Cooperative Adaptive Cruise Control (CACC) in the Context of Vehicle to Vehicle Communications: An Overview

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The National Center for Sustainable Transportation Undergraduate Fellowship Report

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A National Center for Sustainable Transportation Research Report

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>5</td>
</tr>
<tr>
<td>Cooperative Adaptive Cruise Control</td>
<td>6</td>
</tr>
<tr>
<td>Background</td>
<td>6</td>
</tr>
<tr>
<td>Benefits</td>
<td>8</td>
</tr>
<tr>
<td>Theory</td>
<td>9</td>
</tr>
<tr>
<td>Gap Regulation</td>
<td>9</td>
</tr>
<tr>
<td>Coordination</td>
<td>10</td>
</tr>
<tr>
<td>Case Study</td>
<td>10</td>
</tr>
<tr>
<td>Truck Platooning</td>
<td>10</td>
</tr>
<tr>
<td>Limitations</td>
<td>13</td>
</tr>
<tr>
<td>Policy</td>
<td>13</td>
</tr>
<tr>
<td>Technology</td>
<td>13</td>
</tr>
<tr>
<td>Conclusions</td>
<td>13</td>
</tr>
</tbody>
</table>
Introduction

Traffic affects a staggering amount of people and causes loss in productivity, excess consumption of fuel, and mental/physical health strain. A study done by the University of Waterloo in Canada found that on average, a U.S. driver spends 42 hours stuck in traffic and wastes 19 gallons of petrol in traffic each year [1].

A traffic congestion remedy that is quickly emerging is Cooperative Adaptive Cruise Control (CACC), classified as Level one in the six levels of autonomous driving by the Society of Automotive Engineers (SAE). The SAE levels of autonomy start from zero - all vehicle controls (braking, steering inputs, acceleration/deceleration), driving environment monitoring/dynamic tasks (blind spot recognition, signaling, turning, determining safe lane changes), and driving modes (adjustments to varying traffic scenarios such as expressway merging, high speed cruising, traffic jams, etc.) are all handled by the driver - whereas computers handle these tasks in autonomy level six (See Table 1) [2]. CACC provides the foundations for higher levels of autonomy, as it allows for vehicles and infrastructure to communicate traffic/accident information, vehicle position, speed, and relative acceleration/deceleration with each other to perform more complicated driving tasks.

<table>
<thead>
<tr>
<th>SAE level</th>
<th>Name</th>
<th>Narrative Definition</th>
<th>Execution of Steering and Acceleration/ Deceleration</th>
<th>Monitoring of Driving Environment</th>
<th>Fallback Performance of Dynamic Driving Task</th>
<th>System Capability (Driving Modes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Automation</td>
<td>the full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Human driver</td>
<td>n/a</td>
</tr>
<tr>
<td>1</td>
<td>Driver Assistance</td>
<td>the driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task</td>
<td>Human driver and system</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>2</td>
<td>Partial Automation</td>
<td>the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task</td>
<td>System</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>3</td>
<td>Conditional Automation</td>
<td>the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene</td>
<td>System</td>
<td>System</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>4</td>
<td>High Automation</td>
<td>the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>5</td>
<td>Full Automation</td>
<td>the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>All driving modes</td>
</tr>
</tbody>
</table>

Table 1: Society of Automotive Engineers Levels of Automated Driving

- Automated Driving is classified in 6 distinct levels (0-5) that are determined through the computer’s capability to execute steering, acceleration/deceleration, monitor driving environments, react to the
environment, and formulate different driving modes for various tasks (e.g. off-road driving or stop-and-go traffic).

b. Levels 0-2 (level 3 in some situations) refer to semi-autonomous driving, where computers can handle driving controls, but require human control to react to external stimuli and direct the car to its location.

c. Levels 4-5 refer to fully autonomous driving, where computers are able to fully control vehicular controls, react to external stimuli, and direct the car to its location.

CACC combines adaptive cruise control (ACC) - a technology present in most premium automobiles that uses radar (though more advanced systems using lidar are currently being researched by Google and Nvidia) to monitor the speed of the vehicle in front and adjust the current vehicle’s speed accordingly and dedicated short-range communications (DSRC) technology, which allows vehicles to share information vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) using Dedicated Short-Range Communications (DSRC). Additional research of V2V/V2I technology attempts to assess the technology’s ability to reduce driver distraction by limiting the number of factors that drivers account for (blind spot recognition, reaction times, etc.), through the scope of this report focuses solely on the current technologies that used for CACC and the theory to implement the technology. In the following sections, the report discusses the benefits of CACC/DSRC, operational theory, case studies, and limitations of the technology.

**Cooperative Adaptive Cruise Control**

**Background**

CACC requires two main components to function – adaptive cruise control (ACC) and Dedicated Short-Range Communications (DSRC).

One of the main propositions for adopting CACC is the higher of level of service (LOS) that it delivers. CACC increases LOS through the creation of platoons, vehicle bundles that are spaced relatively close together. Cars following the lead car benefit from individual fuel efficiency gains caused by drafting – less air resistance caused by drafting behind the “clean air” behind the lead car. Consequently, more space is utilized and more efficiency gains come from platooning.

![Figure 1: A vehicle platoon](http://www.niquette.com/puzzles/denslckp.htm)

a. The formation of platoons minimize vehicle gaps, allowing more highway space to be utilized and increasing the amount of cars that can be on the highway. Platoons increase fuel efficiency as well, by decreasing drag. The combined effect from platooning increases fuel efficiency and reduces congestion.
ACC uses sensors such as radars, lidars, and cameras for vehicles to digitally record and control their speed, acceleration, and relative location (to the obstacles around it) [4]. Vehicles equipped solely with ACC have the potential to form platoons as well, but ACC only reacts to information recorded by the vehicles sensors, which at best can only account for the obstacles in the vehicle’s immediate surroundings. As a result, average data transmission delay for ACC vehicles is 1.5 seconds per vehicle length (from sensor, data processing, control, and actuation), which is similar to human reaction times [5] but much slower than DSRC (100 milliseconds). Delay has a cumulative effect, in a three-vehicle platoon, the rear car would take 3 seconds to react to the front vehicle, because the vehicle in the rear of the platoon takes 1.5 seconds to react to the vehicle directly in front of it, the vehicle in front also takes 1.5 seconds to react to the vehicle leading the platoon resulting in a staggering amount of communication delay from front to back. Communication delay ultimately prevents the viability of platooning using the technology, which stresses the need for DSRC to improve the feasibility of the CACC.

**Figure 2: Adaptive Cruise Control (ACC) communication Gap**

(http://crankydriver.com/blog/images/Reports/ADAS/acc_gap.jpg)

a. ACC has a minimum delay of 1.5 seconds when responding to the acceleration/deceleration of the car in front which prevents vehicles to closely follow one another (to form platoons) and is the main reason why dedicated short range communications (DSRC) need to be established between vehicles.

DSRC allows vehicles to relay this information to one another and infrastructure using dedicated transmitters made by aftermarket or automobile part manufacturers. DSRC works by broadcasting data packets containing vehicle speed, position, and acceleration to through a peer-to-peer network established with nearby vehicles in a 75 MHz spectrum of the 5.9 GHz band, a communications wavelength designated by the Institute of Electrical and Electronics Engineers (IEEE) and the Federal Communications Commission (FCC) specifically for V2V/V2I communications [6]. The data transmitted must follow the standards set for standard wireless vehicular communications in the IEEE 1609 family, which establishes security, management, architecture, and communications for DSRC in the 5.9 GHz band [7]. Data packets are transmitted at a high frequency, allowing the data packets to be sent to vehicles 1000 meters around.
Figure 3: Dedicated Short-Range Communications (DSRC) allows vehicles to communicate between themselves (V2V) and infrastructure (V2I), updating the road network with vehicle speed, position, and traffic situations. This technology will allow vehicles to work with one another to improve traffic flow, promote safer driving, and create detailed traffic maps. (https://www.researchgate.net/profile/Bernd_Wolfinger/publication/264894205/figure/fig4/AS:272619257724942@1442008904243/Figure-1-General-model-of-vehicular-networks-AP-access-point.png)

Benefits

Allowing vehicles to communicate their speed, acceleration, and relative position to external networks every hundred milliseconds, creates an extremely detailed map of traffic flow which can be used to coordinate smoother traffic. Platoons of closely following vehicles can reduce vehicle hours spent on the road and improve air flow within platoons (due to drafting). Ultimately, CACC is a step forward in reducing congestion, consumption, and creating a communication network for autonomous vehicles.

CACC has potential to increase flow in areas that experience extreme congestion in dense city centers, interstate highways, and traffic signals. Congestion is reduced through headway (time distance between vehicles) reduction, from 1.4 seconds (average “time headway” due to reaction time from a human driver) to 0.6 seconds (using CACC). This “time headway” is determined by gap determination algorithms that gauge optimal stopping distances through various parameters (vehicle stopping distances, brake strength, vehicle weight, speed, other parameters) [8]. A recent study determined that lane capacity can be nearly doubled from 2200 Vehicles-per-hour (VPH) to 4000 VPH due to reduced headway.

Platoons reduce traffic congestion by reducing time spent on the motorway and increasing the aerodynamic efficiency of vehicles through drafting. Time spent in traffic can be nearly halved from doubling lane capacity and efficiency increases as well. In an electric vehicle CACC simulation study conducted by UC Berkeley, energy savings of 15.6% (in highway driving) and 73.4% (in urban driving) [11] were achieved in the following vehicle. In case studies, the efficiency of diesel powered trucks was increased by a maximum of 10.24% (see Case Study).
Theory

Assuming CACC gains sizable market adoption, the following strategies summarize the theory of maintaining safe, efficient distances and coordinating platoons.

Gap Regulation

Gap regulation, the allowable distance between vehicles, is an area that is has been researched heavily [8]. With most issues involving the establishment of safe following distances to maximize platoon size and drafting between vehicles. Constant clearance/distance gap and constant time gap are two theories that have been suggested, but lack significant field implementation. These theories have been simulated by computers to ensure safety under varying conditions, the National Automated Highway Systems Consortium (NAHSC) – a group of transportation stakeholders such as automotive manufacturers, infrastructure builders, and state/local transportation agencies in partnership with the Federal Highway Administration (FHWA) established a Constant-Safety-Factor Criterion which attempts to limit the accident area to one platoon or less [10]. They establish the minimum following distance to be determined by the vehicle within the platoon that has the longest braking distance.

Constant clearance or constant distance gap is a method of gap regulation that couples vehicles closely together in platoons. The issue with this method is that communication only occurs between vehicle to vehicle (V2V). Therefore, a long string of cars (more than 10 vehicles) will begin to have difficulty communicating with one another due to the limited range of DSRC (around 300 meters). Research on creating vehicular ad hoc networks (VANETs) - localized networks of data clouds. VANETs extend the range data transmission by intertwining mobile vehicular networks to relay large packets of data from one cluster to another (see Figure 4).

Figure 4: A Vehicular Ad hoc NETwork (VANET) allows vehicles to communicate large amounts of vehicle data to cars outside of the range of the leading car’s DSRC transmission. Data “clouds” are created using DSRC with vehicles queued 300 meters between one another. The car at the end of the queue transmits the “cloud” to the vehicle at the start of the following queue to quickly transmit relevant information from greater distances than DSRC allows. (http://ns2projects.org/wp-content/uploads/2015/11/Architecture-of-VANET.png)
The constant time gap method attempts to model the gaps created naturally, in which a gap is created based on the time it takes for the rear bumper of the lead car and the front bumper of the following car to pass a DSRC connected highway infrastructure. This method is similar to the distance gap, but requires the measurement of time distance gaps using highway infrastructure. Constant time gap helps supplement constant clearance gap by relaying traffic information to highway segments downstream.

**Coordination**

Coordinating platoons becomes difficult when accounting for external variables such as lane changes, drunk drivers, or other issues that may occur. The scope of coordination occurs at two main levels: local and global.

Local coordination deals with V2V and V2I communication on the highway, and helps guide vehicles to form clusters. The issue with this method is frequently disassembling and reassembling clusters offset the benefits from platooning. Further investigation needs to be done to find method of how to cluster vehicles with similar destinations together. In addition, it is difficult to instruct vehicles to formulate clusters with current vehicular infrastructure. Workable solutions is to introduce “intelligent” lane markings, radio towers that relay DSRC signals, GPS based lane identifications, infrared camera markings, vehicle based confirmation, and simple driver visual confirmation – these technologies would be able facilitate the clustering process.

Global coordination attempts to couple vehicles with similar destinations together on highway ramps to maximize platoon time. If vehicles wait for clusters to form, the economy gains and vehicle-hours deducted from platooning would be minimal. Therefore, global coordination is probably reserved for clustering fleets into platoons, because they are forced to gather and wait for platoons to form at pit stops or filling stations.

**Case Study**

**Truck Platooning**

A case study conducted by the FHWA through the Exploratory Advanced Research program researched the consumer response and efficiency gains of the technology on truck fleet [9]. The study was conducted in two phases.

Phase 1 conducted a broad overview about the benefits and response to the technology, where 54% of fleet managers had positive to extremely positive responses to the technology and 39% of managers said that fleet drivers would have a positive response to the technology. Computational fluid dynamics simulations determined that platooning would significantly increase efficiency even in distances greater than 100 feet.

Phase 2 of the study provided a more detailed study of the technology. In the case of user interviews, the fleet managers provided great interest in CACC on the fuel savings alone. One
firm noted that if the technology were applied to global economies of scale through different fleet operators, millions of gallons of fuel a year could be saved. Managers stated that global coordination would be easy to implement due to fleets gathering at truck/pit stops; the typical wait time at a truck stop averages 15 minutes. Firms were willing to partner up with one another (rather than individually scheduling fleet platoons) to maximize the amount of fuel savings. This partnership introduced the need for a system for designating lead cars, due to the increased fuel consumption of being a lead car. Managers did not raise significant concerns for fleet driver adoption of CACC. They noted fleets are likely to accept innovative technologies as long as veteran drivers adapt them first and perform demonstrations to less experienced drivers.

More detailed computational fluid dynamics revealed the benefits of the technology in a theoretical level. The test was conducted using a speed of 65 MPH in two truck platoons. Results show that the lead truck has the greatest effect on the drag reduction (see Figure 5) and that there are minute efficiency gains in gaps greater than 50 feet – gaps should be kept as short as safely possible.

![Figure 5: CFD Results for Truck Platooning](image)

**Figure 5: CFD Results for Truck Platooning**

- Leading truck is represented at with blue circles and red triangles, drag reduction % is not affected by offsetting at all.
- Following Truck is represented with blue squares and red diamonds, drag reduction % is significantly affected at distances under 40 feet.
In a real road test track evaluation of truck platooning at the National Center for Asphalt Technology (NCAT), the GPS and Vehicle Dynamics Laboratory in Auburn University installed a prototype version of Peloton’s CACC system on the trucks. Testing of the trucks was at distances of 30, 40, 50, 75, and 150 feet with Peterbilt 579 trucks with aerodynamic packages and trailers equating a total weight of 65,000 pounds. The NCAT test track is oval-shaped and 7.5 miles long with 2400-foot radius turns. The trucks completed seven platooning laps and fuel was measured gravimetrically and compared with baseline test and the control truck. The fuel savings at 30 feet were less than those at 50 feet, the results of the tests are shown in Figure 6 below with peak savings being 6.96% fuel savings at 30 feet and 10.24% at 50 feet.

![Figure 6: Road Test Result of Truck Platooning (Fuel Savings vs Following Distance in feet)](image)

- a. Following vehicles (represented by green triangles) reach a maximum fuel savings art 50 feet and linearly decrease with increasing following distance
- b. Teaming vehicles (represented by blue circles) reach a maximum fuel savings at 30 feet follow a linear trend of fuel savings with increasing following distance
- c. Leading vehicles (represented by red squares) reach a maximum fuel savings at 30 feet and decrease in fuel savings exponentially with increasing following distances
Limitations

Policy

Unfortunately, current transportation policy does little to incentivize the adoption of CACC technology. It would be difficult and cost-ineffective to implement the technology with a lack of users. To rapidly increase the adoption of CACC, the National Highway Traffic Safety Administration (NHTSA) must mandate that all new vehicles have DSRC and ACC installed or have old vehicles retrofitted with CACC sensors/communication devices.

Assuming the government is unable to incentivize usage through policy, other policies can be implemented to incentivize adoption by manufacturers/consumers. Creating High-Occupancy-Toll (HOT) lanes, which follow the same principle as High Occupancy Vehicle (HOV) lanes give the government a means to enforce incentives such as lower bridge tolls and faster flowing, open lanes. HOT lanes would help form a policy mechanism for incentivizing reduced bridge tolls (due to efficient driving funding mechanisms from lane access fees) which would fund Intelligent transportation system (ITS) infrastructure - 2.4 or 5GHz routers can be fitted onto infrastructure to provide passengers in HOT lanes with WiFi connections.

Technology

Current ACC technology is adequate to record the velocity, acceleration, and relative position of vehicles. However, further research on DSRC needs to be conducted to create a stable network of connected vehicles. Current technology is only able to relay information between vehicle 300 meters ahead, in situations with 10 or even 20 car platoons, the data being relayed from the first car on the platoon to the last car may experience significant delay due to transmission delays. To address this issue, current research on VANETs are being conducted to transmit data between the lead car and following cars seamlessly.

Conclusions

When CACC gains a sizable share of the market, it will be able to mitigate traffic congestion and improve overall fuel efficiency. However, to fully implement this technology there needs to be aggressive development from all parties involved to create an expansive vehicle, highway, and network infrastructure.

The propagation of these technologies can be influenced by many different stakeholders. Automobile manufacturers can begin incorporating DSRC and CACC in all new vehicles to allow vehicles to quickly communicate with one another on the road. By passing supporting policies, governments can help incentivize adoption of the technology. Engineers can create more ITS infrastructure on the highway to provide comprehensive highway network coverage for vehicular communication. Lastly, software developers should create more robust communication networks and gap/coordination algorithms to utilize CACC for smoother traffic flow.
A vast amount of research on CACC simulations has been conducted to prove the viability of the technology. However, further research needs to be conducted on the implementation of CACC communications on the road. Creating automated driving algorithms that promote safer driving (blind spot monitoring/reacting, self-parking/driving, crash avoidance, other safe driving practices) and more environmental driving practices (drafting, reducing unnecessary braking, quickest route calculation, etc.) would bring society a step closer to autonomous vehicles which would reduce the psychological stressors that arise from commuting.
References


