Meta-Analysis of Adaptive Cruise Control Applications

Operational and Environmental Benefits

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16. Abstract

With the increasing adoption of adaptive cruise control (ACC) and development of cooperative adaptive cruise control (CACC), their effect on traffic, energy, and emissions is an ever more urgent question. Using the rapidly growing body of research on these impacts, this report presents a systematic review and meta-analysis of 67 recent studies. The majority were simulation studies with a few field tests. While the assumptions and methodology between studies in our review differ widely, a meta-analysis of maximum reported capacity improvements and fuel savings confirmed that CACC applications tend to increase capacity and fuel savings over manual driving due to shortened following time gaps and greater string stability from connectivity. In contrast, ACC applications do not always show capacity improvements, and if so, these improvements are more modest on average than for CACC systems. We found that ACC systems do, however, appear to smooth driving through less braking and reduced hard acceleration events such that fuel consumption is reduced, but not on average as much as CACC systems.

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Executive Summary

With the increasing adoption of adaptive cruise control (ACC) and development of cooperative adaptive cruise control (CACC), their effect on traffic, energy, and emissions is an ever more urgent question. Using the rapidly growing body of research on these impacts, this report presents a systematic review and meta-analysis of 67 recent studies. The majority were simulation studies, with a few field tests also included. Our systematic review showed that research has shifted from ACC to CACC technologies over the past five years and many recent studies are focused on CACC. The following U.S. Department of Transportation report provides meta-analyses of ACC and CACC vehicle-following time gaps, roadway capacity improvements, and fuel savings under a broader automated vehicle benefits research program.

The time gap from the lead vehicle to the following vehicle often factors into whether an automation system will achieve operational and environmental benefits compared to a human driver. In a meta-analysis of following time gaps across studies, CACC applications produced consistent time gap reductions, but the average of ACC time gaps was greater than the average gaps for naturalistic, manual driving. This potential increase in time gaps from CACC to ACC applications is most likely linked to drivers being more confident in the predictability of following a connected vehicle than a human-driven vehicle when they are not in control of their own acceleration or deceleration.

While the assumptions and methodology between studies in our review differ widely, our meta-analyses of maximum reported roadway capacity improvements and fuel savings confirmed that CACC applications tend to increase capacity and fuel savings over manual driving. This is likely due to shortened time gaps and greater string stability resulting from connectivity. The CACC studies showed an increase in capacity (or observed throughput) ranging from 3 - 100%, with an average of 59%. In contrast, ACC studies did not always show capacity improvements, and if they did, these improvements were more modest on average than for CACC systems. Capacity changes ranged from -26 - 66% for ACC driving, with an average of 7%. On the other hand, ACC systems do, however, appear to smooth driving through less braking and reduced hard acceleration. The studies of ACC or CACC applications showed fuel savings in the range of 2 - 47%, though impacts between systems were mostly indiscernible with an average savings of 10% for ACC and 11% for CACC. It should be noted that for most of these studies, reported benefits come from simulations rather than field observations.

Introduction and Background

There is a rapidly growing body of research on the potential impacts of connected and automated vehicles (CAVs). The surge in publications has been particularly notable for studies on the impacts of adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC). Adaptive cruise control technologies have origins in the early intelligent transportation system initiatives of the 1970s and 1980s that aimed to reduce traffic congestion, expand highway capacity, and improve travel efficiency (*1*). Despite the burgeoning research field, there is little consensus on the magnitude of operational and environmental benefits from ACC and CACC systems. This report provides a systematic review of ACC and CACC studies relevant to operational performance and environmental impacts through a meta-analysis of key parameters and results as part of the U.S. Department of Transportation's research on an automated vehicle benefits framework.

Working Definitions

In simple terms, adaptive cruise control assists the driver in acceleration and deceleration behind a lead vehicle at a desired following time or distance. These automated driving systems typically rely on radar, LIDAR, or high-resolution cameras to safely monitor preceding traffic (*2*). Japanese automotive manufacturers first began to offer ACC as a luxury feature for driver convenience in 1995, and ACC features in Europe and the U.S. followed shortly thereafter (*3*). Vehicle automation systems have matured over time; according to an industry survey of model year 2017 passenger vehicles, 16 manufacturers offer roughly 180 models with ACC functionality (*4*). While researchers, industry, and government have coalesced around the terminology for ACC and CACC systems in recent years, there is still some debate over the attributes that comprise these systems (*3*).

Cooperative adaptive cruise control couples ACC functionality with vehicle communication technology, most commonly between vehicles. Although CACC systems have been prototyped and modeled for some time, contemporary production vehicles with ACC lack the necessary vehicle-to-vehicle (V2V) and/or vehicle-to-infrastructure (V2I) communication systems to constitute full CACC driving (*5*). As discussed in the Vehicle Controls section below, although ACC and CACC longitudinal control systems fall squarely into the SAE J3016 Level 1 of automation (*6*), some manufacturers combine them with lateral controls, namely lane-keeping technology, for Level 2 driving.

Systematic Review

During the summer of 2018, we reviewed 67 CAV impact studies using the following selection criteria:

- either ACC or CACC technologies or both,
- both simulations and field tests,
- network- and corridor-level applications on freeways,
- quantifiable impacts to vehicle operations, fuel use, and emissions, and
- studies of passenger vehicles (a few heavy-duty vehicle studies also included for reference).

Given these filters, most of the compiled studies were published in 2016 or later (Figure 1a). In order to track all relevant ACC publications, each study was cited and entered into the Zotero reference management software (*7*). We then manually added multiple keyword tags that, for example, included "CACC," "V2V," and "freeway." This tagging process enabled further keyword searches and facilitated the extraction of reported values for the respective meta-analysis of time gap settings, fuel efficiency gains, and capacity improvements. A list of the major fields considered in this systematic review and common tags added can be found below (Figure 1b). An addendum to this report contains a brief discussion of relevant studies published after our original systematic review and meta-analysis was completed in 2018.

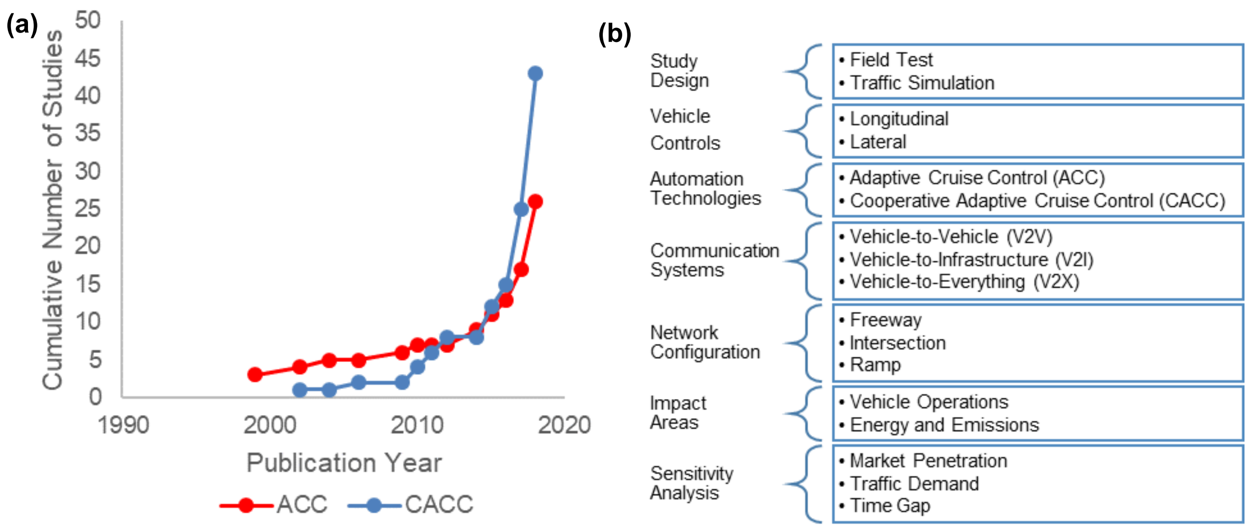

Figure 1. (a) a cumulative plot of the relevant publications for ACC (n=26) and CACC (n=43) by year, and (b) a list of the major fields considered and some common tags in the systematic review

Meta-Analysis

Although meta-analysis is most common in health sciences and medicine, it is also applicable to transportation research. A meta-analysis selects a subset of studies from a systematic review in order to combine pertinent qualitative and quantitative data for a single conclusion with greater statistical power. Elvik suggests the best meta-analyses focus on what results a paper achieves rather than the differences in methods and approaches between studies. Elvik also warns of publication bias by omitting studies that show few-to-no effects (*8*).

A few systematic reviews and/or meta-analyses of adaptive cruise control applications exist, but none have aggregated operational and environmental results. Xiao and Gao consider the history of ACC development, including various efforts to test controllers and prototypes along with discussions on a wide variety of impact areas. Their review notes that early studies allude to potential benefits in both capacity and energy/emissions (*3*). As our meta-analysis confirms, Hoogendoorn, van Arem, and Hoogendoorn found that studies conducted as of 2014 were primarily simulation-based, focused only on longitudinal control, and did not consider behavioral effects of automation on surrounding vehicles (*9*).

Two papers closely resembling ours have been published recently, but one focuses on signalized intersections rather than freeways, and the other does not significantly investigate environmental impacts. Rios-Torres and Malikopoulos summarize the literature on centralized and decentralized CAV control strategies at intersections and on-ramps. Their review found that few papers reported fuel efficiency improvements, but the most common improvement was 45 - 50% savings (*10*). Tian et al. sorted CAV benefits into three general categories: safety, mobility, and environmental impacts. They found certain technologies may create benefits in one or more category, while negatively impacting another. For example, greater stop-and-go activity caused by safety-designed collision avoidance systems might increase emissions (*11*). Unlike these related papers, our meta-analyses specifically developed quantitative impact ranges for highway applications of ACC and CACC. The next section of this report presents the findings of our systematic review and meta-analyses.

Methods and Discussion

Using the keyword tags described above, we produced summary statistics for the meta-analyses of time gaps, capacity improvements, and fuel savings of ACC and CACC applications. The discussion of study methodologies is organized into the following fields: study design, vehicle controls, communication systems, roadway configuration, and impact areas.

Study Design

Of the ACC and CACC impact studies reviewed, a large majority were modeling scenarios. Field testing of ACC and CACC systems did not begin in earnest until roughly ten years ago, and the number of field studies are greatly lagging behind simulation-only studies. Perhaps this is to be expected with nascent technology, as it may not be feasible to evaluate global objectives such as traffic flow, highway capacity, and fleet fuel efficiency without higher market penetration and adoption of these CAV driving systems. Nonetheless, with the multitude of production vehicles equipped with ACC and the numerous hours of CACC prototype testing from OEMs, sensor developers, government, and universities, there seems to be some hesitancy or latency in publishing results from field data.

Traffic Simulations

A few preliminary traffic simulation studies on highly idealized networks first suggested that CACC may positively affect string stability, roadway capacity, and energy/emissions (*12–14*). Over time, simulations of ACC and CACC became more sophisticated and incorporated realistic inputs. Vander Werf et al., who adjusted the desired time gaps downward to 1.4s for ACC and 0.5s for CACC, found little-to-no benefit for ACC but significantly improved network capacity for CACC. They also conducted a sensitivity analysis of time gaps at 100% penetration, and results varied widely depending on the time gap chosen, ranging from roughly a 20% decrease in capacity to a nearly 30% increase (*15*). Van Arem et al. focused on how CACC-equipped vehicles could potentially improve traffic flow when a lane drop occurs or a dedicated lane is added. Their simulations predicted that at high penetration rates, the dedicated lane will improve performance for all vehicles—not just those equipped (*16*).

Some studies compared ACC and CACC systems in stochastic microscopic traffic simulations or agent-based models (*17*, *18*). Shladover, Su, and Lu utilized AIMSUN to show that one lane with 100% penetration of CACC-equipped vehicles could double in throughput from approximately 2,000 to 4,000 vehicles per hour (*17*). The most recent simulations model CAVs in complex, real-world networks with observed speeds and traffic volumes by vehicle class. Shelton et al. modeled CACC vehicles on a 12-mile stretch of a congested urban interstate in Texas with multiple lanes and many entry and exit ramps. Their results suggest that the connected vehicles may form platoons that block other traffic from maneuvering, subsequently reducing throughput (*19*). Mattas et al. implemented a CACC model on the road ring network around Antwerp, Belgium to investigate the potential impacts at various penetration levels and several potential demand scenarios. The authors found that increasing levels of CACC penetration in all demand scenarios improved speed and delay metrics during rush hour and resulted in a faster return to free-flow after rush hour. However, congestion reduction did not necessarily correspond with decreased fuel consumption and emissions (*20*).

Many models of the impacts of ACC and CACC are implemented in traffic microsimulation software platforms, which enable researchers to design a realistic road network and model individual vehicle trajectories across a simulation timeframe. Such platforms can also include traffic animations and other visualizations. The most common platforms utilized were PTV Vissim and Aimsun, both of which allow users to enter custom driver models as well as measured speed and traffic counts.

Field Tests

Some of the earliest field tests assessed the ability of the ACC controller to follow the lead vehicle and brake safely under naturalistic driving conditions (*21*, *22*). Pioneering CACC field tests were primarily concerned with string stability, reductions in vehicle jerk, and the velocity and acceleration/deceleration responses to signals from inter-vehicle wireless communications (*2*, *23*). While these field studies focused on safety impacts or local objectives of the ACC or CACC vehicles, others have done more to consider the global operational and environmental objectives.

For example, Bu et al. showed the variation in time gap setting to the measured time gap for a commercial ACC system and a prototype CACC system in a proving ground experiment. They found that the CACC controller yielded shorter, better-regulated time gaps than the ACC controller. These results were confirmed on a public highway (*24*). Milanés et al. also tested a factory-shipped ACC system versus a custom CACC system in real-world traffic, including time gap changes for cut-in and cut-out events in a four-vehicle string. The new CACC system reduced gap variability, accommodated cut-in vehicles gracefully, and generally improved response time and string stability due to the information available about vehicles further ahead (*25*). Stern et al. conducted an experiment with one CAV and 20 conventional vehicles around a circular test track. Results showed approximately a 43% reduction in the entire fleet's fuel consumption, along with smaller deviations in vehicle speeds and fewer braking events (*26*). Other research has shown similar benefits for CACC-enabled truck platoons, which have the added advantage of reducing aerodynamic drag (*27–30*).

Despite much progress in ACC models and experiments, these studies have remained largely siloed. Only recently have models been validated through field testing. Milanés and Shladover have compared speed traces and headways of instrumented vehicles with ACC and CACC controllers to those from the Intelligent Driver Model (IDM). While the IDM controller produces smooth vehicle following, it has remarkably slower response and large variations in gap clearance (*31*). Schakel, van Arem, and Netten developed IDM+ to better mimic of the performance of a field-tested vehicle with a CACC-based advisory system (*32*).

Vehicle Controls

Studies of adaptive cruise control vehicles are overwhelmingly oriented towards longitudinal controls. None of the studies we reviewed separately addressed lateral control logic such as cooperative lane change and/or lane positioning. Although many studies included lane change, they assumed the driver would be responsible for lateral control of the vehicle. A novel V2V communication strategy proposed by Schmidt enabled CACC vehicles in adjacent lanes to safely merge (*33*). Liu et al. implemented a custom cooperative lane change algorithm within their CACC microsimulations (*34*). Talavera et al. considered the congestion and fuel consumption impacts of adding Level 2 lane-centering capabilities to a CACC system through computer vision and global positioning systems (GPS). Microsimulation results point to improved capacity and fuel efficiency with minimum delay (~15 milliseconds) (*34*).

Time Gaps

The following time gap between vehicles in an ACC or CACC string is a critical component for determining system performance. Shladover et al. organizes gap regulation based on constant clearance or distance, constant time, and constant safety-criterion (*5*). Our review is almost exclusively of constant time gap regulation, but there are some mentions of constant clearance for heavy truck applications. Minderhoud and Bovy have shown that highway capacity is inversely correlated to the time gaps of adaptive cruise control systems, where shorter gaps result in larger capacity improvements (*12*). More recently Mamouei, Kaparias, and Halikias presented evidence to suggest that a system-optimal ACC driving strategy with tight headways will lead to more fuel-efficient behavior (*35*). Furthermore, Nowakowski et al. found in real-world driving that V2V communications in CACC applications allow for shorter time gaps than automated vehicle-following without communication or manual driving; in fact, drivers prefer these narrower gaps (*36*). Shladover et al. then modeled those preferred ACC and CACC gaps to conclude that CACC systems have greater potential to increase capacity than ACC systems due the shorter gaps (*17*). Given the high time gap sensitivity, we have compared the gaps reported for ACC, CACC, and manual driving below across the studies selected in our meta-analysis (Table 1).

The following boxplot of the reported time gap includes data from simulations and field tests but omits studies of heavy trucks and intersections (Figure 2). In certain cases where simulations ran multiple time gap settings, each gap was included. For time gaps set over a range, the midpoint was selected. These results indicate that CACC systems have the shortest gap, particularly when the outliers at 3 seconds are excluded, with a consensus around 0.5 and 0.6 s as the most often selected gaps (mean = 1.05 s). Our findings align with California Partners for Advanced Transportation Technology (PATH) research that suggested ACC systems have an acceptable time gap range of 1.1 - 2.2 s, while the range for CACC systems is 0.6 - 1.1 s (*36*).

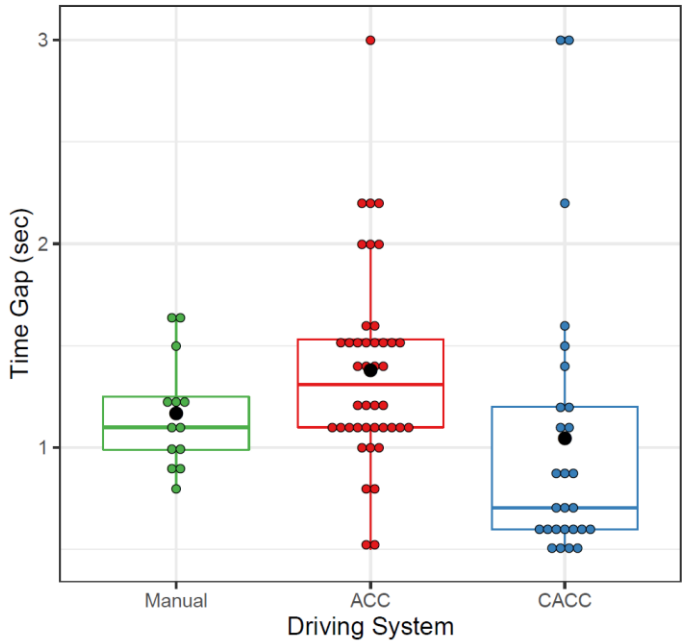

Figure 2. Meta-analysis of reported following time gaps for ACC (n=42), CACC (n=27), and manual (n=13) driving on freeways (black dots represents mean gaps)

Interestingly, we find that manual driving has a lower mean time gap (1.17 s) than ACC (1.44 s), with less variability. In testing of preferred gaps, Nowakowski et al. proposed that some drivers might have been less comfortable with the shorter gap settings when behind another manually driven vehicle but were more accepting of tighter gaps when following a CACC-equipped vehicle or keeping a safe following distance when driving themselves. The California PATH report describes the bimodal nature of ACC time gap acceptance (*36*). Calvert et al. make an important distinction between the desired time gaps and the actual operational headways, which tend to be higher than the initial desired gap setting because of the conservative driving style of ACC systems. Moreover, ACC systems have desired time gaps of 1.2 - 1.8 s whereas human drivers have desired gaps of 0.5 - 1.5 s. Under these circumstances, Calvert et al. found that the distribution of ACC time gaps in congested traffic flow skew longer than the distribution of gaps from manual driving (*37*).

Table 1. Summary of reported following time gaps (in seconds) and following distances (in feet) for manual, ACC, and CACC driving from studies reviewed (n=47)

Time Gap (in seconds unless otherwise noted)			Intersection?	Field?	Heavy?	Source
Manual	ACC	CACC				
	0.8, 1.0, 1.2, 1.4					(*12*)
1.1 (mean)	1.4	0.5				(*15*)
	1.4	0.5				(*16*)
1.64 (mean)	1.53 (mean), 1.1 (mode)	0.705 (mean), 0.6 (mode)				(*17*)
	1.2	0.6				(*18*)
0.99	0.55					(*19*)
	1.1, 1.6, 2.2	1.1, 1.6, 2.2				(*20*)
	1.1, 1.5, 2.2	0.6-1.1		Y		(*24*)
	1.1, 1.6, 2.2	0.6, 0.9, 1.1		Y		(*25*)
	2			Y		(*26*)
		0.2-0.8 s (20-75 ft)		Y	Y	(*27*)
		30-150 ft		Y	Y	(*28*)
		0.14-3			Y	(*29*)
		15 ft (field), 0.6 and 1.1 s (simulated)			Y	(*30*)
	1.1	0.6		Y (ACC only)		(*31*)
1.2 (mean)	1.2	1.2				(*32*)
		0.5				(*33*)
		3				(*34*)
1.1 (mean)	2 (platoon optimal), 0.5 (network optimal)					(*35*)
1.64 (mean)	1.53 (mean), 1.1 (mode)	0.705 (mean), 0.6 (mode)		Y		(*36*)
	1.5 (mean)					(*37*)
0.9	1.1	0.6				(*38*)
	1.1			Y		(*39*)
1.25	1.53 (mean), 1.1 (mode)	0.705 (mean), 0.6 (mode)				(*40*)
1.2						(*41*)
	1.1	0.6				(*42*)
0.8 (mean)	0.6		Y			(*43*)
	1.1					(*44*)
	1.1	1.2		Y		(*45*)
		0.6				(*46*)
0.9	1.1	0.6				(*47*)
		0.52, 1.4 (two different models)				(*48*)
		0.9				(*49*)
1 (mean)	1.22 (mean), 1.0 (mode)					(*50*)
	3	3				(*51*)
	1-3			Y		(*52*)
		1.32 (mean), 1.2 (mode)			Y	(*53*)
		up to 150 ft		Y	Y	(*54*)
	1					(*55*)
	0.8-2.0					(*56*)
	0.2		Y			(*57*)
	1.5					(*58*)
	1.5	1.5				(*59*)
	1					(*60*)
1.5	1.5					(*61*)
	1.5		Y			(*62*)
	0.8, 1.1					(*63*)

Driver Models

In order to simulate longitudinal and lateral vehicle controls in a stochastic traffic model, a driver model is needed. Many contemporary traffic simulators allow users to edit or completely override the default driving behavior, such as importing longitudinal driver models for ACC and CACC systems. Users can enter their ACC or CACC driver model through a dynamic link library (DLL) or the component-object model (COM) interface. In addition, it is important to denote which model was used to represent naturalistic driving as baseline behavior, because the baseline model will affect any benefit estimates. Often, the default naturalistic driving behavior is defined by the traffic microsimulation software selected. For freeways, PTV Vissim utilizes the Wiedemann 99 vehicle-following model, while Aimsun utilizes the Gipps model (*64*). Other features incorporated into the driver model, such as a collision avoidance system, may also impact behavior and are worth mentioning explicitly in documentation of the simulation.

The most prevalent ACC model is the Intelligent Driver Model (IDM) based on the work of Treiber et al. This model was later enhanced to more closely mimic ACC behavior, which has the main objective of maintaining the desired time gap while also maintaining at least the minimum allowed following distance (*61*, *65*). Specifically, IDM set a maximum acceleration along with a desired speed and deceleration values. Since its original development, IDM has been modified on numerous occasions to better represent a CACC controller with shorter time gaps and enhanced string stability by minimizing traffic oscillations.

Another popular model, MIXIC, was originally developed by Van Arem as a CACC model that would smooth driving for equipped following vehicles in the string through a minimization function for acceleration and deceleration (*16*). Twelve studies we reviewed adopted IDM, IDM variants, or MIXIC. Of the other studies reviewed, many implemented similar ACC and/or CACC models that included their own modifications to the control algorithms. Most models include an acceleration objective function with default values for the desired time gap, minimum distance at jam density, and acceleration/deceleration bounds. Lateral controls, when considered, could also be overridden with cooperative lane change models in the traffic simulations (*66*).

Communication Systems

The key distinction between an ACC and a CACC system is the incorporation of communications technologies into the information the vehicle uses to determine its following behavior. Typically, modelers simulate these systems by reducing the time gap between vehicles, which directly leads to road capacity increases. However, there are potential benefits to communication outside of reduced following distances. Ge et al. discuss, for example, that the addition of communications can improve the response time to a lead vehicle beyond line-of-sight, such as around a curve, and can mitigate stop-and-go traffic (*67*).

As noted by Shladover et al., there are two main types of communications based on the devices with which the vehicle is interacting: 1) other vehicles on the network, and/or 2) fixed infrastructure, primarily roadside devices or traffic signals (*5*). This meta-analysis found that most of the research reviewed on CACC focused on the former, with 29 studies principally on V2V communications. Nine studies included V2I applications, and another nine considered the possibilities of combined V2V and V2I systems.

Vehicle-to-Vehicle Communications

In determining the potential benefits of V2V-enabled CACC systems—commonly designed for highway applications–simulations rarely focus on the commercial integration of these technologies. Rather, these modeling efforts either modify existing or establish new vehicle-following models that reflect expected CACC performance, usually in the form of reduced headways and fewer fluctuations in speed and acceleration. Few authors explicitly modeled the performance of the V2V communications. Baur et al., however, considered the effect that message transmission probability has on system performance (*18*). The authors found that implementing a realistic communications-reception model increases the average time gap and the number of safety-critical incidents on the network, further suggesting that simulation studies can at best provide an upper bound for the potential benefits of CACC systems.

Early field tests of CACC systems often had limited communication systems and were not integrated with the automation technologies. Schakel et al., for example, demonstrated a system that sent an advisory message to the driver for a desirable acceleration response, but ultimately it was the driver's responsibility to perform the action (*32*). Recent field tests of wireless V2V technologies typically rely on dedicated short-range communication (DSRC) systems to pass speed and positional data between vehicles and interface with a production ACC controller to gain access to sensors and actuate the controls (*24*, *25*, *45*).

Vehicle-to-Infrastructure Communications

Early stage research into V2I systems has evaluated the benefits of infrastructure connectivity in specific scenarios. The largest portion of this research discusses the potential capacity increases and fuel use reductions associated with using CACC at signalized intersections. For example, Asadi and Vahidi consider a V2I CACC system designed to improve fuel economy by minimizing the braking and idling at signalized intersections (*57*). They find that capacity improvement is largely dependent on signal timing, but even when only a small travel time benefit is realized, fuel economy gains can be substantial. There are several studies that predict fuel use at intersections can roughly be cut in half with V2I communications (*57*, *68*, *69*). Other efforts have focused on the benefits that V2I can bring to driving on roundabouts (*41*) or rolling terrain (*68*, *70*). Additionally, some recent research has attempted to show the benefits of V2I systems when combined with other technologies, including signal coordination (*71*) and speed harmonization (*39*).

Roadway Configuration

Many applications of adaptive cruise control systems are designed for specific roadway applications. This review found that the vast majority of ACC and CACC systems were simulated and tested on freeways; only a few studies have evaluated impacts at intersections, roundabouts, and ramps. Different freeway enhancements, such as dedicated lanes, can potentially be tailored to provide greater benefits than the ACC and CACC systems alone.

For example, Liu et al. discuss how a dedicated lane for CACC traffic could improve performance across the network as a whole, with the greatest benefit appearing at mid-level market penetrations (40–60%). At lower penetrations, there are not enough equipped vehicles to warrant the loss of capacity for manual vehicles. At higher penetrations, there is a high enough volume of equipped vehicles that strings can reliably form outside of a managed lane (*48*). An additional aspect of roadway configuration that researchers have largely overlooked is the impact of the network geometry on individual links. Our earlier research demonstrates large differences in link-level performance related to the number of lanes and the presence of on- and off-ramps (*47*).

Impact Areas

While the U.S. Department of Transportation's Automated Vehicle Benefits Framework runs across a broad spectrum of impact areas (*72*), this systematic review examined two primary areas: operational performance and environmental benefits. In the sections below we present meta-analyses of capacity improvements and fuel savings due to the implementation of adaptive cruise control technologies over the relevant studies assessed in our review. Of the studies reviewed, 29 considered operations and traffic effects, 22 considered energy and emission effects, and 11 considered both areas, which helps explore synergistic benefits.

Operational Performance

Although there are many ways to determine impacts to traffic operations and network performance for CAV technologies, as discussed above, our review emphasized freeway capacity improvements of ACC and CACC driving systems as compared to manual driving.

Capacity Improvements

Traffic flow analysis was a common theme among the ACC and CACC studies reviewed, and many reported changes in capacity. Given the sample of 25 studies with reported capacity changes for either ACC, CACC, or both, we compiled a summary table to compare maximum capacity improvements across studies (Table 2). For consistency, if multiple scenarios were tested, such as multiple penetration rates or time gap settings, the reported mean percent change with greatest magnitude is listed. Several of these percentages were interpolated using plots or fundamental diagrams provided where no value was directly referenced. For certain studies, traffic throughput based on input volume has been provided instead of capacity. Those throughput results have been labeled accordingly. A visualization of the capacity improvements for ACC and CACC systems on freeways only can be found in Figure 3a below.

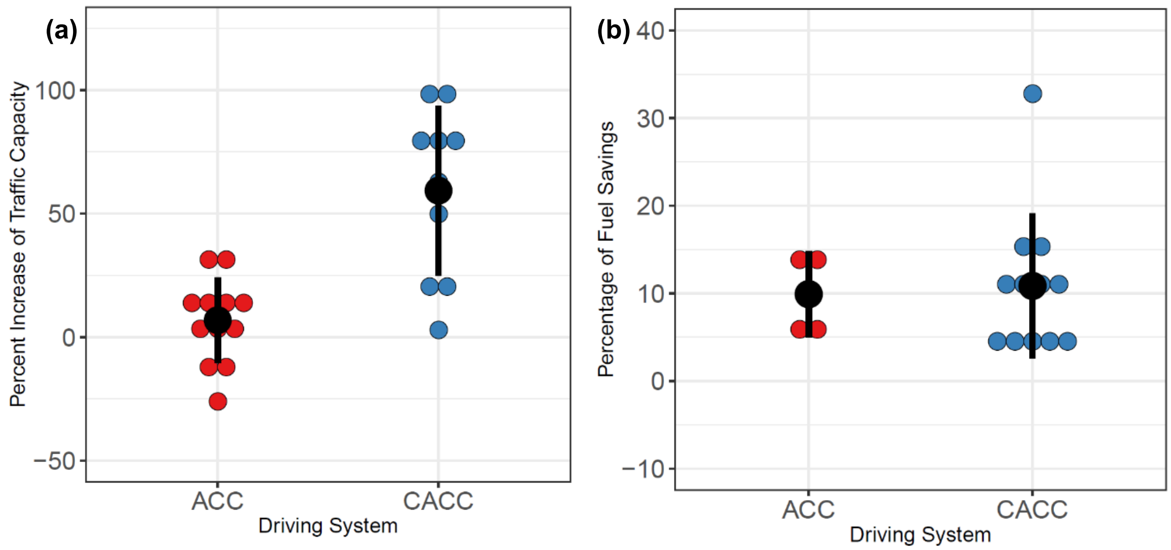

Figure 3. Meta-analysis of (a) maximum reported capacity improvements for ACC (n=12), CACC (n=10) systems on freeways, and (b) maximum reported fuel savings for ACC (n=4) and CACC (n=12) systems on freeway (black dots represents mean with whiskers of one standard deviation)

Notably, several studies showed decreases in capacity or no change in capacity under ACC driving (*35*, *37*, *44*, *73*). The same disbenefits in capacity were not present for CACC scenarios, which would suggest that those ACC applications were suffering from extended time gaps and/or reduced string stability. When studies showed a capacity improvement for ACC, it was generally more modest than for CACC. For example. one ACC study (*74*) showed a maximum increase of approximately 60%, whereas several CACC studies (*15*, *17*, *20*, *66*, *67*) predicted capacity would double or nearly double compared to the current average highway capacity of 2,200 vehicles per lane per hour (*75*). While some of those CACC studies with high capacity improvements have older, more idealized scenarios on simplified networks, some are recent with complex networks and real-world traffic data (*20*, *66*). It seems there are other factors, such as the control logic and traffic simulation platform, that lead to the wide spread of capacity improvements for CACC applications. Few studies evaluated ACC and CACC systems under the same model conditions (*15*, *74*), which would be useful for future analysis.

Table 2. Summary of the maximum percent changes to road capacity (or traffic throughput for a specified input volume) for ACC and CACC driving systems over manual driving from the studies reviewed (n=23)

Maximum Capacity Improvements (percent change against manual driving)		Intersection/V2I?	Source
ACC	CACC		
13%			(*12*)
~30%	~100%		(*15*)
	~3%		(*16*)
	97%		(*17*)
	63%		(*19*)
14% (throughput)			(*26*)
-26% (throughput)			(*35*)
-14%			(*37*)
	12% (throughput)	Y	(*39*)
	50%		(*40*)
	25% (throughput)	Y	(*41*)
-10%			(*44*)
	16%		(*47*)
	80%		(*48*)
7%			(*50*)
33%			(*56*)
10% (vs. another ACC control model)			(*58*)
6–8%			(*61*)
18% (throughput)			(*63*)
	82%		(*66*)
	8% (throughput)	Y	(*71*)
~66%	~100%	Y	(*74*)
	77%		(*76*)

Environmental Benefits

Along with traffic operations, environmental benefits including changes in fleet fuel consumption and emissions, were considered in our review. Fuel savings and emissions reductions are correlated with smooth traffic flow and, as such, are good indicators of network performance.

Energy and Emissions Models

Modern energy and emissions models are based on modes across different ranges of vehicle acceleration, speed, and power. Many of these models allow users to calculate both tailpipe emissions and fuel consumption at a network scale using measured or simulated vehicle trajectories. Eilbert et al. and Mamouei et al. have laid out a three-layered process for modeling CACC-equipped vehicles first in a traffic simulation software and then through an energy and emissions model (*35*, *38*). The U.S. Environmental Protection Agency's regulatory Motor Vehicle Emission Simulator (MOVES) and VT-Micro were the most common energy and emissions models in our review of ACC and CACC studies.

Fuel Savings

We produced a meta-analysis of maximum fuel savings for ACC and CACC applications from manual driving based on a sample of 20 studies in our review (Table 3). If multiple scenarios were evaluated, then the highest reported mean benefit is listed for consistency. A visualization of the fuel savings for ACC and CACC systems on freeways only can be found in Figure 3b. Despite having less dependable increases to highway capacity, it appears that ACC systems do generate fuel savings, presumably due to less braking, fewer hard accelerations, and generally exhibiting smoother driving than a human driver. With only four ACC studies assessing fuel consumption, we cannot draw a broad conclusion, but two of the four studies were field tests that show fuel savings (*52*, *77*). There were a few CACC field studies utilizing V2I (*69*, *70*), or testing heavy-duty trucks (*27–29*), but curiously there were not any CACC-equipped passenger vehicles that were field-tested on freeways. CACC applications with V2I communications at intersections showed promising fuel savings, all upwards of 30% in the field. For freeway CACC simulations, results varied greatly—reducing fuel consumption by 3% to nearly one-third (*34*, *53*). Real-world testing of CACC driving for fuel savings at freeway speeds would greatly help validate these model results.

Table 3. Summary of the maximum changes to fuel consumption for ACC and CACC driving systems over manual driving from the studies reviewed (n=20)

Maximum Fuel Savings (percent change against manual driving)		Heavy?	Field?	Intersection/V2I?	Source
ACC	CACC				
	6.4%	Y	Y		(*27*)
	6.96%	Y	Y		(*28*)
	13%	Y	Y		(*29*)
	12%	Y			(*30*)
	32.8%				(*34*)
12%					(*35*)
	15.71%				(*47*)
	2.17%				(*49*)
5.3%			Y		(*52*)
	3.05%				(*53*)
	47%			Y	(*57*)
	15%				(*59*)
	45%			Y	(*68*)
	45% (field), 41.9% (modeled)		Y	Y	(*69*)
	21.2%		Y	Y	(*70*)
15.8%			Y		(*77*)
6.53%	9.11%				(*78*)
	31%			Y	(*79*)
	10%				(*80*)
	4%				(*81*)

Emission Reductions

Many, but not all, of the ACC and CACC studies with fuel savings analysis included emission results. Since criteria pollutant emissions and fuel consumption are not directly proportional, it would be logical to report energy and emissions if the model reports both results. Criteria pollutants affect local air quality, especially fine particulate matter (PM2.5) and nitrogen oxides (NOx), and so would have different environmental effects than fuel savings. There have been a few CACC studies that showcase fuel savings and emission reductions together for passenger vehicles (*38*, *81*) and for commercial trucks (*30*, *54*). Future field tests could include portable measurement devices for accurate testing of fuel consumption and emissions.

Conclusions and Future Research

This report presents a systematic review of 67 studies implementing ACC and CACC systems to evaluate operational and environmental benefits. We find the pace of publications has risen tremendously over the last three years, particularly for CACC studies. ACC publications seem to be lagging in spite of many manufacturers now shipping production vehicles with ACC functionality. This review is dominated by simulation studies. Field tests have been limited in scope, often occurring in controlled environments or on public roads with light congestion. More field testing in real traffic conditions is warranted, especially for CACC systems, to validate model results from the simulation studies.

Network performance and environmental benefits are highly sensitive to the time gap between vehicles. On average, we find drivers accept the shortest time gap for CACC applications, most frequently at 0.6 seconds, likely from confidence in the predictable driving of the lead CACC vehicle. Manual driving usually leads to a slightly longer time gaps ranging from 0.8 - 1.6 s based on the studies reviewed, whereas ACC applications seem to be bimodal, which have either a gap setting 1.1 s to eliminate cut-in vehicles or a 1.5 s gap likely due to a lack in trust of the ACC system being able to stop in time. For these reasons, ACC driving appears to have a higher average time gap than manual driving in our meta-analysis. Additional evaluations of time gap acceptance between ACC and CACC driving would be useful.

Our meta-analyses of maximum capacity improvements and fuel savings against manual driving suggest that CACC systems will perform better on average than ACC systems due to shorter time gaps and more stable strings. We observe that the longer time gaps and lack of connectivity for ACC translate to more modest capacity improvements than CACC. Though only four studies were considered, our findings also indicate some fuel savings for ACC applications from smoother driving with a reduction in braking and rapid accelerations. Real-world fuel consumption and emissions testing could confirm these environmental benefits.

The performance of CAV technologies such as ACC and CACC has important policy implications. Technology-specific benefits from these production or near production-ready automated driving systems will inform future highway capacity guidelines and long-range transportation plans. Recent impact assessments of ACC and CACC systems will serve as building blocks for forward-looking research on the impacts of highly connected and automated vehicles.

Addendum

Adaptive cruise control research continues to expand rapidly. Several relevant ACC and CACC studies have been published since this initial meta-analysis was completed in the summer of 2018. Based on recent ACC and CACC publications and peer review comments on an abbreviated version of this report published in the 2019 Transportation Research Board Annual Meeting proceedings (*82*), we have a few addendum notes below. Much of the latest ACC and CACC analysis has been sponsored by the Federal Highway Administration and is captured in their compendium of Exploratory Advanced Research (EAR) Program results through 2018 (*83*).

Recent research from the European Commission has confirmed our meta-analysis finding that ACC driving systems have similar and possibly even slower reaction times than human drivers (*84*). Testing the following time gaps on a commercially available controller, Makridis et al. found 0.9 - 1.3 s reaction times with the ACC system turned on and 1.4 - 1.5 s reaction times when the vehicle was manually driven with ACC disabled. These real-world reaction times are a bit higher than the values referenced in literature, which often use idealized, low values in modeling scenarios. This work supports the mixed conclusions of ACC benefits shown in the meta-analysis (*85*).

Measured reaction times and any subsequent benefit estimates can be affected by the selected vehicle communication technology. All the studies with connectivity in our meta-analysis used dedicated short range communications (DRSC) radio signals, but some manufacturers have announced that 5GLTE cellular technology will be integrated into their production vehicles shortly (*86*). Most of the studies included in the meta-analysis assumed instantaneous communications, but sensor delay and actuator lag needs to be considered in time gap settings of a CACC controller (*55*). Further investigation of impacts from signal delay for V2V and V2I communication technologies is warranted.

Study design does not need to be siloed to either traffic simulations or field tests; some new ACC and CACC research incorporates parameters from both types of experimental protocols: hardware-in-the-loop (HIL). These HIL testbeds enable instrumented, real-world vehicles to interact with virtual vehicles from traffic simulations by replicating early-stage CAV deployment conditions without the excessive labor and equipment costs of field tests (*87*). Another recent paper has demonstrated how a HIL system can be run to minimize fuel consumption through an integrated vehicle and powertrain optimal controller (*88*). Results from HIL testing are encouraging and could improve ACC and CACC model calibration in order to estimate benefits from more widespread CAV deployment.

Additionally, it is worthwhile to specify the distinction between automated vehicle strings and platoons, particularly as real-world CACC testing begins to ramp up. This meta-analysis has highlighted a number of field studies of CACC strings, which can occur anytime at least one connected ACC vehicle is made to follow a lead connected ACC vehicle—often on test tracks or in controlled environments. On the other hand, CACC platoons tend to form organically in scenarios with higher levels of automation and connectivity, where it moves as a single unit with small time gaps and headways between vehicles in the platoon. True cooperative automation can only be achieved with significant market penetrations of connected automated driving systems such as CACC technology (*89*). Many of the simulation studies included in the meta-analysis have considered platoons, but CACC platooning cannot be fully field tested until there is a greater saturation of automated vehicles and greater interoperability of V2V communication systems.

As automation technologies and communication systems have matured, and in some cases been integrated into production vehicles, field tests have started to transition from closed courses to public roads. Ma et al. recently tested five connected and automated vehicles bundled with CACC, cooperative merge, and speed harmonization technologies on Interstate 95 managed lane facilities in Virginia against five human-driven vehicles. They found the bundled CAV string to have superior stability and a greatly reduced mean time gap over the human-driven string (*90*). In another recent study, Knoop et al. tested seven SAE Level 2 vehicles with ACC systems and radio transceivers (suitable for voice communications between drivers rather than advanced V2V communications) in mixed traffic conditions over nearly 500 kilometers of highway in the Netherlands. Based on their results, they recommended that vehicles equipped with these Level 2 systems not be used to form strings of more than 3-4 vehicles due to possible unstable following behavior (*91*).

Beyond the few studies cited in the meta-analysis, some researchers have begun to compare the potential benefits of ACC and CACC applications. Talebpour and Mahmassini examined the scatter of fundamental flow-density diagrams for automated and manually-driven vehicles with and without V2V communications, but we could not determine any specific estimates of roadway capacity improvements from the diagrams. Automated vehicles with connectivity showed less scatter in the fundamental diagrams than manually-driven connected vehicles, resulting in improved string stability along with greater possible gains in throughput (*92*). James et al. have published new research on calibrating various ACC models with recent field data from ACC production vehicles. As some studies in the meta-analysis have suggested, their findings show that small market penetrations of ACC (<25%) would increase capacity and large ACC penetrations (>75%) would decrease capacity (*93*). These results corroborate the meta-analysis recommendation of pairing vehicle automation and connectivity to achieve the greatest benefits.

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