, rather than intentional aggressive driving behavior.

As previously stated, drivers actually need to intervene during highly critical situations since ACC cannot decelerate quickly enough within this critical moment. This may be an issue for drivers in the Risky group since they responded later to critical events whenever ACC was

engaged. This group was not as aware (as the Conservative group) that ACC does not actually function well when a lead vehicle brakes hard. Hence, additional training on ACC would be useful since this lack of awareness can have serious safety implications.

4.3 Summary

This chapter applied cluster analytic methods using data collected from a driving simulator study conducted in Iowa City, IA. The cluster analysis was composed of driver performance measures and provided insights on different driver groups based on use patterns. Recognizing these different use patterns will help tailor the design and training of these safety-based systems to account for individual differences. However, a survey study (Bato & Boyle, 2011) found that drivers' ACC use preferences were different in rural and urban environment. Therefore, examining use patterns across different regions is of interest and examined in the next chapter of this dissertation.

Chapter 5: Braking Behaviors Analysis (Aim 4)

The purpose of Aim 4 is to examine differences between novice and experienced ACC users within a region (Washington State) as well as between two regions (Iowa and Washington). In this chapter, the protocol for the simulator experiment conducted in Washington State is discussed. This simulator experiment collected data from ACC and non-ACC users. The analyses described focuses firstly, on the outcomes for Washington State, and then secondly, compares the findings to those obtained in a simulator study in Iowa (discussed in the previous chapter 4). Differences in driving behaviors and performance between novice, experienced, and non-ACC users are therefore discussed in this chapter. The data collection and analyses were approved by the UW IRB (#39910).

5.1 Driving Simulator Study

Participants

There were 15 experienced ACC users and 30 non-ACC users recruited for this study. Within the non-ACC users group, participants were further separated into those that were trained and provided ACC during the simulator drive, and those that did not encounter ACC at all in the simulator drive. The participants all had a valid Washington State driver's license and ranged in age from 25 to 75-years-old. They had to own or have driven either a Toyota or Lexus model vehicle, and drive at least 3,000 miles per year. Particularly for ACC users, they needed to have used ACC on average, at least once per month.

There were several factors that warrant exclusion from the study. Drivers who require any special equipment to help them drive (e.g. pedal extensions, hand brake or throttle, spinner wheel knobs) were not included in the current study. If the participants have a history of seizures, epilepsy, Ménière's Disease, any inner ear, dizziness, vertigo, hearing, or balance problems, they

were not included in the study as well. If the participants suffer from a heart condition such as disturbance of the heart rhythm or a heart attack or a pacemaker implanted within the last 6 months, they were also excluded. Additionally, if the participants currently suffer from narcolepsy, they were excluded from the study. Finally, individuals who have a history of motion sickness, or who are identified as exhibiting risks (e.g. pregnancy female) for simulator sickness were not included in the study.

The mean age for experienced ACC users was 57.7 years (sd=13.3, min=29, max=73). There were nine males with a mean age of 63.2 years (sd=9.9) and six females with a mean age of 49.3 years (sd=14.0). Participants' median self-reported driving distance with ACC was 2,7750 miles (range=7000 to 6,1750). The mean age for non-ACC users who used the ACC in this experiment was 53.2 years (sd=15.1, min=26, max=75). There were also nine males with a mean age of 54.4 years (sd=15.7) and six females with a mean age of 51.3 years (sd=15.5). The mean age for non-ACC users who did NOT use ACC in this experiment was 54.0 years (sd=16.3, min=27, max=75). There were also nine males with a mean age of 54.4 years (sd=18.9) and six females with a mean age of 53.3 years (sd=13.2).

Apparatus

The driving simulator: The University of Washington's fixed-based driving simulator (National Advanced Driving Simulator MiniSim, a Mini version of NADS-1) was used in this study (see Figure 22). The visual system consists of three liquid crystal display projectors that projected a 270-degree photo-realistic virtual environment. The steering wheel and ACC system are based on Toyota. Data from the driving simulator is collected at 60 Hz. The ACC system had the same functionality as the one used on NADS-1.

Figure 22. NADS MiniSim driving simulator

Driving Environment and Task

The previous research of ACC users (Xiong, Boyle et al., 2012) was validated with the same simulated driving environment that was described in Chapter 4. The differences included 11 events for this main study rather than 14 events as in Chapter 4 and had an estimated drive time of about 23 minutes (rather than 30 minutes). The three events eliminated were based on rural environments most likely to occur in Iowa (but rarely Washington State given different geographic features). Of the 11 that were kept, four occurred in a rural environment, six occurred in an interstate environment, and one stop vehicle event occurred in a residential environment.

Procedure

Upon arrival to the testing facility, participants completed an informed consent form and surveys covering general questions about their driving style and background, previous experience with ACC (ACC user only), health history, and trust in ACC (ACC user only). After that, participants were provided with an overview presentation of the simulator and drive, and the ACC system to be used on their drive (participants that used ACC in this experiment).

Immediately after, they completed two practice drives estimated 8-minute in total. The first practice drive, which occurred in the rural environment, was designed to let all participants become familiar with the simulator. The second drive, which occurred in an interstate environment, was designed to let participants who used the ACC system in this experiment become familiar with the ACC system. The main study began after participants reported they were comfortable in the simulator and understood the task. Participants who used the ACC system were instructed to drive with ACC engaged as much as they were comfortable doing so, but also to drive as they would normally. Participants who did not use the ACC system were instructed to drive as they would normally. After the drive, participants completed a questionnaire to assess the realism of the simulator.

5.2 Statistical Analysis

5.2.1 Use pattern

Xiong and Boyle (2012) suggested that there could be three subgroups of experienced ACC users based on their ACC use patterns. These subgroups were determined using cluster analysis and for consistency, the same methodology was applied in this chapter for participants recruited in Washington State.

5.2.1.1 Clusters of Washington State ACC users

There were 14 experienced and 13 novice ACC users included for the forthcoming analysis. Three participants' data was excluded due to simulator recording issues. Variables included in the cluster analysis were: total number of times ACC was disengaged, percentage of time the short, medium, or long gap settings were selected, the total number of warnings issued, and the difference between average set speed and speed limit. For the Washington experienced ACC

group, the Pseudo F (PSF) statistics suggested that three clusters (PSF=9.77) was appropriate (compared to 2 [PSF=5.58] and 4 clusters [PSF=9.24]). A three-cluster solution was also identified for the Washington novice ACC group (Figure 23).

Figure 23. Dendrogram of cluster analysis for novice ACC users

5.2.1.2 Comparison of ACC use pattern

These cluster groupings showed similar characteristics to the cluster groups from chapter 4 and were therefore also classified as Conservative (C), Moderately risky (M), and Risky (R). For example, drivers in the Conservative group selected the lowest set speed and longer gap settings. Drivers in the Moderately risky group were most likely to set shorter gap settings, but they also drove moderately safe as demonstrated with less number of warnings compared to the Risky group. Drivers in the Risky group had the most number of warnings (Table 12).

There were also differences noted in use patterns between the two states. In Iowa, drivers set faster speed and closer time headway distance when compared to Washington State drivers. The study conducted in Iowa included three more events and as such, there were more opportunities to disengage ACC as well as generate more warnings (Table 12). Proportionately, the Moderately Risky drivers in Iowa disengaged their ACC more often than Risky and

Conservative drivers, and typically set higher speeds. In Washington (experienced and novice drivers), it was the Conservative group that disengaged ACC most often and had the least number of warnings. However, this Conservative group did set lower speeds.

Use of ACC did differ based on experience level in Washington State. More specifically, novice ACC users intervened more often (greater number of ACC disengaged) compared with experienced ACC users. Novice ACC users also set their system at lower speeds and longer gap settings compared to experienced ACC users. That is, novice users appear to have a more conservative attitude when they are first exposed to a new technology. After they get more familiar with the system, their behavior appears to change. They will either rely more on the system or reject to use it due to the low trust in the system. Given these different use patterns and interaction with ACC system, differentiating the ACC system control algorithm to adapt to different users and environmental setting could be one way designers can improve the system.

Table 12. Mean values for ACC use pattern by cluster group

ACC groups	Clusters (sample size)	Numbers of ACC disengaged	Number of warnings	D Speed (Set -posted [m/s])	% of gap setting		
					Short	Medium	Long
Iowa experienced ACC users	C (n=12)	13.83	0.42	-1.27	1.6%	4.9%	93.5%
	M (n=7)	15.86	0.29	0.20	32.6%	54.1%	13.3%
	R (n=4)	9.50	3.25	0.15	0.0%	2.9%	97.1%
Washington experienced ACC users	C (n=7)	9.43	0.00	-1.50	0.0%	0.5%	99.5%
	M (n=2)	5.50	0.50	-0.51	1.0%	94.6%	4.4%
	R (n=5)	7.20	1.60	-0.23	0.0%	3.0%	97.0%
Washington novice ACC users	C (n=4)	13.25	0.00	-1.94	0.0%	0.0%	100.0%
	M (n=2)	9.00	0.50	-0.74	0.0%	19.9%	80.1%
	R (n=7)	7.00	1.60	-1.09	0.0%	0.5%	99.5%

Note: C: conservative group, M: Moderately risky group, R: Risky group

5.2.2 Braking behavior of Washington State drivers

Because ACC is a longitudinal assistance control system, it is important to consider the ACC functionality and the drivers' response under different conditions with a lead vehicle. Four events were examined in the forthcoming analysis: Non-Critical deceleration on straight road,

Critical deceleration on curve road, Critical deceleration on straight road, vehicle cut in on straight road.

5.2.2.1 Non-critical event

One participant from the experienced ACC (E) user group deactivated ACC during this event therefore was excluded from this analysis. All other participants (including the novice ACC group [N], and non-ACC users) had ACC active and were included in this analysis.

Comparison of longitudinal control among three groups

Speed and headway distance control are two main features of ACC. Drivers in the Non-ACC group (without using ACC) had a significantly longer headway distance (Non-ACC vs. E, $p<0.001$; Non-ACC vs. N, $p<0.001$) compared with the other two groups (with ACC) (Figure 24). Therefore, from system functionality and traffic flow aspect, drivers with ACC maintained shorter headway distance compared with those of without using ACC. There were no significant differences in speed control. However, greater variations for Non-ACC compared with the other two groups were examined from this experiment.

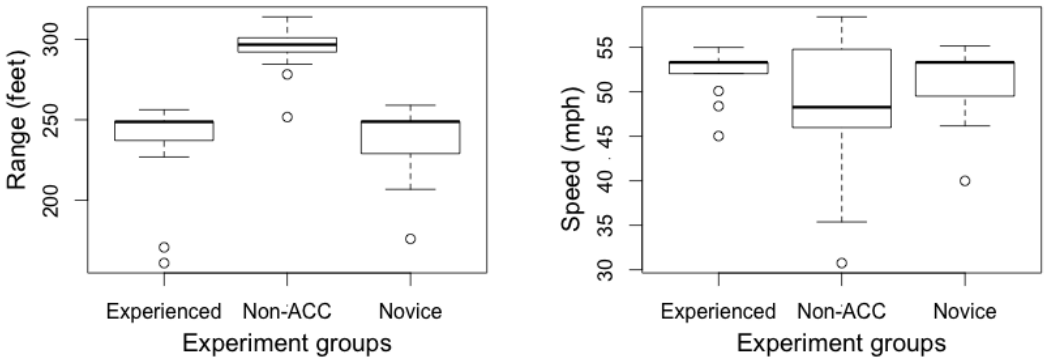


Figure 24. Comparison of distance headway and speed control among three experiment groups

Minimum TTC is again used to quantify the severity of the driving situations. Drivers in the Non-ACC group had a significantly longer TTC compared to experienced ACC drivers ($p=0.02$)

(Figure 25). Therefore, drivers without ACC were more conservative than those of experienced ACC users. Non-ACC users, as a baseline comparison, had longer headway distance, greater speed variations and minimum TTC compared with ACC users. Similar results were also observed during critical events on both curve and straight roads.

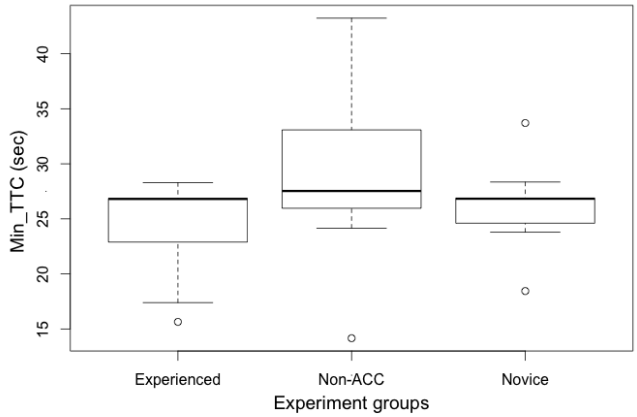


Figure 25. Min-TTC for three experiment groups under non-critical event

5.2.2.2 Curve critical event

There were 14 participants from the experienced ACC group (one was omitted because of missing values). One participant among the 14 participants did not intervene at all. The analysis also included nine participants in the novice ACC group (out of 15 possible). Four were excluded because one were driving lower than the stated speed (35mph), one intervened prior to ACC actually braking; and three had ACC deactivates.

When encountering a hard braking from a lead vehicle, how drivers respond to this event is critical. Experienced ACC users had significantly quicker response time to lead vehicle braking compared with novice ACC group ($p=0.04$). Experienced ACC users showed significantly less

speed differences from the lead vehicle compared with novice ACC group (p=0.04) (Figure 26). However, there were no significant differences on minimum TTC between these two groups.

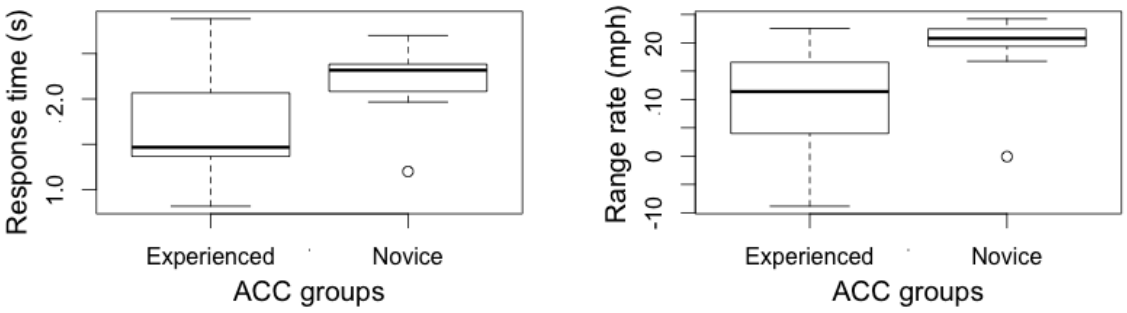


Figure 26. Response time and range rate between ACC users under a curve critical event

5.2.2.3 Critical event on straight road

All participants from the experienced ACC user group (n=15) and 12 participants from novice ACC user group were included in this analysis (one missing data point occurred in the novice group during this event). There were no significant differences in drivers' response time, range rate and minimum TTC between these two groups (Figure 27).

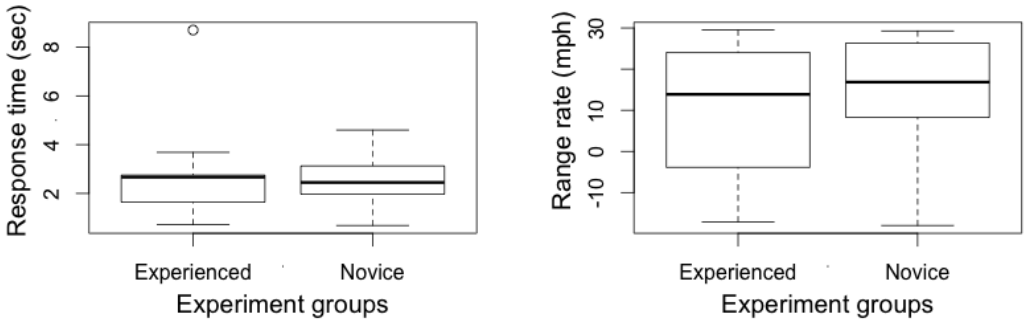


Figure 27. Response time and range rate between ACC users under a straight critical event

Overall, drivers driving with ACC can maintain more stable longitudinal control compared with driving without ACC, which can enhance traffic flow. Experienced ACC responded quicker and drove slower when compared to novice ACC users on curvy road condition. But there were no significant difference between the two ACC groups on straight road condition. This could be due to each driver groups understanding of ACC operations.

There were seven questions related to drivers' understanding on how ACC would help avoid crash with the lead vehicle under different conditions. Each question was answered on a 4-point Liker-type scale ranging from 1 (Not at all) to 4 (To a great extend). Two questions were related to previous situation (hard braking and curvy road). The mean value of answers to the question, "*you are following the vehicle on curvy road"*, was 2.3, which means most experienced ACC users know ACC won't work well on curvy road, therefore they responded quicker to lead vehicle braking on the curvy road. However, the mean value of answers to the question, "*you are following a vehicle that brakes suddenly as in emergency situation"*, was 3.3, which means most experienced ACC users think that ACC would help in hard braking situation, therefore they responded to lead vehicle braking on straight road not as quick as on the curvy road.

5.2.2.4 Vehicle cut-in

There were 13 experienced ACC users (one missing data; one without ACC use) and 12 novice ACC users (one did not use ACC during this event) included in this analysis. Non-ACC group was also included in this event analysis and one participant was excluded from it given how far behind their vehicle was during the cut-in event.

Given the cut-in scenario, there were no significant differences on speed and headway distance control among these three groups. In terms of minimum TTC, there were also no significant differences, which was different from previous situations. However, experienced

ACC users showed greater min TTC variations compared with the other two groups. Some drivers encountered more severe situations than others (Figure 28). Among non-ACC group 13 out of 14 drivers started to brake before the vehicle cut-in. There was five out of 12 novice ACC users started to brake ahead of the time when vehicle cut-in. Only three out of 14 experienced ACC users started to brake before the vehicle cut-in, which may cause more severe situations.

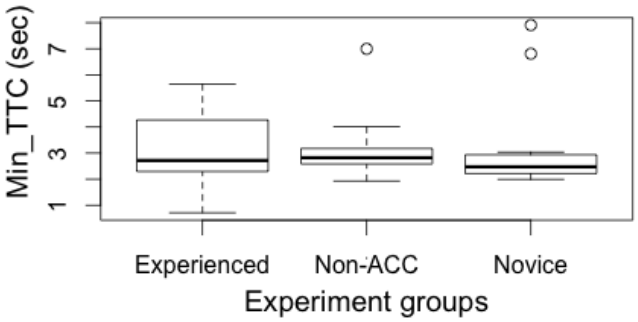


Figure 28. Min-TTC of three experiment groups under cut-in event

During this scenario, the vehicle braked after it cut-in. The response time was defined as the differences between the onset of drivers' brake and cut-in vehicle brake. As mentioned before some drivers started to brake before vehicle cut in. Therefore, negative response time appeared. There were no significant differences on response time to the vehicle cut-in event between experienced and novice ACC users at 5% significant level but novice ACC users did show a significantly quicker response to the event than experienced ACC users at 10% significant level ($p=0.07$) (Figure 29).

Under this vehicle cut-in situation, most non-ACC (13 out of 14), half of the novice ACC (5 out of 12), and few experience ACC users (3 out of 14) braked based on the turn signal instead of braking because of the vehicle in front. This appears to be a proactive response, which could be perceived as safe driving under the dynamic roadway conditions. Conversely, most experienced

ACC users did not take this proactive approach and waited for ACC to brake. ACC did brake when the cut-in vehicle was detected. However, these usually cause an abrupt braking and may lead to severe situation especially when the cut-in vehicle starts to brake. Safety consequences associated with this kind of events need to be further examined in the future.

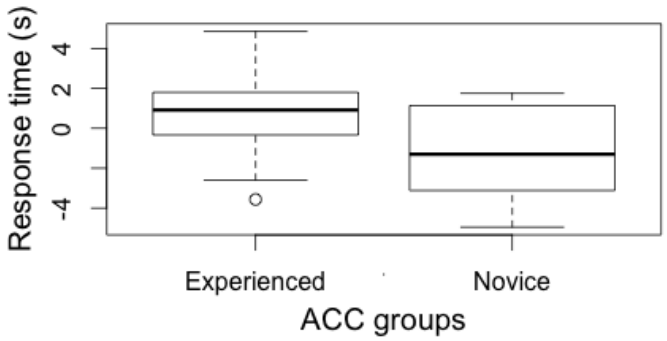


Figure 29. Response time to a vehicle cut-in event

5.3 Summary

Three cluster groups were observed in drivers located in Iowa and Washington: Conservative, Moderately risky, and Risky group. Even though they were classified similarly, there were differences based on the findings of the simulator study. More specifically, Washington drivers tend to follow vehicles at further distances and lower speeds with ACC when compared to Iowa drivers, and this is consistent with the survey outcomes of Bato and Boyle's (2011).

The study in Iowa included only experienced ACC users, but the addition of this subgroup in Washington does demonstrate that there are differences between novice and experienced ACC users. Novice users intervened more often and set lower speeds with ACC when compared with experienced users. Whether these differences are geographically based is not known and is a

limitation of this study. However, these differences do suggest that there is some behavioral adaptation with drivers having a more conservative attitude or behavior when they first use ACC compared with more experienced users.

This chapter revealed differences in ACC use patterns across region and experience using two controlled simulator settings. Although more varied driver groups were anticipated, the findings from this chapter suggest that drivers use of ACC and responses to certain lead vehicle braking scenarios, are dependent on their knowledge of the system, their willingness to take risks, and their overall trust of the system.

Chapter 6: General Conclusions

This study took a system approach to examine the influence of safety outcomes based on the use of adaptive in-vehicle technology. Past studies have focused on the system outputs without considering the underlying factors that generate the outputs. More specifically, two components (driver and ACC system) from the driver-system-vehicle system are examined in great detail by using a naturalistic study data. The factors influencing drivers' actions, the response capability of the in-vehicle systems, and the external demands from the roadway and other vehicles are considered in this dissertation. The interactions between components (driver and system) are examined by using data from controlled driving simulator studies. The goal of this research was to provide a greater understanding of how drivers adapt to novel in-vehicle systems that are intended to enhance driver safety. The analytical models developed as part of this research show that not all drivers would use these adaptive systems effectively. In fact, there are many different driver groups and individuals adapt differently based on their level of experience, propensity to take risks, and acceptance of the system. The implications of driver adaptation to systems that are also adapting to changes in the driver state and environment are growing concerns with the increasing prevalence of such systems in future vehicles. Driver capabilities and workload need to account for by designers, engineers, and policy makers when making decisions on integrating these systems in our vehicles.

6.1 Study Limitations

The findings of this study do encompass some limitations that do need to be noted. The data for novice ACC users was based on a FOT that was conducted over a relatively short period of time (3 weeks of ACC use). Hence, there are limitations with regards to capturing severe near-

crash data. Some mediating factors such as users' motivation and attitudes/biases were also not available in the original dataset and were therefore, not included in the logistic regression model.

In terms of simulator study, it is noted that validation of this simulator study to real world driving is still needed. Several speed validation studies using simulators and instrumented vehicles show that the outcomes are not always the same but are consistent (Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008) with similar increases/decreases in speed and acceleration for various conditions (Godley, Triggs, & Fildes, 2002). In the current study, the sense of realism is assessed by soliciting drivers' perception of the driving simulator and ACC system to their own vehicle. Further studies are needed on-road to examine these issues in greater detail. Given that there are few early adopters using the same ACC configuration, the number of participants that can be recruited in any one region is limited. To overcome the limited sample size, the bootstrapping technique was used to help identify differences among ACC users.

6.2 Contribution and Publications

One of the study goals was to establish a conceptual model of adaptive behavior (Figure 3) in the driving domain and identify factors that influence drivers' adaptation and overall safety. The conceptual model provides a framework for the design and analysis of safety-based systems that also account for the operator's responses from continuous feedback. Drivers' response was quantified based on how close they were to a lead vehicle with ACC engaged. The findings showed that the driver would either allow ACC's automation to take over or override ACC to brake manually. With ACC on, drivers were more likely to intervene (brake manually) with no lane change activity, this could be considered a positive consequence (Chira-Chavala & Yoo, 1994; Ervin, Sayer et al., 2005). However, drivers were less likely to intervene at higher speeds,

which may decrease safety since responding time to safety critical situations is increased. Hence, factors identified by this study can actually provide insight into further examining whether drivers' response is appropriate or if collisions can be reduced. A more general finding from this research is that the design of safety-based systems needs to account not only for changing range and headways, but also road type, traveling speed, and individual differences among users. This work has been published to *IEEE Transaction on Intelligent Transportation Systems* (Xiong and Boyle, 2012).

The driver-system-vehicle model (Figure 2) identifies factors that can impact behavioral adaptation and safety in a shared and cooperative system, such as an ACC. A better understanding of drivers' adaptive behavior to ACC will provide valuable insights for systems tailored for individual differences and more focused driver training. This study demonstrates that some users are more aware of the system capabilities and as such, appear to drive safer than others who are less aware. Other users have more trust in their driving skills and are able to cooperate with ACC. But there is also a group of ACC users that demonstrate greater overreliance on ACC with less understanding of the system capabilities and limitations. Recognizing these different use patterns will help enhance design and training for not only ACC but also other in-vehicle technologies to improve driving safety. This work has been published in *Human Factors* (Xiong, Boyle et al, 2012).

In addition to drivers' behavior, system effectiveness is another essential factor for safety. As a human-automation interaction design, effectiveness of an ACC system depends on appropriate time to automatically brake or to alert the driver to manually brake. A good design should consider both the external environment (situation severity) and the capability of the controllers (driver and system). This study examined the effects of external demand and attention

devoted by the controller (driver and ACC) over time. The combination of these measures provides insights on the design of driver assistance system and understanding of ACC functionally and how it responds to various situations. This work will be submitted to *Accident Analysis & Prevention*.

A comparison of novice and experienced ACC users were examined through the driving simulator experiment using a between-subjects design. The simulator controlled the lead vehicle braking events, which are not as readily observed in a more naturalistic on-road study. This particular design provides a means to examine adaptation of drivers' braking behaviors when encountering some safety critical events. Experienced ACC users (when compared to novice drivers) were able to respond much quicker to a hard braking event on a curvy road but slower to a vehicle cut-in event. The experienced drivers may adapt to driving situations differently because they are aware of the limitations of ACC on curvy roads. Conversely, they also seem to be less aware of their situation on straight roads, relying more on ACC to take control for vehicle cut-in events. More informative design, such as incorporating vehicle-to-vehicle communication, could be considered in future vehicles.

6.3 Future Research

This study captures some of the initial ACC users' adaptive behaviors using naturalistic data from almost a decade ago. It would be useful to test the predictive nature of the regression model using more recent data. Future studies should also examine the usefulness of this model to predict outcomes for long-term use of ACC.

Driving simulator studies are used to examine ACC use patterns and differences between novice and experienced ACC users. On road validation for the simulator studies is still needed. The behavioral outcomes from this study provide insights for the introduction of other novel

systems placed inside the vehicle. Additional research is needed to understand how drivers' adaptive behaviors to ACC by changing the algorithms (for gap setting and the threshold for triggering alerts) based on the factors that we identified in this study. This will help us to further examine driving safety with ACC and improve the system design.

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Appendix 1: Driving Questionnaire

As part of this study, it is useful to collect information describing each participant. The following questions ask about you and your health, your personal vehicle, and your driving patterns. Please read each question carefully. If something is unclear, ask the research assistant for help. Your participation is voluntary and you have the right to skip questions if you choose.

Demographic Information

1) What is your birth date? __ __ / __ __ /__ __ __ __
2) What is your gender? ❒ Male ❒ Female

Driving History

3) How old were you when you started to drive (including driving before licensure)?

_____

4) What year were you first licensed (not issued a permit) to drive a passenger vehicle?

_____

5) How often do you drive? (Check the most appropriate category)
   - ❒ Less than once weekly
   - ❒ At least once weekly
   - ❒ At least once daily
6) What speed do you typically drive on the interstate/highways when the speed limit is 60 miles per hour? _____mph
7) What speed do you typically drive in suburban areas when the speed limit is 30 miles per hour? ____mph
8) How **frequently** do you drive in the following conditions? (Check the most appropriate answer for each condition)

	Never 1	Rarely 2	Sometimes 3	Very Often 4	Always 5
Clear road conditions with good visibility	❒	❒	❒	❒	❒
Rain	❒	❒	❒	❒	❒
Snow	❒	❒	❒	❒	❒
Low/no sunlight	❒	❒	❒	❒	❒
In heavy – "stop-and-go" – traffic	❒	❒	❒	❒	❒
In heavy traffic that is flowing	❒	❒	❒	❒	❒
On interstates (e.g. I-5, I-90, I-405, etc.)	❒	❒	❒	❒	❒
On highways (e.g. US-2, US-12, US-101, etc.)	❒	❒	❒	❒	❒
On city streets with traffic lights	❒	❒	❒	❒	❒
In residential areas	❒	❒	❒	❒	❒
On curvy roads	❒	❒	❒	❒	❒
On hilly roads	❒	❒	❒	❒	❒
On roads with lower speed limits	❒	❒	❒	❒	❒
When tired or when otherwise impaired	❒	❒	❒	❒	❒
When performing tasks (e.g., using cell phone, map, radio, GPS, etc.)	❒	❒	❒	❒	❒
When other people are in the vehicle	❒	❒	❒	❒	❒

9) How **comfortable** do you feel when you drive in the following conditions? (Check the most appropriate answer for each condition)

	Very Uncomfortable	Uncomfortable	Neither Comfortable or Uncomfortable	Comfortable	Very Comfortable
Clear road conditions with good visibility	❒	❒	❒	❒	❒
Rain	❒	❒	❒	❒	❒
Snow	❒	❒	❒	❒	❒
Low/no sunlight	❒	❒	❒	❒	❒
In heavy – "stop-and-go" – traffic	❒	❒	❒	❒	❒
In heavy traffic that is flowing	❒	❒	❒	❒	❒
On interstates (e.g. I-5, I-90, I-405, etc.)	❒	❒	❒	❒	❒
On highways (e.g. US-2, US-12, US-101, etc.)	❒	❒	❒	❒	❒
Freeway on- or off-ramps (i.e. entering or exiting)	❒	❒	❒	❒	❒
On city streets with traffic lights	❒	❒	❒	❒	❒
In residential areas	❒	❒	❒	❒	❒
On curvy roads	❒	❒	❒	❒	❒
On hilly roads	❒	❒	❒	❒	❒
On roads with lower speed limits	❒	❒	❒	❒	❒
When tired or when otherwise impaired	❒	❒	❒	❒	❒
When performing tasks (e.g., using cell phone, map, radio, GPS, etc.)	❒	❒	❒	❒	❒
When other people are in the vehicle	❒	❒	❒	❒	❒

Violations

10) Within the past five years, how many tickets have you received for the following?

	0	1	2	3+
Speeding	❒	❒	❒	❒
Going too slowly	❒	❒	❒	❒
Improper passing	❒	❒	❒	❒
Reckless driving	❒	❒	❒	❒
Following another car too closely	❒	❒	❒	❒
Driving while intoxicated	❒	❒	❒	❒
Other (please specify **type** and **frequency** of violation) _____				

Accidents

11) In the past five years, how many times have you been the driver of a car involved in an accident? If you have had one or more accidents, please describe in the space provided.

- ❒ 0 (Go to question 13)
- ❒ 1
- ❒ 2
- ❒ 3 or more

Accident 1

Was another vehicle involved?	❒ No	❒ Yes
Was a pedestrian involved?	❒ No	❒ Yes
Were you largely responsible for this accident?	❒ No	❒ Yes
Did you go to driver's rehabilitation?	❒ No	❒ Yes
Weather Condition: _____ Month/Year:_____		
Description:		

Accident 2

Was another vehicle involved?	❒ No	❒ Yes
Was a pedestrian involved?	❒ No	❒ Yes
Were you largely responsible for this accident?	❒ No	❒ Yes
Did you go to driver's rehabilitation?	❒ No	❒ Yes
Weather Condition: _____ Month/Year:_____		
Description:		

Accident 3

Was another vehicle involved?	❒ No	❒ Yes
Was a pedestrian involved?	❒ No	❒ Yes
Were you largely responsible for this accident?	❒ No	❒ Yes
Did you go to driver's rehabilitation?	❒ No	❒ Yes
Weather Condition: _____ Month/Year:_____		
Description:		

Vision and Hearing

12) What type of prescription glasses or contact lenses are you wearing as you drive in today's study? (Check only one)

❒ None (Go to question 15)
❒ Single Lens Glasses
❒ Bifocals
❒ Trifocals
❒ Contact Lenses

13) What type of visual problem do you have? (Check only one)

❒ Distance - can only see items that are near without glasses
❒ Near - can only see items that are far away without glasses
❒ Distance and Near - cannot see items that are near or far without glasses
❒ Other,

explain_____

14) Do you have an undiagnosed or diagnosed hearing problem?

❒ No (Go to question 16)
❒ Undiagnosed but suspected problem
❒ Diagnosed but untreated
❒ Diagnosed and treated

15) Do you currently use a hearing aid? (Check only one)

❒ No
❒ Yes

Motion sickness

16) How often do you experience motion sickness? (Circle only one)

0	1	2	3	4	5	6	7	8	9	10
Never										Always

17) How severe are your symptoms when you experience motion sickness (Circle only one)

0	1	2	3	4	5	6	7	8	9	10
None										Severe

18) Have you taken any medication in the past 48 hours? (Check only one)

❒ No
❒ Yes (Please list all)

_____

19) Have you consumed any alcohol or other drugs in the past 24 hours? (Check only one)

❒ No
❒ Yes (Please list all) _____

Appendix 2: Driving Style Questionnaire

The following questions ask about your driving style. If something is unclear, ask the research assistant for help. Your participation is voluntary and you have the right to omit questions if you choose.

1) Sometimes when driving things happen very quickly. Do you remain calm in such situations?
   - ❒ Never or very infrequently
   - ❒ Quite infrequently
   - ❒ Infrequently
   - ❒ Frequently
   - ❒ Quite frequently
   - ❒ Very frequently or always

2) Do you plan long trips in advance, including places to stop and rest?
   - ❒ Never or very infrequently
   - ❒ Quite infrequently
   - ❒ Infrequently
   - ❒ Frequently
   - ❒ Quite frequently
   - ❒ Very frequently or always

3) Do you dislike people giving you advice about your driving?
   - ❒ Never or very infrequently
   - ❒ Quite infrequently
   - ❒ Infrequently
   - ❒ Frequently
   - ❒ Quite frequently
   - ❒ Very frequently or always

4) Do you exceed the 60 mph limit on interstates/highways?
   - ❒ Never or very infrequently
   - ❒ Quite infrequently
   - ❒ Infrequently
   - ❒ Frequently
   - ❒ Quite frequently
   - ❒ Very frequently or always

5) Do you ever drive through a traffic light after it has turned to red?
   - ❒ Never or very infrequently
   - ❒ Quite infrequently
   - ❒ Infrequently
   - ❒ Frequently
   - ❒ Quite frequently
   - ❒ Very frequently or always

6) Do you exceed the speed limit in business areas?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

7) Do you ignore passengers urging you to change your speed?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

8) Do you become flustered when faced with sudden dangers while driving?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

9) How often do you set out on an unfamiliar trip without first looking at a map?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

10) Are you happy to receive advice from people about your driving?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

11) Do you drive cautiously?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

12) Do you find it easy to ignore distractions while driving?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

13) Do you drive fast?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

14) Do you pass vehicles on a four lane roadway if you have the opportunity?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

15) Is your driving affected by pressure from other drivers?
- ❒ Never or very infrequently
- ❒ Quite infrequently
- ❒ Infrequently
- ❒ Frequently
- ❒ Quite frequently
- ❒ Very frequently or always

Appendix 3: ACC Questionnaire for ACC Users

The following questions ask about you and your experience with Adaptive Cruise Control (ACC). If something is unclear, ask the research assistant for help. Your participation is voluntary and you have the right to skip questions if you choose.

1) What is the production year, make, and model of your vehicle with ACC?

Year (e.g. 2006)	Make (e.g., Toyota)	Model (e.g., Sienna XLE)
__ __ __ __		

2) How long have you owned/ driven this vehicle? Years _____ Months _____

3) Did you purchase the vehicle new or used?
   - ❒ New
   - ❒ Used

4) How many miles have been driven in this vehicle since you purchased it (either new or used)? _____

5) What percentage of the miles driven since you purchased this vehicle are yours? __%

6) How long after you purchased this vehicle did you begin using ACC?
   - ❒ Immediately
   - ❒ Less than one week after
   - ❒ Less than one month after
   - ❒ Less than one year after
   - ❒ More

7a) On average since you've owned this vehicle, how often do you use ACC while driving? (0 – 100%) _____

7b) On average in the last six months how often do you use ACC while driving? (0 – 100%) ___

8) How does your average frequency of ACC use in the last 6 months compare to your use beforehand?
   - ❒ No change
   - ❒ I used it less often than I did before
   - ❒ I used it more often than I did before
   - ❒ I haven't used ACC for more than 6 months

9) Which best describes your motivation for purchasing your vehicle with ACC?
   - ❒ I wasn't aware that my vehicle had ACC when I purchased it.
   - ❒ I wanted other features included in the optional package, but wasn't specifically interested in ACC.
   - ❒ I wanted this vehicle and/or the optional package because it included ACC.
   - ❒ I'm a car technology enthusiast and had to have ACC as soon as it became available.

10) How did you initially learn to use ACC? (Please check all that apply)
   - ❒ Dealer demonstration
   - ❒ Owners Manual
   - ❒ Demonstrations or reviews on the internet/ in magazines
   - ❒ Self-taught
   - ❒ Did not learn
   - ❒ Other, please specify _____

11) Was there anything difficult about learning to use ACC?
- ❒ No
- ❒ Yes

If Yes, please explain

_____

12) What methods did you use to answer additional questions about the system's operation or to learn more about how your ACC system works? (Please check all that apply)
- ❒ No additional learning
- ❒ Dealer demonstration
- ❒ Owners Manual
- ❒ Demonstrations or reviews on the internet/ in magazines
- ❒ Self-taught
- ❒ Other, please specify _____

13) Does ACC create any new driving problems or safety concerns for you?
- ❒ No
- ❒ Yes

If Yes, please explain

_____

14) At what following distance do you usually set your ACC?
- ❒ At the shortest setting, which is as close to the lead vehicle as my ACC allows
- ❒ At a medium setting
- ❒ At the longest setting, which is as far from the lead vehicle as my ACC allows
- ❒ I don't know

15) Thinking about specific driving environments or conditions, how does the length of your following distance change when not using ACC compared to using ACC?

	Shorter distance than with ACC	About the same as with ACC	Longer distance than with ACC
Residential areas	❒	❒	❒
Urban area/Cities	❒	❒	❒
On highways (e.g. US-2, US-101, etc.)	❒	❒	❒
On interstates (e.g. I-5, I-90, etc.)	❒	❒	❒
Freeway on- or off-ramps (i.e. entering or exiting)	❒	❒	❒
Curves	❒	❒	❒
Hills	❒	❒	❒
Rain	❒	❒	❒
Snow	❒	❒	❒
Low/no sunlight	❒	❒	❒
In heavy – "stop-and-go" – traffic	❒	❒	❒
In heavy traffic that is flowing	❒	❒	❒
On city streets with traffic lights	❒	❒	❒
On curvy roads	❒	❒	❒
On roads with lower speed limits	❒	❒	❒
When tired or otherwise impaired	❒	❒	❒
When performing tasks (talking on cell phone, etc.)	❒	❒	❒
When other people are in the vehicle	❒	❒	❒

16) Please rate how often you use ACC in the following situations?

17) How has your use changed since you began using the system?

	Never 1	Rarely 2	Sometimes 3	Very Often 4	Always 5	Use More Now 1	Use Less Now 2	Use Remains the Same 3
Clear road conditions with good visibility	❒	❒	❒	❒	❒	❒	❒	❒
Rain*	❒	❒	❒	❒	❒	❒	❒	❒
Snow*	❒	❒	❒	❒	❒	❒	❒	❒
Low/no sunlight*	❒	❒	❒	❒	❒	❒	❒	❒
In heavy – "stop-and-go" – traffic	❒	❒	❒	❒	❒	❒	❒	❒
In heavy traffic that is flowing	❒	❒	❒	❒	❒	❒	❒	❒
On interstates (e.g. I-5, I-90, etc.)	❒	❒	❒	❒	❒	❒	❒	❒
On highways (e.g. US-2, US-101, etc.)	❒	❒	❒	❒	❒	❒	❒	❒
Freeway on- or off-ramps (i.e. entering or exiting)	❒	❒	❒	❒	❒	❒	❒	❒
On city streets with traffic lights	❒	❒	❒	❒	❒	❒	❒	❒
In residential areas	❒	❒	❒	❒	❒	❒	❒	❒
On curvy roads	❒	❒	❒	❒	❒	❒	❒	❒
On hilly roads	❒	❒	❒	❒	❒	❒	❒	❒
On roads with lower speed limits	❒	❒	❒	❒	❒	❒	❒	❒
When tired or otherwise impaired	❒	❒	❒	❒	❒	❒	❒	❒
When performing tasks (e.g., using cell phone, map, radio, GPS, etc.)	❒	❒	❒	❒	❒	❒	❒	❒
When other people are in the vehicle	❒	❒	❒	❒	❒	❒	❒	❒

18) Please note other changes in your **ACC use** that you've noticed since you began using ACC.

_____
_____

_____
_____

19) For each of the following statements, please state how much you agree or disagree.

Based on my current use of ACC…	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Not Applicable
I tend to change lanes less often when using ACC	❒	❒	❒	❒	❒	❒
I set ACC to follow vehicles at high speed and close distances	❒	❒	❒	❒	❒	❒
I tend to follow the vehicle ahead more closely when I use ACC than when I'm not using ACC	❒	❒	❒	❒	❒	❒
I tend to perform other tasks (e.g., use of cell phone, map, radio, GPS, etc.) **more often** with ACC on	❒	❒	❒	❒	❒	❒
I tend to change my route so I can use ACC more	❒	❒	❒	❒	❒	❒
Using ACC reduces my stress while driving	❒	❒	❒	❒	❒	❒
I rely more on ACC than when I first started using it	❒	❒	❒	❒	❒	❒

20) For each of the following statements, please state how much you agree or disagree.

Compared to when I began using ACC…	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Not Applicable
I tend to change lanes less often when using ACC	❒	❒	❒	❒	❒	❒
I set ACC to follow vehicles at high speed and close distances	❒	❒	❒	❒	❒	❒
I tend to follow the vehicle ahead more closely when I use ACC than when I'm not using ACC	❒	❒	❒	❒	❒	❒
I tend to change my route so I can use ACC more	❒	❒	❒	❒	❒	❒
Using ACC reduces my stress while driving	❒	❒	❒	❒	❒	❒

21) Please note other changes in your **driving** that you've noticed since you began using ACC.

_____
_____

_____
_____

22) If you encountered a stopped car ahead in your lane with the ACC system engaged, how do you think the system would react?

❒ Detect the vehicle in the lane ahead, start to slow until stopped

❒ Detect the vehicle in the lane ahead, start to slow, but the driver needs to stop vehicle

❒ System will not detect stopped vehicle

❒ Don't know

23) Does the ACC system warn or alert you if you get too close to the vehicle ahead and need to intervene by applying the brakes?

❒ No (skip ahead to Question 25)

❒ Yes (continue with Question 24)

24) Is the warning only active when the ACC is in use, or is the warning active even when the system is off?

❒ The warning is active only when ACC is in use

❒ The warning is active regardless of the ACC system's status (on/off)

25) How quickly do you notice and react to unexpected road hazards when ACC is turned on, compared to when it is turned off? (Please check only one)

❒ Much slower

❒ Slower

❒ Neither slower nor quicker

❒ Quicker

❒ Much Quicker

❒ Don't know

26) For each of the following situations, please rate how much you think that ACC would help you in avoiding a crash with the vehicle in front of you if…

	Not at all	Very Little	Somewhat	To a Great Extent	Don't know
You are following the vehicle in stop-and-go traffic	❒	❒	❒	❒	❒
The vehicle stopped in your lane	❒	❒	❒	❒	❒
You are following the vehicle on a curvy road*	❒	❒	❒	❒	❒
You are following a vehicle that brakes suddenly, as if in an emergency situation	❒	❒	❒	❒	❒
You are following a vehicle that slows to a stop	❒	❒	❒	❒	❒
You approach a motorcyclist in the lane in front of you	❒	❒	❒	❒	❒
You are following a very dirty vehicle	❒	❒	❒	❒	❒

27) Have you ever hit something in front of your vehicle with ACC turned on?

❒ No

❒ Yes

If Yes, please describe the situation and what you hit

_____

_____

28) In driving your own car, did you ever have a crash or near crash because you thought the ACC system was activated, but wasn't?

❒ No

❒ Yes

29) For each of the following statements, please state how much you agree or disagree.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Not Applicable
The sounds made by the ACC system are easy to understand	❒	❒	❒	❒	❒	❒
The lights/symbols on the ACC system are confusing	❒	❒	❒	❒	❒	❒
The ACC following distance setting is easy to understand	❒	❒	❒	❒	❒	❒
The ACC cruise speed setting is confusing	❒	❒	❒	❒	❒	❒

30) Based on your use of ACC, please state how much you agree or disagree with the following statements.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I feel safe using the ACC system	❒	❒	❒	❒	❒
I am a safer driver now that I use ACC	❒	❒	❒	❒	❒
More cars cut me off or pull in front of me when I am using my ACC	❒	❒	❒	❒	❒
My ACC system is very reliable	❒	❒	❒	❒	❒

Appendix 4: ACC Questionnaire for Non-ACC Users

The following questions ask about your feeling with Adaptive Cruise Control (ACC). If something is unclear, ask the research assistant for help. Your participation is voluntary and you have the right to skip questions if you choose.

Adaptive Cruise Control (ACC) is a new technology different from regular cruise control. Regular cruise control is found in most cars and maintains a constant speed without you keeping your foot on the accelerator pedal. ACC does this as well but it also **automatically slows your vehicle down without you pressing your foot on the brake pedal.** The ACC laser or radar sensors can detect moving vehicles in front of your own vehicle and, if required, slow your vehicle.

1) <u>Based just on the description of ACC above</u>, please state how much you agree or disagree with the following statements:

Statement:	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
A. I trust an ACC system would work	1	2	3	4	5
B. I would use ACC often	1	2	3	4	5
C. I feel that ACC would allow me to do other things while driving (e.g. use cell phone, map, radio, GPS, etc.)	1	2	3	4	5
D. I think ACC would reduce my stress while driving	1	2	3	4	5
E. ACC can be set to improve traffic flow (e.g. it can be set to follow vehicles at a *high* speed and *close* distance.) I would set ACC to this setting	1	2	3	4	5
F. ACC can be set to improve driver comfort (e.g. it can be set to follow vehicles at a *low* speed and *far* distance.) I would set ACC to this setting	1	2	3	4	5
G. More technology in my car is always better	1	2	3	4	5
H. In general, technology is beneficial and is an important part of my life	1	2	3	4	5

2) Based on your using of ACC in the simulator, please state how much you agree or disagree with the following statements:

Statement:	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
A. I feel safe using the ACC system	1	2	3	4	5
B. ACC is convenient to use	1	2	3	4	5
C. Using ACC reduces my stress while driving	1	2	3	4	5
D. The sounds made by the ACC system are easy to understand	1	2	3	4	5
E. The lights/symbols on the ACC system are confusing	1	2	3	4	5
F. The ACC following distance setting is easy to understand	1	2	3	4	5
G. The ACC speed setting is confusing	1	2	3	4	5

Appendix 5: Trust in ACC Questionnaire

The following questions ask about your degree of trust in inanimate objects. Just as with people, we are capable for forming relationships of trust with objects we encounter in everyday life. To answer the survey questions, please place a perpendicular line along the axis to indicate your answer. First complete the PRACTICE QUESTIONS, before completing the SURVEY QUESTIONS. If something is unclear, ask the research assistant for help. Your participation is voluntary and you have the right to omit questions if you choose.

PRACTICE QUESTIONS

To what extent do you trust your watch to display the correct time?

Not at All _____ Extremely High

To what extent does your calculator produce the correct answer?

Not at All _____ Extremely High

To what extent does your oven bake at a temperature indicated by the dial?

Not at All _____ Extremely High

SURVEY QUESTIONS

1. To what extent does the ACC system perform its function properly?

   Not at All _____ Extremely High

2. To what extent can the ACC system's behavior be predicted from moment to moment?

   Not at All _____ Extremely High

3. To what extent can you count on the ACC system to do its job?

   Not at All _____ Extremely High

4. To what extent does the ACC system perform the task it was designed to do?

   Not at All _____ Extremely High

5. To what extent does the ACC system respond similarly to similar circumstances at different points in time?

   Not at All ____ Extremely High

6. What is your degree of *faith* that the ACC system will be able to cope with future driving situations?

   None at All ____ Extremely High

7. What is your degree of *trust* in the ACC system to *respond* accurately?

   None at All ____ Extremely High

8. What is your degree of *trust* in the ACC system's *display*?

   None at All ____ Extremely High

9. What is your *overall degree of trust* in the ACC system?

   None at All ____ Extremely High

10. What is your degree of *trust* in your cooperation with the ACC system?

    None at All ____ Extremely High

11. How confident do you feel about your previous trust ratings?

    None at All ____ Extremely High

12. What is your degree of self-confidence to manually intervene with the ACC system?

    None at All ____ Extremely High

Appendix 6: Wellness Questionnaire

Directions: Circle one option for each symptom to indicate whether that symptom applies to you right now.

1. General Discomfort.....None.....Slight.....Moderate .....Severe
2. Fatigue .....None.....Slight.....Moderate .....Severe
3. Headache .....None.....Slight.....Moderate .....Severe
4. Eye Strain .....None.....Slight.....Moderate .....Severe
5. Difficulty Focusing .....None.....Slight.....Moderate .....Severe
6. Salivation Increased .....None.....Slight.....Moderate .....Severe
7. Sweating .....None.....Slight.....Moderate .....Severe
8. Nausea .....None.....Slight.....Moderate .....Severe
9. Difficulty Concentrating .....None.....Slight.....Moderate .....Severe
10. "Fullness of the Head" .....None.....Slight.....Moderate .....Severe
11. Blurred Vision .....None.....Slight.....Moderate .....Severe
12. Dizziness with Eyes Open ....None.....Slight.....Moderate .....Severe
13. Dizziness with Eyes Closed ..None.....Slight.....Moderate .....Severe
14. *Vertigo .....None.....Slight.....Moderate .....Severe
15. **Stomach Awareness .....None.....Slight.....Moderate .....Severe
16. Burping .....None.....Slight.....Moderate .....Severe
17. Vomiting .....None.....Slight.....Moderate……..Severe
18. Other _____ .....None.....Slight
    Moderate……..Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is a feeling of discomfort which is just short of nausea.

Appendix 7: Simulator Realism Questionnaire

For each of the following items, circle the number that best indicates how closely the simulator resembles an actual car in terms of appearance, sound, and response.

General Driving	Strongly unrealistic	Moderately unrealistic	Slightly unrealistic	Slightly realistic	Moderately realistic	Strongly realistic
Response of the seat adjustment levers	1	2	3	4	5	6
Response of the gear shift	1	2	3	4	5	6
Response of the brake pedal	1	2	3	4	5	6
Response of accelerator pedal	1	2	3	4	5	6
Response of the speedometer	1	2	3	4	5	6
Response of the steering wheel while driving straight	1	2	3	4	5	6
Response of the steering wheel while driving on curves	1	2	3	4	5	6
Feel when accelerating	1	2	3	4	5	6
Feel when braking	1	2	3	4	5	6
Feel when passing other cars	1	2	3	4	5	6
Feel when driving straight	1	2	3	4	5	6
Feel when driving on curves	1	2	3	4	5	6
Feel of approximate speed when driving 30 mph	1	2	3	4	5	6
Feel of approximate speed when driving 45 mph	1	2	3	4	5	6
Feel of approximate speed when driving 55 mph	1	2	3	4	5	6
Feel of approximate speed when driving 65 mph	1	2	3	4	5	6
Sound of the car	1	2	3	4	5	6
Sound of other vehicles	1	2	3	4	5	6
Sound of ACC deceleration limit exceedance alert	1	2	3	4	5	6
Sound of ACC termination alert	1	2	3	4	5	6
Appearance of roads and road markings	1	2	3	4	5	6
Appearance of intersections	1	2	3	4	5	6
Appearance of other vehicles	1	2	3	4	5	6
Appearance of rear-view mirror image	1	2	3	4	5	6

Appearance of rural scenery	1	2	3	4	5	6
Appearance of residential scenery	1	2	3	4	5	6
Appearance of interstate scenery	1	2	3	4	5	6
Appearance of signs	1	2	3	4	5	6
Ability to read road and warning signs	1	2	3	4	5	6
Ability to negotiate curves	1	2	3	4	5	6
Ability to keep straight in your lane	1	2	3	4	5	6
Ability to respond to traffic	1	2	3	4	5	6
Ability to maintain control while driving straight	1	2	3	4	5	6
Ability to maintain control while in curve	1	2	3	4	5	6
Similarity of ACC display to your own vehicle	1	2	3	4	5	6
Similarity of ACC controls to your own vehicle	1	2	3	4	5	6
Similarity of ACC feel to your own vehicle	1	2	3	4	5	6
Similarity of ACC headway distance to your own vehicle (distance between your vehicle and the one ahead of you)	1	2	3	4	5	6
Similarity of ACC's performance around curves to your own vehicle	1	2	3	4	5	6
Similarity of ACC speed control to your own vehicle	1	2	3	4	5	6
Overall similarity of simulated ACC to your own vehicle	1	2	3	4	5	6
Overall appearance of driving scenes	1	2	3	4	5	6
Overall feel of the car when driving	1	2	3	4	5	6
Overall similarity to real driving	1	2	3	4	5	6