Cooperative Adaptive Cruise Control:

Human Factors Analysis

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FOREWORD

Traffic is an increasing concern in many urban areas, and traffic congestion is growing at a faster rate than can be alleviated solely by additional road construction. This report examines a technology called Cooperative Adaptive Cruise Control (CACC) that aims to increase traffic throughput by safely permitting shorter following distances between vehicles.

This report establishes a framework that the can be used to evaluate the human-factors, safety, and implementation issues associated with CACC. This document discusses CACC benefits and identifies various ways in which the CACC concept could be realized as well as human-factors-related issues of implementation. Several research areas are suggested to address these issues.

Human-factors, operations, safety, and transportation researchers can use this report as a starting point to further define and execute critical research studies. These studies will, in turn, help facilitate the safe implementation of this mobility-enhancing technology in the years to come.

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Traffic congestion is growing at a faster rate than can be alleviated solely by additional road construction. Various Intelligent Transportation Systems technologies aim to increase and improve transportation via non-traditional means. Cooperative Adaptive Cruise Control (CACC) is one such technology, intended to increase traffic throughput by safely permitting shorter following distances between vehicles. Both vehicle-to-vehicle and vehicle-to-infrastructure communications help such endeavors at the micro- and macro-levels of traffic management. This report identifies the various ways in which the CACC concept could be realized and the human-factors-related implementation issues. Several research areas are suggested to address these human-factors issues.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ACRONYMS AND SYMBOLS

ACC	Adaptive cruise control
BRT	Brake response time
CACC	Cooperative Adaptive Cruise Control
CCC	Conventional cruise control
DSCR	Dedicated short-range communications
HOV	High-occupancy vehicle
I2V	Infrastructure-to-vehicle
ITS	Intelligent Transportation Systems
SA	Situation awareness
SPAT	Signal phase and timing
v/h/l	Vehicles per hour per lane
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle

EXECUTIVE SUMMARY

Cooperative Adaptive Cruise Control (CACC) technology presents the possibility of increasing traffic throughput without requiring construction of additional lanes. Direct radio communication between equipped vehicles and roadway infrastructure permits vehicles to travel closer together and better informs drivers of the surrounding driving environment. In addition to improved capacity, CACC presents environmental benefits by increasing efficiency and reducing fuel usage.

As CACC-equipped vehicles can only employ the system when following other equipped vehicles, the quickest realization of highway throughput benefits can be achieved by congregating equipped vehicles in restricted lanes. Once penetration rates rise, benefits will expand to all highway lanes and significant capacity increases will be possible. Benefits can also be gained in arterial intersection environments. The CACC system capabilities supplemented by signal phase and timing (SPAT) information from the infrastructure can inform drivers of the most efficient speed at which to approach and pass through an intersection. This information would not only save time for drivers but also reduce emissions and fuel usage.

Although already demonstrated as technically feasible, CACC faces many hurdles related to the abilities and limitations of the humans using the system. Numerous human-factors-related issues may impact the success of a new system and need to be addressed before implementation can be considered. Application, use, reliance, and trust of automation have numerous pitfalls, all exacerbated when applied to dynamic and fast-pace environments such as highway travel. Additionally, the effect CACC usage may have on a driver’s workload (increase or decrease) directly impacts performance, safety, and overall situation awareness (SA). CACC system success relies on an accurate understanding of general driving behaviors such as car-following, lane position variability, and lane-changing. Each of these is heavily influenced by a variety of both deliberate and reflexive human judgments, which are prone to errors and misguided decisions.

To determine how these human-factors issues affect CACC technology, research scenarios are presented for exploration. The proposed studies involve several research methodologies, including microsimulation, low- and high-fidelity simulation, and field research. Data gathered from this future research will be crucial to the success of CACC technology and can probably be applied to other driving-related automation.

PROJECT BACKGROUND AND OBJECTIVES

BACKGROUND

Delay on the Nation's highway systems is a major cost to motorists and businesses, amounting to over $100 billion in lost time and wasted fuel for urban areas in 2010.[(1)] Congestion has steadily worsened because the population of drivers, number of vehicles, and travel volume continue to increase at a faster rate than system capacity. Miles of travel increased by 76 percent between 1980 and 1999, but miles of highway increased by only 1.5 percent.[(2)]

Severe commute congestion is experienced daily by many drivers in urbanized areas. In 1982, the annual average delay per commuter was 14 h. It had climbed to 34 h in 2010 and is forecasted to increase to 41 h by 2020.[(1)] Large city areas see delays far beyond the national average, such as 74 h in the Washington, DC, metropolitan area in 2010. But congestion also varies significantly from day to day because demand and capacity are constantly changing at any given location, often due to the influence of incidents and other temporary factors. Roughly 40 percent of the average travel delays now occur outside of normal rush-hour periods, limiting predictability, increasing driver frustration, and significantly impacting business production and deliveries.

The effect of congestion depends to a large extent on what users expect in terms of speed, travel time, and delay when these conditions exist. Slowing the growth of congestion and delay improves urban travelers' mobility and productivity and curbs economic inefficiencies. The use of highly integrated Intelligent Transportation Systems (ITS), such as electronic information and communication technology, may extend the capacity of the existing infrastructure system, improving traffic flow and reducing bottlenecks. One proposed ITS technology, CACC, has the potential to address the problem of recurring congestion and reduced mobility.

CACC CONCEPT

The CACC concept envisions drivers sharing vehicle control with an automated system that includes pervasive vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Using dedicated short-range communications (DSRC), vehicles communicate directly with other nearby equipped vehicles to coordinate and adjust longitudinal control through throttle and brake activations. These automated responses occur much more quickly than humanly possible, allowing equipped vehicles to safely travel closer together and increasing the road capacity.

Additionally, equipped vehicles broadcast performance data to roadway infrastructure via DSRC to enable the infrastructure to monitor traffic flow and incidents. Using these data, the infrastructure could develop predictive traffic models and broadcast targets such as speed, following distance, and acceleration and deceleration rates to CACC-equipped vehicles to optimize traffic flow. While the potential throughput benefits are clear in highway environments, infrastructure-emitted information could also promote significant improvements in arterial settings. For example, using broadcasted SPAT information, CACC could influence approaches to red-light intersections to reduce delays, emissions, and fuel consumption.

Although an engaged CACC system would monitor and control a vehicle's speed, drivers would continue to steer their vehicles and be responsible for identifying situations that might require evasive actions. Hence, similar to the use of a conventional cruise control (CCC) system, drivers are assumed to be in control and responsible even though the automated systems are guiding their vehicles at some level. CACC technology would allow cars to travel closer together more safely but is not intended to be a safety system in the same sense as collision warning and stability control systems.

OBJECTIVES

Implementing a concept such as CACC entails a large number of factors, the least of which is simply equipping vehicles with the necessary technology. This analytical report attempts to identify a few of the most probable manners in which the CACC concept could be realized and to investigate the human-factors issues that could be associated with such implementations. Possible methods for investigating and addressing these human-factors issues are presented, including test scenarios and the equipment and resources that would be necessary for the research.

The actual research testing is outside the scope of this analysis. Additionally, issues related to system engineering and policy or legal matters (e.g., privacy concerns or responsibility in the case of an accident when a CACC system is engaged) are beyond the reach of this report. It is assumed that the CACC concept, as described in the previous section, is feasible and will function as described.

CACC BENEFITS

Because many of the benefits and potential human-factors issues of the CACC concept pertain to shorter following distances between vehicles, it is important to ensure terminology used in this report corresponds to industry standards, especially since the *Highway Capacity Manual* modified its definitions of *gap* and *headway* between the 2000 and 2010 editions.(3,4)

In this report, *headway* is the time between which identical parts of successive vehicles pass a point on a roadway (e.g., front bumper to front bumper). *Gap* is the time between which the front bumper of a following vehicle passes the same point on a road as the rear bumper of the preceding vehicle. Many studies researched for this analysis used the term *headway* when it was apparent they intended the current definition of *gap*. For example, the procedural section of one study indicated that participants were instructed to estimate "the headway between the front bumper of the vehicle you are driving and the rear bumper of the lead vehicle."(5) Terminology discrepancies such as these have been corrected in this report.

THROUGHPUT BENEFITS

The CACC concept purports to improve traffic throughput via two key aspects: (1) decreasing the following distances between vehicles to allow more vehicles to fit in a lane and (2) increasing the flow's string stability, the attenuation of traffic disturbances in the upstream direction, which would reduce traffic jams and increase overall average speed.(6)

The 2010 *Highway Capacity Manual* indicates the general maximum flow rate for a multilane highway at 60 mi/h is 2,200 vehicles per hour per lane (v/h/l).(4) A microsimulation in which all traffic operated with a 1.1-s gap demonstrated a similar rate, showing a throughput of 2,100 v/h/l.(7) Additional microsimulations have been performed to evaluate the effects of adding vehicles that utilize technologies such as adaptive cruise control (ACC) and CACC.

ACC aids drivers by automatically adjusting longitudinal speed as the immediately preceding vehicle dictates. While this is a convenience for the driver, the available preset time gaps that a driver can select are typically larger than the average time gap seen with manual driving (see Willingness to Utilize Automation section). Therefore, ACC use has been shown to have very little benefit for throughput, especially as the penetration rate increases. (See references 7–11.) Typical throughput benefits for ACC peak at about 7 percent over manual driving when penetration is in the 20–60 percent range. Beyond 60 percent penetration, there tends to be a negative throughput effect, since more vehicles are traveling at gaps greater than under manual control.(7) Studies have shown conflicting data on the string stability effects of ACC. Some indicate that it helps even out minor fluctuations and disturbances, but others have shown that the time delay of the ACC system regulating speed has a destabilizing effect. (See references 8, 9, 11, and 12.)

Microsimulations evaluating CACC usage have shown the concept to deliver dramatic effects on throughput. Because CACC-equipped vehicles can only utilize a shorter time gap behind other CACC-equipped vehicles, benefits are slow to develop and not evident until the penetration rate approaches 40 percent. (See references 7, 10, 11, and 13.) At that point, however, throughput gains are quadratic and quickly approach 4,250 v/h/l at 100 percent usage when a time gap of 0.5 s is simulated.(7) Another CACC microsimulation allocated several time gaps (1.1, 0.9, 0.7, and 0.6 s) across the simulated CACC traffic and still reflected a highly elevated throughput value of 4,000 v/h/l.[10] However, these substantial results require heavy traffic volumes; at lighter levels, vehicles are already at free-flow rate.

A CACC-specific microsimulation modeled traffic in which non-CACC vehicles were equipped with a "Here I Am" module that broadcasts performance information to allow CACC-equipped vehicles to follow at reduced gaps.[10] While not including the longitudinal control capabilities, this added technology permits CACC benefits to appear at lower penetration rates and rise in a more linear manner. Another study looked at the absolute minimum acceptable gaps to avoid collisions and showed that with CACC, it might be possible to utilize gaps as small as 0.31 s, depending on speed.[14] Furthermore, if CACC technology could react based on the instant brake pressure is applied in the lead vehicle rather than actual vehicle deceleration, this time savings may permit gaps as short as 0.15 s. However, the consequent effect of the much smaller gaps on drivers' capability to steer their vehicles is not yet known.

Because CACC-equipped vehicles perform speed adjustments more quickly than both manual and ACC-driven vehicles, string stability benefits are also realized. Under normal manual control, a small but sudden change in velocity can have an increasing effect upstream, as more and more extreme reactions (later and harder braking) are observed. However, a field study with six CACC-equipped vehicles showed that even with a following gap as short as 0.5 s, string stability was not sacrificed.[6] Stability is not only improved because CACC is able to react quickly to the vehicle immediately in front, but DSRC permits CACC-equipped vehicles to monitor vehicles further downstream and react even before the immediately preceding vehicle has slowed. Some studies have indicated that utilizing distance and speed information for up to three predecessor vehicles in a platoon helps smooth traffic performance.[15,16] Infrastructure-to-vehicle (I2V) broadcasts also promote stability by recommending the same speed for all vehicles (speed harmonization) and by warning drivers or directly influencing a vehicle's speed due to downstream disturbances not yet evident to a driver, including reductions in average speed, accidents, lane closures, or queues of stopped or slowly moving vehicles (queue warning).

ENVIRONMENTAL BENEFITS

The secondary benefit of a more stable, higher-throughput highway environment is a more fuel-efficient state of operation. Fewer traffic jams due to late reactions or overreactions to downstream issues equate to fuel savings. Additionally, I2V communications have the ability to either directly influence a vehicle's performance or inform a driver of downstream issues that could affect traffic flow, such as an accident, road work, or lane merges. By receiving this information before they are visually aware of an issue, drivers have the ability to adjust their speed or position to more efficiently pass through or around the deviation.

In an arterial environment, I2V communications have the ability inform drivers of upcoming intersections and their signal phases, which can smooth deceleration and acceleration rates and reduce the need to come to a complete stop. In addition to simply reducing travel time, these benefits can have a significant environmental effect. A microsimulation of a four-intersection corridor with either manual or CACC-driven vehicles reflected improvements of up to 36 percent in emissions, 37 percent in fuel savings, and 22 percent in average speed for the all-CACC traffic model.[17]

CONCEPT IMPLEMENTATION

As previously discussed, the CACC concept has several benefits. Closer following distances and improved string stability of traffic flow reduce traffic jams and increase overall throughput. Additionally, these effects produce secondary benefits, including reduced fuel consumption and emissions. In a large urban freeway environment, the impact can be substantial. In arterial settings, large or small, CACC supplemented with I2V communications can produce similarly effective results. Implementing the concept in these two environments, however, poses challenges that need to be considered.

FREEWAY ENVIRONMENTS

The greatest impact of traffic congestion is on large urban highways, so it makes sense to focus on promoting the CACC concept in these environments. However, a CACC-equipped vehicle is not able to travel at reduced time gaps unless the preceding vehicle is also equipped and has the system actively engaged. This means that until the penetration rate reaches a certain level, around 40 percent based on several microsimulation studies, throughput improvements will remain elusive. (See references 7, 10, 11, and 13.) Getting this new technology into a sufficient number of vehicles is difficult for several reasons.

First, vehicles in the United States are being kept for longer periods, slowing the introduction of new cars equipped with the latest technologies. From 1995 to 2009, the average age of U.S. light vehicles (passenger cars and light trucks) increased 21 percent to 10.2 years.[18] The factors for this rise include an increase in quality and durability of vehicles and economic issues that likely encourage longer ownership.

Second, car manufacturers are reluctant to introduce technology (and cost) to a vehicle if it is not seen as an immediate benefit to the consumer. If a driver is unable to utilize CACC due to low penetration in surrounding vehicles, he is unlikely to spend extra money for the technology. Many new technologies are rolled out slowly, first in luxury vehicles in which cost is not typically a major factor for the consumer, then trickling down to economy vehicles as production costs decrease and benefits increase. Even at the point at which CACC could be included in all new cars, long average turnover rates imply an extended rollout period.

Third, retrofitting technology into existing vehicles is not always easy or cost-effective. Standards adopted to implement a technology in new vehicles may not be viable for older vehicles. Additionally, the aftermarket cost of a technology is usually much higher than original equipment, decreasing the likelihood of adoption.

Therefore, implementing the CACC concept in a freeway environment will likely require a staged approach.

Restricted/Managed Lanes

Similar to the use of restricted lanes to encourage carpooling or alternative-energy vehicle usage, restricted lanes could be utilized to congregate CACC-equipped vehicles and increase penetration rates in those lanes. Although the overall penetration rate would be low, the rate in restricted lanes could rise enough to demonstrate throughput increases. Limiting the initial infrastructure needs to provide I2V communication to a few managed lanes would also allow capabilities to grow as needed and keep initial costs at a minimum. Although I2V communications need to be thoroughly vetted before being introduced, a staged approach to communicating with a larger and larger set of vehicles could help ensure a better operating environment.

Restricting CACC usage to a lane or set of lanes involves hurdles and drawbacks, however. The locations that could benefit most from traffic relief, urban areas, are also more likely to have limits on freeway expansion. If restricted lanes are not already utilized and new lane construction is not possible, reserving one or more existing lanes for a small percentage of vehicles would restrict non-equipped vehicles to fewer lanes, worsening overall traffic flow.

Areas that already utilize restricted lanes (e.g., for high-occupancy vehicles (HOVs)) could permit CACC-equipped vehicles to join those lanes; however, the magnitude of the effect may depend on the number of restricted lanes and the other vehicles permitted to use them. In scenarios with a single restricted lane, CACC-equipped vehicles would be blended with non-equipped vehicles, increasing volume but eliminating CACC benefits except in the case of coincidental platoons. Additionally, if the restricted lane was intended for HOVs, permitting single-occupant CACC-equipped vehicles to join (with little benefit) may reduce HOV benefits, reducing throughput. In order for a symbiotic relationship to succeed with mixed equipage vehicles, extensive education of and cooperation from lane users may be required. V2I communication could help CACC-equipped drivers but would not be useful for non-equipped HOV drivers.

However, with two restricted lanes, lane usage could be split to consolidate CACC-equipped vehicles. The left lane could be restricted to CACC-equipped vehicles and the right lane to CACC, HOV, and alternative-energy vehicles. Dual lanes could also decrease the possibility of controlled lane users from being restricted to a single lead-vehicle speed. As previously stated, however, dual restricted lanes may not be possible in many areas most in need of CACC technology benefits due to space or budget.

With any use of restricted lanes, automated controls would be necessary to prevent non-equipped vehicles from utilizing the lanes. Unless CACC-equipped vehicles include an externally visible indicator when the system is engaged, CACC usage cannot be visually enforced as can be done with HOV restrictions. However, DSRC broadcasts by equipped vehicles could be used to grant access if restricted lanes are physically separated. If the lanes are not physically controlled, checkpoints could identify vehicles not broadcasting and permit photo enforcement, similar to current speed and red-light camera technologies.

Once CACC penetration rates increase to a near majority, it is less likely that an area would need specialized lanes to obtain CACC benefits. The restricted lanes could simply join the overall freeway pool (unless a region maintains a need for HOV or alternative energy vehicles), the infrastructure for I2V communications could be expanded to cover most or all lanes, and throughput increases would be more widely realized.

Full-Lane Coverage

Phased implementation would allow drivers of non-equipped vehicles to witness the benefits, providing demand for the technology. This, in turn, would give car manufacturers the incentive to provide the technology in more vehicles, and ultimately, CACC would become a commonplace technology, similar to CCC.

As Su's 2011 microsimulation indicated, adding a "Here I Am" module to non-CACC vehicles would permit CACC-equipped vehicles to follow at shorter gaps.[10] This may provide enough artificial penetration to achieve benefits earlier than projected and permit all freeway lanes to experience throughput increases. Although this would involve retrofitting existing vehicles, it would not involve the more extensive requirements to regulate the vehicle's throttle and brake activations and, therefore, would likely be an easier, less expensive solution. Policy related to how to encourage or pay for this retrofit would need to be researched.

ARTERIALS

The arterial environment is more dynamic than a typical freeway, including intersections, a wide variety of vehicle maneuvers, commercial and residential driveways, and pedestrians. Therefore, rather than providing a shorter time gap, CACC has the potential to produce better string stability and a reduction in delays and stops. Benefits of V2I and I2V communications could include more efficient movement of vehicles through an arterial section, saving travel time and reducing fuel usage and emissions.

As a CACC-equipped vehicle approaches a red-light intersection, SPAT information could be utilized by the infrastructure to determine the most appropriate speed for the vehicle to pass through as quickly as possible without stopping. The I2V transmission could automatically adjust the vehicle's speed or simply provide the suggested speed to the driver.

In the opposite manner, rather than SPAT being preset (e.g., green light duration based on time of day) or based on actuation sensors that are only triggered once a vehicle has crossed or stopped at the intersection, the infrastructure could adjust the SPAT based on vehicle-communicated traffic volume. Not only would this allow signals to favor sections with the heaviest congestion, it would also permit more fluid adjustments for unusual or unexpected changes in traffic patterns. Increased congestion due to a special event, construction, or nearby accident could be alleviated more easily without the need for manual adjustment of the signal control network or police assistance.

Beyond the scope of this analysis, the DSRC capabilities of CACC technology could also enable safety benefits along an arterial corridor. I2V communications could warn drivers of intersecting vehicles appearing to be running a red light, pedestrian crosswalk activations, approaching emergency vehicles, etc.

IMPLEMENTATION ISSUES

This analysis assumes that the technological requirements for the CACC concept are viable and function as expected. However, technical validity does not necessarily translate into successful operation and implementation. There are a host of human-factors issues that may come into play and affect if and how CACC technology is utilized.

AUTOMATION

Several benefits have been identified for the application of automation in the driving environment. In addition to the throughput and environmental benefits of the CACC concept, other driving-related automation has been touted to improve performance and reduce driver stress, error, and workload.(19) As a bonus to car manufacturers, new automation may increase car purchases by people that desire the latest technologies.

The benefits of the CACC concept stem from automated throttle and braking to permit vehicles to follow more closely, removing or reducing human interaction from the longitudinal control. These improvements are attained by addressing key mechanisms in the braking process, which can be broken down into five key components, as follows:(20)

- Perception of an event or lead-vehicle slowing, including brake light onset.
- Processing of information to interpret the event.
- Decision to take action.
- Selection of the appropriate response.
- Initiation of the response.

The first four components are cognitive and subject to numerous delays, depending on the environment, SA, workload, and individual differences of the driver, to name a few. It has been demonstrated that by using automation, vehicles are able to adjust to speed changes more quickly than solely by manual human reaction. Numerous studies have measured human brake response time (BRT), the time from event onset (usually brake lights of the lead vehicle) to initial pressure on the vehicle's brake pedal, under various conditions. When research study participants are perfectly attentive to a simulated driving response task, average human BRT can be as little as 0.47 s.(5) Age, gender, and training play major factors, as well. Young athletes, who tend to have higher than average hand-eye coordination, have been shown to have BRTs in the 0.51–0.55-s range in real traffic.(21) Younger drivers, in general, have quicker BRTs, and reaction times tend to increase with age. Additionally, male drivers typically have faster BRTs than female drivers.(22)

When braking is aided or controlled by an automated system, the cognitive delays that humans inherently express are all but eliminated, allowing initial brake application to occur remarkably faster, in less than 0.1 s.(23) It is important to note, however, that braking capabilities with CACC are primarily geared toward maintaining a set time gap by utilizing specific acceleration and deceleration models to provide a comfortable ride for the vehicle's occupants. Emergency stopping maneuvers require significant brake force and may or may not be part of an implemented CACC system. Other technologies, such as collision avoidance systems, may complement CACC to provide automation for emergency situations. In any event, it is critical that drivers understand the limits of automation and utilize it as intended.

Willingness to Utilize Automation

At the heart of the CACC concept is the ability to increase traffic throughput by vehicles traveling closer together. Even if the technology is sound, it will only be successful if drivers are willing to travel more closely.

Most official guidelines from highway-safety organizations suggest a 1–2-s gap.(5) Research studies looking at participant-specified comfortable time gaps in manual driving have generally supported this guidance. In one study, 95 percent of the participants followed the lead vehicle at a gap of 1.68 s or less and had an overall average of 0.98 s, which supports findings from previous comfort gap studies.(5,24,25) Similarly, a study having participants either fall back to or approach a comfortable following gap revealed an average time gap of 1.1 s.(26) A study looking at how time gaps affect perception of risk, difficulty, effort, and comfort found that all measures were rated low until the time gap dropped below 2 s and continued to climb as the gap decreased.(27) In the study, the general range of time gaps selected was 1.67–1.78 s. Two naturalistic studies also supported these time gaps for manual driving, with averages of 1.64 and 1.6 s.(28,29)

Automation of time gaps using ACC or CACC provides the driver with a few preset time gaps to choose from. A recent quasi-naturalistic study comparing gap acceptance between manual, ACC, and CACC driving found that drivers were willing to drive at closer time gaps when using automation.(28) Whereas the average manual time gap was 1.64 s, the most commonly utilized ACC gap setting was 1.1 s (selected in 50.4 percent of engagement time), which was the shortest of the available time gaps (1.1, 1.6, and 2.2 s). Options for the CACC system were 0.6, 0.7, 0.9, and 1.1 s, and the shortest time gap was selected in 55 percent of the system's engagement time.

Somewhat paradoxically, research showed that while drivers rated their comfort with fully automated driving very high when they were the lead vehicle, comfort dropped to a negative rating for over 70 percent of the participants when a merged vehicle became the lead.(30) Similarly, an ACC study that involved naturalistic driving in three European countries indicated that such systems are generally viewed as a comfort system and utilized less frequently when traffic is dense, which is when the CACC concept would have its biggest potential impact.(31) So, although research has shown closer following distances to be acceptable, some reluctance to rely on automation or timely utilization exists and could affect the actual utilization of CACC technology.

Additionally, some drivers may choose not to utilize automation due to its restrictions. A study looking at driving behavior with ACC categorized the participants based on their responses to a driving style questionnaire.(32) Drivers delegated to the "speed" group, where driving fast appeared to be a chief priority, identified the ACC system as uncomfortable and not useful.(33) So, even though the CACC system may technically provide a more efficient means of transportation, some drivers prefer to manually manage speed and maneuvers. Unfortunately, the driving behavior of this group is likely a promoter of instability in traffic flow and would benefit most from the CACC system.

Application of Automation

Though automation is usually proposed to "supplant human activity," it typically just changes the nature of the human role, which may have unanticipated or unintended consequences.[34] Automation may be able to perform at a higher level than humans, as is the case with BRT, but humans are usually left in charge to monitor the system, leading to a variety of potential issues. As automation allows a system to perform better than if it were manually controlled by a human, system failures may put the human in his least capable situation.[35] In the case of CACC, drivers would be following a lead vehicle at a much shorter time gap than they may be able to accommodate in the event of a CACC system failure.

In monitoring roles, humans have been shown to perform with less than stellar degrees of success. Studies have demonstrated that drivers perform worse when reacting to automation failures than to critical events under manual control and that performance diminishes as levels of automation increase.[36] Automation use in other industries, such as aviation and maritime, have provided many instances in which monitoring failures have resulted in untimely, inappropriate, and even non-existent human responses. (See references 37–40.) Many of these issues pertain to how the automation was understood and utilized.

Trust and Reliance

In order for automation to be utilized, a certain level of trust must exist between the user and the technology. Trust evolves over time in complex individual, cultural, societal, and organizational contexts and is usually based on a technology's ability to achieve a particular goal.[41] Automation utilization requires a user to be vulnerable to the automation's actions with the expectation that it will be successful in helping the user achieve a specific goal, and correct utilization of automation requires that the correct level of trust be placed on it.[42] Incorrect levels of trust result in three possible outcomes, as follows:[34]

- *Misuse:* Users violate critical assumptions and rely on the automation inappropriately.
- *Disuse:* Users reject the automation's capabilities and do not utilize the automation.
- *Abuse:* Designers introduce an inappropriate application of automation.

How someone determines their level of trust in automation depends on an accurate understanding of the purpose, operation, and historical performance of the automation.[43] Unfortunately, users do not always make the correct assessments of these components and often use or rely on automation inappropriately.

A primary and understandable goal for most automation is high reliability. A system with a high failure rate, after all, is not likely to achieve much long-term success. While high reliability fosters trust and likely results in accomplished goals, it also promotes an undesirable side effect. Several studies have shown a complacency effect for highly reliable systems, where users tend to over-rely on the automation, using the automation beyond its intended scope or failing to adequately monitor for malfunctions. Novice users, who may have never experienced a system failure or have only been exposed to automated functionality, may not be able to recognize a malfunction or adequately regain system control when necessary. Surveillance task studies have revealed troubleshooting complacency for participants that had not experienced system failures during training sessions.[44]

Reliance bias increased with those that had practiced system failures as system reliability began to increase. Monitoring performance has been better in variable reliability trials than in totally reliable trials, indicating over-reliance on highly reliable automation.[45]

Experienced users are equally prone to over-reliance and complacency when system reliability is high. Pilots have been shown to rely on automation in situations well beyond the system's intended use and to ignore conflicting evidence of expected and actual automation performance.[19,38] In 1995, a passenger ship ran aground near Nantucket, MA, when the crew blindly relied on a failing navigation system, ignoring numerous position information system displays clearly indicating the ship was drifting off course.[40]

Reliability is not the only factor involved in system trust, however. An interesting study on ACC looked at the relationship between participants' mental model of how the ACC system functioned and their level of trust with the technology.[46] Over 10 consecutive days, participants interacted with ACC technology using a driving simulator. At the end of each day, participants provided a rating of trust and a graphic representation of how they understood the ACC technology to operate. For the groups in which the ACC system malfunctioned 50 or 100 percent of the time, mental model representations changed each day and level of trust with the system never increased. For the group in which the ACC system functioned flawlessly 100 percent of the time, level of trust ratings did not climb until the fourth day, which coincided with the day in which the mental model of the system became fixed. This study demonstrated that having faith in one's understanding of how a system works improves the level of trust in technology, possibly even more than reliability itself. Interestingly, participants' graphic representations, while unchanged after 4 days, never matched the actual system model. This indicates that drivers may end up fully trusting a system by incorrectly believing they understand how it functions, which can lead to inappropriate usage of automation.

Improper trust in automation has been shown in several ACC-related research studies. In a study comparing automated and manual driving, the majority of participants in the automated driving scenarios braked in emergency situations only after a collision alert sounded, indicating they were waiting on the automation to react rather than maintaining an active role.[47] Comparing manual driving with the use of CCC and ACC in fog conditions, another study found that average speeds were significantly higher with ACC use, signifying that drivers were relying on ACC to slow the car when necessary, even in reduced visibility.[48] (Fog can also have a negative impact on the functioning of the ACC system.) That same study also showed that speeds approaching curves in fog conditions were reduced much later in both CCC and ACC scenarios, again suggesting that drivers may utilize automation at inappropriate times, either due to over-reliance, misguided trust, or misunderstanding of the automation's intent or capabilities.

Carryover Effects

One effect of automation on driving behavior that has not been studied much is the impact it has on driving performance after returning to manual control. In the instance of CACC, drivers may become accustomed to driving at very close time gaps. If a driver were to continue at such a gap after switching to manual mode, this could create an extremely dangerous scenario.

An extensive set of experiments in a study on fully automated driving included two scenarios that evaluated carryover effects when switching back to manual driving.[30] The first scenario reflected mixed results, where lane-keeping behavior was better, speed control was worse, and selected time gaps were unaffected when the driver switched back to manual control. However, when the automated driving period was extended before switching back to manual control (4 min in one scenario versus four consecutive trials of nearly 30 mi), significantly smaller time gaps were selected in manual driving. As drivers become more accustomed to CACC technology, this potential carryover effect stands to be a legitimate concern.

WORKLOAD

Although there are several theories on what attention is and how people allocate it, all ultimately concur that there are limits to how much information a person can attend to at one time. This limit may vary based on the specific task, a person's level of arousal or experience, and the ultimate goal, but at any single point in time, there is an upper limit on what can be processed.(49) *Workload* is the overall level of attention demand a task (or group of tasks) presents. As demand for or complexity of one task increases, one's overall workload increases and the ability to attend to new information decreases. The more experience someone has with a task, however, the less demanding the task becomes and the less impact it has on the person's workload levels. Therefore, novice driver workload levels are often maxed out with typical vehicle control tasks, which leaves them with little capacity for other driving-related tasks, such as hazard identification and prediction.(19)

As previously stated, one touted benefit of using automation in vehicles is to reduce driver stress and workload.(19) Automation removes the need for a driver to actively perform a specific action, and the driver theoretically has more cognitive ability available for other actions. Several studies have shown that technologies such as ACC reduce workload levels, and it is reasonable to believe that CACC should realize similar gains.(50,51)

Although reducing workload is usually a positive result, reductions below a certain level can have a negative effect. Human performance is optimal when workload levels are in between extremes, as professed by the Yerkes-Dodson Law.(49) When arousal levels are too low, humans tend to perform below their abilities. As arousal levels increase, so does performance, up to a point at which a task begins to overwhelm human capabilities and performance begins to suffer. This trend creates an inverted U shape when graphed—a positive slope up to some threshold, followed by a negative slope when arousal levels surpass competencies. Reducing a driver's workload level frees up attentional resources but can reduce arousal to the point at which performance suffers. A study comparing manual and fully automated driving found that in automated conditions there was a significant decrease in heart rate and percent road center gazes, which pertain to a region surrounding the most common fixation points.(52)

These physiological changes can translate into negative consequences while driving. In a study in which workload levels varied, participants reported an increase in mind-wandering during low workload scenarios and demonstrated a reduction in horizontal gaze dispersion and side mirror checks.(53) Previous research has indicated that when the primary task does not require executive control in the brain, it permits one's focus to switch to internal information processing (i.e., mind-wandering).(54) As this underload occurs, delayed reactionary performance can occur, which could have catastrophic consequences when traveling at short CACC time gaps.(36,47,51)

Automation-reduced workload does free up more attention capacity for a driver. This can be a huge benefit when the driver uses this available capacity for driving-related tasks, such as scanning for hazards or predicting future states of the driving environment. Unfortunately, increased attention capacity does not necessarily translate to increased driving-related performance. Drivers may also be encouraged to attend to non-driving-related tasks.

DISTRACTION AND SITUATION AWARENESS

With a portion of the driving task aided by automation, the driver has the ability to put additional attention resources toward improving surveillance performance or other driving-related tasks. However, numerous studies regarding driving automation, including ACC, have demonstrated that this spare capacity is often used to engage in non-driving-related secondary tasks. Radio interaction and DVD player usage, number and duration of off-road glances, and other secondary tasks all increased under some form of automated driving.(52,55,56) Additionally, tests on such secondary tasks showed that performance on these tasks improved under automated driving, which demonstrates the additional attention allocated to them.(57,58) Apparently, the more driving automation involved, the more drivers are willing to rely on automation to permit them to perform non-driving related tasks.

Increased secondary task engagement has a direct impact on a driver's SA, the driver's perception of various elements in the driving environment, comprehension of their meaning, and prediction of their status in the near future.(59) These three components of SA can be viewed as the operational, tactical, and strategic levels of driving, which incorporate navigational knowledge, environment and interaction knowledge, spatial orientation, and various vehicle statuses.(60,61) Any increase in non-driving-related secondary tasks decreases these SA knowledge sets and, therefore, negatively impacts driving performance. Emergency situations, such as an unexpected conflict or automation system malfunction, require quick reactions, which are based on an appropriate SA level.

Several studies on BRT with automation clearly demonstrate the potentially disastrous effects distraction and reduced SA can promote. Even when participants were expecting the braking event or had ample information to anticipate the need to brake, drivers utilizing ACC had much higher BRTs than those manually controlling the vehicle.(20,47,57) The braking performance itself also demonstrated reduced SA, as deceleration rates with ACC were twice that of CCC and significantly less safe with ACC when compared to manual driving.(55,57) Similarly, participants in automated driving scenarios in other research studies only applied the brakes after a collision alert sounded, significantly reducing the minimum time to contact.(47) They also exhibited the worst performance when trying to regain driving control from the automated system.(62)

Participants in early research on ACC provided feedback indicating they liked being able to feel the ACC system deceleration, as it made them aware the system was reacting to some conflict.(55) This indicates that rather than maintaining the necessary SA for conflict identification, drivers were relying on automation to alert them when it was necessary to surveil and take action. With closer following gaps, CACC usage may not permit adequate time for a driver to recover from failed SA maintenance.

Several behavioral theories may explain willingness to undertake secondary tasks. Risk Homeostasis Theory speculates that people seek to maintain a certain level of risk. As an environment becomes safer, riskier behavior may transpire; as an environment exceeds one's acceptable risk level, fewer risks will be taken.(63) If automation is perceived to make the driving environment safer, sensation seekers may be more willing to engage in risky behavior, such as non-driving-related secondary tasks.(64) Research on such individuals has shown that they perform better at secondary tasks, take longer to respond to lead vehicle brake lights, initiate more unsafe braking events, and demonstrate worse lane position variability when driving with ACC engaged than when driving manually.[57]

While CACC may enable drivers to travel more closely to a lead vehicle and provide additional traffic-related information to the driver, the automation may have unintended consequences that reduce a driver's awareness of the surrounding environment.

DRIVING BEHAVIOR

In addition to being required for accurate microsimulation modeling, an understanding of general driver behavior is necessary to determine areas in which automation such as CACC may pose risks. Driving behavior studies typically involve areas such as lane-changing, car-following, turning, acceleration, and deceleration; of particular concern for CACC technology are lane-changing and car-following. Although these actions are directly measurable, the motivating forces behind them are more difficult to ascertain and may be prone to human error.

Lane-Changing

Though the CACC concept would eventually apply to all travel lanes, the throughput benefits would be greatest when drivers resist changing lanes and remain in a platoon as much as possible. Not only is a lane change a generally risky maneuver, often involving quick decisions and issues with blind spots, but it can be very disruptive to traffic stability. Several studies have been done to determine why and when drivers change lanes. The results provide conflicting predictions for CACC utilization.

In one driving simulation study, participants displayed a strong tendency to pass a lead vehicle regardless of the lead vehicle's speed.[65] As expected, when the lead vehicle was traveling slower than the participant, the drivers passed in almost every instance. When the lead vehicle was traveling at the same speed as the participant, the participant passed in 66 percent of encounters. Surprisingly, even when the lead vehicle was traveling faster than the participant's average speed, the participants passed roughly 50 percent of the time. What was not clear from the study, however, was why the lane changes were performed. Passing a slower vehicle is obvious, but were the other lane changes due to driver aggression or an increased perception of risk, effort, or workload? The authors assert that one potential cause for passing vehicles moving faster than a driver's average speed is the variability in speed a driver may exhibit. If a lead vehicle is traveling at a speed within a driver's speed variability, the driver is likely to be traveling faster than the lead vehicle at some point and will be more likely to pass. If this is a key factor in lane-changing behavior, CACC technology could provide a big benefit by reducing variability.

Research into how drivers perceive the speed of vehicles in adjacent lanes also provides insight. In comparisons of simulated traffic in two lanes and in actual field-recorded traffic observations, one lane was generally perceived to be traveling faster even though the overall average speed was identical or slower in the selected lane.[66] The general thinking behind this misperception is that vehicles spread out when traveling faster and bunch together when traveling slowly. This makes passing epochs very short (i.e., a fast-moving driver passes many cars in a short period of time) and overtaken epochs very long (i.e., it takes much longer for the same number of vehicles to pass a slow-moving driver). Drivers do not tend to integrate the frequency and duration of these epochs and wrongfully believe the "good" (passing) frequency should equal the "bad" (overtaken) in order for average speeds to be equal. Any difference makes the driver believe he is in a faster or slower lane. Further accentuating this illusion are superficial characteristics, such as a powerful sounding engine or squealing brakes, and the frequency with which a driver tailgates or glances at adjacent lanes.[66] Misperceptions such as these may cause drivers in a higher average speed CACC lane to believe that adjacent non-CACC lanes may be faster, breaking down trust in and usage of the technology.

Untimely lane changes may also be explained by common decisionmaking principles. Utility theory roughly prescribes that decisionmaking is heavily influenced by end goals and final outcomes—people will make decisions based on whatever is likely to provide the best result. However, numerous conflicting examples have given rise to prospect theory, where decisions are based on potential losses and gains rather than true end results.[67] People tend to be risk-averse when posed with potential gains and risk-seeking when posed with potential losses. Therefore, when a driver believes he is losing ground to overtaking vehicles, he may be more likely to change lanes in order to reduce the potential losses.

One study showed willingness for drivers to reduce lane changes under automated control, but the motivation was likely not a positive indicator for the CACC concept. In comparison to manual driving in simulated heavy traffic scenarios, researchers found that under automated control (longitude and latitude), drivers tended to remain in a lane even when the adjacent lane was moving faster.[52] However, these drivers were also much more likely to engage in visually demanding secondary tasks, which may have precluded them from noticing that adjacent traffic was moving faster and indicates reduced attention to the driving task.

Related to lane changes are issues with joining and exiting a CACC platoon. With V2V communication focused on keeping vehicles at very small gaps, it becomes very difficult for a CACC-equipped vehicle to join an existing platoon at any place other than the beginning or end. Similarly, a vehicle attempting to exit a platoon will likely need to adjust its speed to prepare to merge to an adjacent lane, possibly upsetting the stability of the platoon. A microsimulation looking specifically at a merge scenario due to a lane drop demonstrated how platoons negatively impact the merging process.[11] The researchers' suggestions for future research included limiting the length of platoons, infrastructure-based gap-lengthening signals when a downstream bottleneck exists (e.g., construction, lane drop, accident), or additional CACC capabilities to communicate and facilitate lateral merge needs (e.g., turn signal activation by a CACC-engaged vehicle could increase gaps in the applicable part of a platoon).

Car-Following

Car-following is the primary component of the CACC system. Therefore, it is critical to understand how humans behave when behind a lead vehicle and what affects that behavior. A key component of car-following is the time or distance gap behind a lead vehicle. As previously stated, differences in time-gap selection are affected by numerous variables, including age, gender, and weather. Additionally, studies concerned with the use of automation (CCC, ACC, and CACC) have shown drivers are generally willing to travel at shorter gaps than under manual control. What is not clear, though, is if comfort with shorter gaps is based on an accurate interpretation of the environment by the driver.

When estimating following gaps (time and distance), participants in one study were relatively accurate concerning distance but very bad when judging time.[5] The average time-gap estimate in the study was 2.1 s, but 93 percent of the actual gaps were less than 1 s. Studies have also shown that drivers follow larger vehicles more closely even though visibility is reduced.[29,68,69] One possible reason for this is the belief that because larger vehicles take longer to brake, the following driver has more time to react and brake. Research shows that, although braking time is only 8.5 percent longer for larger vehicles, participants follow 14 percent closer.[70] When participants were asked to order vehicles in terms of following distances from short to long, they ordered them passenger car, pick-up truck, bus, and tractor-trailer; however, during driving simulations, researchers did not find any gap differences among the three larger vehicles, indicating that vehicle size may actually change gap perceptions for the driver.[71] Similarly, a study found a discrepancy in gap perception by asking participants to follow at a comfortable gap but varying the starting gap from either extremely close to distant.[26] When participants started far away from the lead vehicle, they closed to an average of a 1.46-s gap; when starting very close to the lead vehicle, they fell back to only a 0.7-s gap.

In addition to perceptual issues, drivers suffer from poor judgment that can affect how and when CACC technology is utilized. Humans are often poorly aware of their skills, typically overly optimistic and miscalibrated.[72] Drivers are prone to overestimating their own performance and underestimating that of others. Asked to rate their performances after a driving simulator study, drivers believed they performed better in automated driving than manual even though anticipation was better, braking was initiated earlier, and minimum time to contact was higher in manual driving.[47] In driving distraction research regarding cell phone conversations, even after witnessing other cell phone users driving erratically, half of the participants indicated they did not find driving while on a cell phone any more difficult; study results indicated that all participants demonstrated performance decrements.[73] Similarly, another study asked participants to estimate the effect cell phone conversation would have on their own driving performance as well as ranking themselves compared to the average U.S. driver on various skill and safety items.[74] In most instances, drivers did significantly worse than they estimated, and in some instances, those that estimated the smallest effect of the cell phone conversations were actually the worst in the group.

In research on acceptance of short gaps, participants were asked to predict the likelihood of accidents for themselves and others at various following gaps. Participants consistently rated others as being more likely to have an accident.[27] Although this study did not test accident rates, it reflects the overconfidence drivers tend to exhibit regarding their own skills and the underestimation of others' skills. This may prove to be an issue when CACC drivers are followed closely by other CACC vehicles; if drivers are not as confident in the following driver's abilities, stress levels may increase.

Poor judgment, as demonstrated by the above research, may have important implications for how safely CACC could be used. Improper confidence in one's abilities, when paired with the effects of reduced workload, may exacerbate the tendency to engage in non-driving-related tasks. Furthermore, previous research on trust and reliance suggests that trust in automation can itself increase the likelihood of a negative result, where a driver may not properly adjust the use of the automation given signs or history of malfunctions.[57]

ISSUES SUMMARY

Table 1 provides a summary of the human-factors issues described in this chapter and the related research utilized for the analysis.

Table 1. Overview of human-factors issues.

Human-Factors Issue	Description	Research Methodology	Reference Numbers of Applicable Research
BRT	Much of the braking process involves the cognitive processes of perception, data processing, decisionmaking, and response selection, all of which are prone to delays. CACC may improve automated BRT but does it provide adequate time for driver intervention?	Simulation	20, 22, 23
		Field Study	5, 21
Automation	Appropriate use of automation for driving tasks requires a certain level of trust and understanding from the driver. Any imbalance invites misuse, disuse, or abuse of the automation. Will drivers utilize CACC appropriately?	Theoretical/Literature Review	10, 34, 35
		Simulation	33, 36, 38, 44–48
		Naturalistic	31
Carryover effects	Behavioral adaptation to CACC time gaps may result in shorter gaps during manual control, which may be a considerable safety risk.	Simulation	30
Gap acceptance	Throughput benefits of CACC depend on drivers being willing to travel at much shorter time gaps than usual. How closely are drivers willing to follow? Are drivers comfortable with succeeding vehicles following as closely?	Simulation	5, 25–27, 30
		Field Study	24
		Naturalistic	28, 29
Workload	Automation purports to reduce driver workload. Does CACC reduce or increase workload? Does driving performance improve or deteriorate? Does CACC embolden drivers to engage in non-driving-related tasks?	Theoretical/Literature Review	19, 36, 49, 54
		Simulation	50–53
SA	Reduced workload from CACC use may enable drivers to engage in non-driving-related tasks. These tasks detract from the awareness of the driving environment and pose a risk, especially during system failures and emergencies.	Theoretical/Literature Review	20, 59, 60
		Simulation	20, 47, 52, 56–58, 61, 62
		Naturalistic	55
Lane-changing	Lane-changing not only reduces the stability benefit of CACC but also introduces additional risk. It is important to understand if CACC usage may encourage or discourage lane-changing.	Theoretical/Literature Review	67
		Simulation	65, 66
		Microsimulation	11
Car-following	Error in human judgment can have a significant effect on how drivers perceive, process, and act on information. Among concerns, driving at close time gaps may reduce time for corrective actions due to poor judgment.	Simulation	5, 27, 29, 47, 57, 69, 71–73
		Field Study	68, 70, 74

BRT = Brake response time.
CACC = Cooperative Adaptive Cruise Control.
SA = Situational awareness.

RESEARCH SCENARIOS

Based on previous research and the potential impact of human-factors issues on CACC implementation, several areas of research are suggested for evaluation and presented in order of significance. For each suggested research question, the proposed independent variable is provided in parentheses.

WILLINGNESS TO UTILIZE CACC

Beyond the technical feasibility of a technology, primary concern pertains to acceptance by the intended audience. CACC provides the greatest benefit in dense traffic in highway environments, allowing more vehicles to travel in a given lane. However, there is a potential for drivers to be less willing to utilize the system in such conditions, preferring to maintain manual control and longer time gaps.

Research Questions

The following research questions relate to drivers' willingness to utilize CACC:

- How does traffic density affect the choice to utilize CACC? (Traffic density)
- Does the number of travel lanes affect the choice to utilize CACC? (Available travel lanes)
- Do available preset time-gap options affect utilization? (Time-gap options)
- Does system reliability affect usage or complacency? (System failure rate, failure timing)

Potential Methodologies

The following methodologies are recommended for addressing the preceding research questions:

- Driving simulation:
    - Advantages:
        - Easier to control scenarios and surrounding traffic.
        - Safety.
    - Disadvantages:
        - Realism, reduced perception of risk.
    - Resources:
        - Mini-simulator or high-fidelity simulator.

WORKLOAD, SITUATIONAL AWARENESS, AND DISTRACTION

Use of CACC should reduce a driver's workload, enabling dedication of additional resources to driving-related tasks such as hazard identification and anticipation. However, a driver may apply these additional resources to secondary, unrelated tasks. These secondary tasks may have negative impacts on a driver's SA, limiting his ability to make emergency maneuvers or quickly retake manual control of the vehicle.

Research Questions

The following research questions relate to workload, SA, and distraction:

- How does use of CACC affect workload and SA levels? (Automation)
- Are drivers more likely to engage in secondary tasks while utilizing CACC? (Automation)
- Do driving behavior and performance change during CACC driving? During secondary tasks? (Automation, secondary tasks)
- How quickly do drivers respond to events under manual and CACC driving? During secondary tasks? (Automation, event onset, secondary tasks)

Potential Methodologies

The following methodologies are recommended for addressing the preceding research questions:

- Driving simulation:
  - Advantages:
    - Easier to control scenarios and surrounding traffic.
    - Safety.
    - Secondary tasks easier to introduce.
    - SA measurement tools may be introduced mid-scenario.
  - Disadvantages:
    - Limitations on real-world secondary tasks.
    - Realism, reduced perception of risk.
  - Resources:
    - Mini-simulator or high-fidelity simulator.

- Field study:
    - Advantages:
        - Realism and ecological validity.
    - Disadvantages:
        - Safety.
        - Control.
    - Resources:
        - Test track.

PLATOON ENTRY/EXIT

As indicated by van Arem et al., CACC platoons can make it difficult for vehicles in adjacent lanes to join an existing platoon.(11) In figure 1, the short gaps in the platoon of vehicles in the top lane hinders the vehicle in the center lane (noted with an X) from joining. Additionally, vehicles that want to exit a platoon may need to adjust their speed based on the adjacent lane before exiting, affecting the platoon stability. In figure 2, the middle vehicle (noted with an X) may disrupt the platoon of vehicles in the top lane by attempting to change lanes. Research is needed on how to aid these maneuvers and minimize their impact.

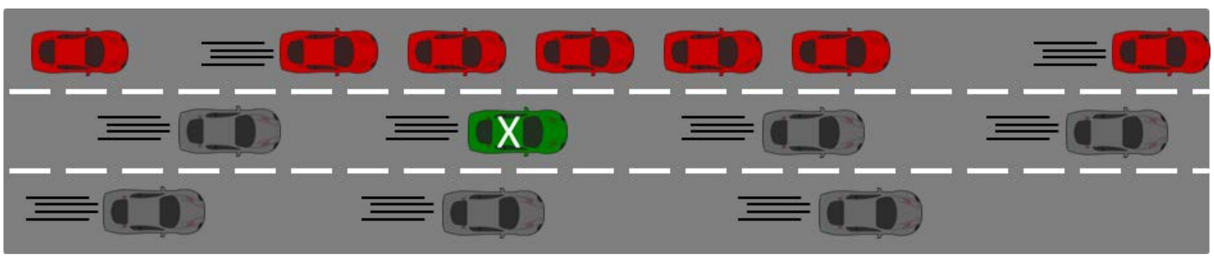

Figure 1. Illustration. Merging into a CACC platoon.

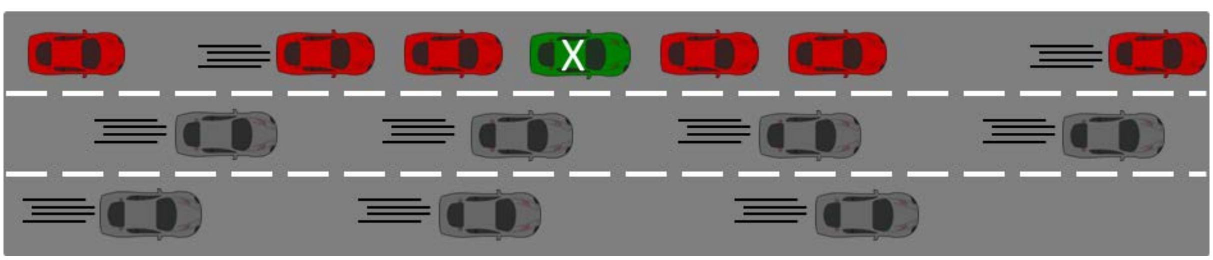

Figure 2. Illustration. Exiting a CACC platoon.

Research Questions

The following research questions relate to platoon entry and exit:

- How does a vehicle exiting a platoon affect traffic stability? (Speed of adjacent lane)
- Can V2V communications facilitate merges and improve performance? (Automation assistance)

Potential Methodologies

The following methodologies are recommended for addressing the preceding research questions:

- Driving simulation:
    - Advantages:
        - Easier to control scenarios and surrounding traffic.
        - Simulated CACC assistance behavior easier than programming vehicles.
    - Disadvantages:
        - Realism low for performing lane changes (no real view of traffic behind driver).
        - Measuring large-scale stability effects may be difficult.
    - Resources:
        - Mini-simulator or high-fidelity simulator.
- Microsimulation:
    - Advantages:
        - Easier to control platoon behavior.
        - Greater ability to look at large-scale effects.
    - Disadvantages:
        - Accurate model for traffic behavior difficult to develop.
    - Resources:
        - Modeling software.

ARTERIAL INTERSECTIONS

Microsimulations have indicated that with appropriate information, drivers could adjust (or I2V communication could directly adjust) approaching speeds to an intersection to reduce deceleration/ acceleration and the need to stop, saving time and fuel. Although the driver would be conscious of the speed change, following vehicles (if not CACC enabled) may not be aware of the upcoming red light or may simply not be willing to follow at what they consider a slower-than-necessary speed. In figure 3, the CACC-equipped lead vehicle initiates deceleration due to an upcoming red light. The non-equipped following vehicle may not be aware of the deceleration impetus, however. This incongruence may lead to passing events by following vehicles, which may not only affect the success of the CACC-induced speed adjustment (i.e., vehicles joining the driver's lane in front of the driver will likely require additional deceleration) but also increase the chance of accidents due to lane changes in intersection environments.

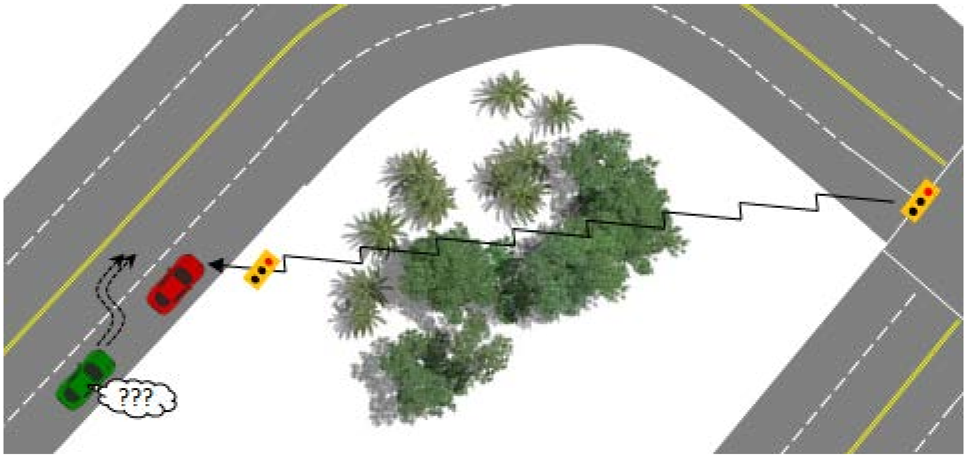

Figure 3. Illustration. CACC-equipped vehicle followed by non-equipped vehicle.

Research Questions

The following research questions relate to arterial intersections:

- How does the following vehicle (participant) react to the lead vehicle slowing? (Deceleration rate)
- Does behavior change based on whether a red light is visible or not? (Visibility of intersection)
- Does behavior change based on travel lane? (Travel lane)
- Does behavior change based on distance to the light when deceleration begins? (Distance to intersection at deceleration)
- Does behavior change based on environment (e.g., commercial, residential, or remote area) or traffic density? (Environment, traffic density)

Potential Methodologies

The following methodologies are recommended for addressing the preceding research questions:

- Driving simulation:
    - Advantages:
        - Easier to control scenarios and surrounding traffic.
    - Disadvantages:
        - Clarity of distant objects (e.g., intersection signals) may not be sufficient. High-fidelity simulator may eliminate issue.
        - Potential lane changes may have participant checking non-existent rear traffic.
    - Resources:
        - Mini-simulator (possibly high-fidelity simulator).
- Naturalistic:
    - Advantages:
        - More realistic data.
        - No participant recruiting (simple observation of vehicles following research vehicle).
    - Disadvantages:
        - Difficult to control traffic and signal phasing.
    - Resources:
        - Vehicle with rear/side recording devices or additional researchers to manually record following vehicle behavior.

CARRYOVER EFFECTS

CACC utilization permits a driver to follow a vehicle more closely than safely possible under manual control. After exposure to these shorter gaps, behavioral adaptation may result in drivers continuing to follow at shorter gaps during manual control, increasing risk.

Research Questions

The following research questions relate to carryover effects:

- How closely do drivers follow a lead vehicle under manual control? Does this vary with speed? (Lead vehicle speed)

- After periods of CACC usage, does the manual driving gap change? Does length of time under CACC control affect the manual gap? (Automation usage duration)

- Does traffic density affect following gap before or after CACC exposure? (Traffic density, automation exposure)

Potential Methodologies

The following methodologies are recommended for addressing the preceding research questions:

- Driving simulation:
    - Advantages:
        - Easier to control scenarios and surrounding traffic.
        - Safety.
    - Disadvantages:
        - Realism, reduced perception of risk.
    - Resources:
        - Mini-simulator or high-fidelity simulator.

FOLLOWING VEHICLE GAP COMFORT

Numerous studies have assessed drivers' comfort with following a lead vehicle at various gaps, regardless of whether they are driving manually or with some variety of automation, including CACC. However, an important aspect that has yet to be researched is how comfortable a driver would be having another vehicle closely following his car. The gaps utilized with CACC would likely be considered tailgating in normal driving conditions, which means drivers may be less accepting of others driving at close distances, especially if they are not certain the following vehicle is under automated control. In figure 4, the middle vehicle may feel comfortable following the lead vehicle but may not be comfortable with the rear vehicle being so close. Studies that show people typically overestimate their own skills and underestimate those of others hint at reduced comfort with succeeding vehicles. As drivers become more comfortable with the technology, their comfort levels for those behind them may increase.

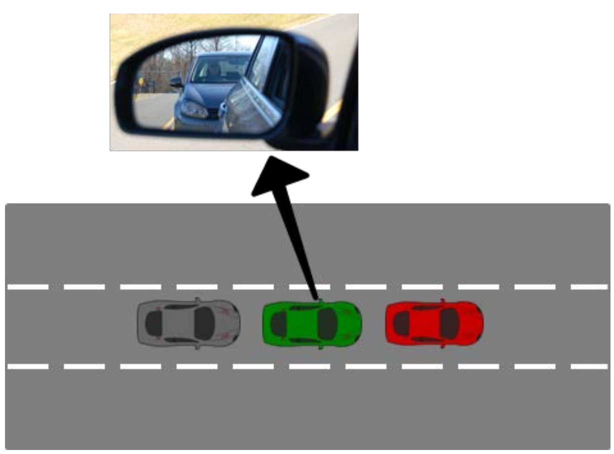

Figure 4. Illustration. Closely following vehicles in CACC platoon.

Research Questions

The following research questions relate to following vehicle gap comfort:

- How comfortable is the participant with a following vehicle at short gap? (Time gaps)
- Does comfort level change after driving a CACC vehicle? (Experience with CACC)
- Does comfort level change if the participant is the lead vehicle or part of a platoon? (Platoon position)
- Does comfort level change as density of surrounding traffic changes? (Traffic density)
- Does comfort level change if the participant knows the following vehicle is manually driven or has CACC engaged? (Following vehicle mode)

If a positive effect is found for knowing the following vehicle is CACC-engaged, follow-up studies could include the best manner of notifying the lead driver. For example, CACC-equipped vehicles may have an indicator light on the front of the vehicle for when CACC is engaged, or drivers may have access to a display that indicates when CACC-engaged vehicles are immediately behind, in front, or to either side.

Potential Methodologies

The following methodologies are recommended for addressing the preceding research questions:

- Field study:
    - Advantages:
        - Realism due to participant being able to truly see the surrounding environment and following traffic.
        - More naturalistic data.
    - Disadvantages:
        - Difficult to provide and control traffic density.
        - Requires multiple CACC-equipped vehicles.
        - Safety.
    - Resources:
        - Three or more CACC-equipped vehicles.
        - Test track.

- Driving simulation:
  - Advantages:
    - Easier to develop and control surrounding traffic.
    - CACC-equipped vehicles simply programmed.
    - May be able to conduct in mini-simulator rather than high-fidelity simulator.
  - Disadvantages:
    - Simulator does not provide a realistic rear environment for the driver. “Mirrors” may show some simulation but the driver cannot turn his head for additional information.
  - Resources:
    - Driving simulator.

CONCLUSION

CACC has the ability to greatly increase throughput on high-volume highways with significantly less cost than traditional lane expansion. In addition to time savings for drivers, CACC presents the environmental benefits of reduced emissions and fuel usage. All of these benefits may also be realized in arterial intersection environments where infrastructure can inform (or directly influence) a driver to adopt the most appropriate speed at which to approach an intersection.

The success of CACC lies heavily in understanding and managing the various human-factors issues that pertain to automation usage. Knowing how, when, and why a driver uses automation, what underlying processes and information are utilized when making decisions, and what secondary activities the automation usage may encourage is critical. The data presented in this report and the proposed research scenarios can help increase the likelihood of successful system implementation and aid the development of necessary training and policy.

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