COOPERATIVE ADAPTIVE CRUISE CONTROL (CACC) DEFINITIONS AND OPERATING CONCEPTS

Steven E. Shladover  
California PATH, University of California, Berkeley  
Richmond Field Station, Bldg. 452  
1357 South 46th Street, Richmond, CA 94804-4648, USA  
phone: 510-665-3514, email: steve@path.berkeley.edu

Christopher Nowakowski (Corresponding Author)  
California PATH, University of California, Berkeley  
Richmond Field Station, Bldg. 452  
1357 South 46th Street, Richmond, CA 94804-4648, USA  
phone: 510-665-3673, email: chrisn@path.berkeley.edu

Xiao-Yun Lu  
California PATH, University of California  
Berkeley, Richmond Field Station, Bldg. 452  
1357 South 46th Street, Richmond, CA 94804-4648, USA  
phone: 510-665-3644, email: xiaoyun.lu@berkeley.edu

Robert Ferlis  
Federal Highway Administration  
Turner-Fairbank Highway Research Center  
6300 Georgetown Pike, McLean, VA 22101, USA  
phone: 202-493-3268, email: Robert.Ferlis@dot.gov

Submission date: 14 November 2014

Number of words including abstract (256) and references (1041)  7596
Number of tables and figures (0) x250  0
Total  7596
ABSTRACT
Cooperative Adaptive Cruise Control (CACC) includes multiple concepts of communication-enabled vehicle following and speed control. This paper presents definitions and classifications to help clarify the distinctions among different types of automatic vehicle following control that are often conflated with each other. A distinction is made between V2V CACC, based on vehicle-vehicle cooperation, and I2V CACC, in which the infrastructure provides information or guidance to the CACC system (such as the target set speed value). In V2V CACC, communication provides enhanced information so that vehicles can follow their predecessors with higher accuracy, faster response, and shorter gaps, resulting in enhanced traffic flow stability and possibly improved safety. A further distinction is made between CACC, which uses constant-time-gap vehicle following (forming CACC strings), and automated platooning, which uses tightly-coupled, constant-clearance, vehicle-following strategies. Although ACC and CACC are examples of Level 1 automation, as defined by both SAE and NHTSA, the vehicle following performance that can be achieved under each scenario is representative of the performance that should be expected at higher levels of automation.

Implementation of CACC in practice will also require consideration of more than the lowest level vehicle-following and speed regulation performance. Because CACC requires interactions between adjacent equipped vehicles, strategies are needed such as ad-hoc, local, or global coordination to cluster CACC vehicles. This paper discusses some of the challenges that must be overcome to implement the clustering strategies, and strategies for separating CACC clusters as they approach their destinations, since potential traffic improvements from CACC will be negated if the vehicles cannot disperse effectively.
INTRODUCTION

Cooperative Adaptive Cruise Control (CACC) is a term that has been used loosely in recent years, so that different people visualize different functions and capabilities when discussing CACC systems. At the heart of each CACC concept is the combination of automated speed control with a cooperative element, such as Vehicle-to-Vehicle (V2V) and/or Infrastructure-to-Vehicle (I2V) communication. The V2V communication provides information about the forward vehicle or vehicles, and the I2V communication provides information about traffic further ahead and about local speed recommendations as part of an active traffic management approach. CACC systems can be implemented with either or both I2V and V2V information sources.

There are two primary transportation system motivations for the development of CACC, improving traffic flow and decreasing fuel consumption, but additional motivations for CACC include safety, comfort, convenience, and customer satisfaction. Along the lines of customer satisfaction, CACC is more attractive than conventional autonomous ACC because the system behavior can be more responsive to the changes in the preceding vehicle speed, providing an enhanced sense of safety because of its quicker response, and the shorter following gaps enabled by the CACC system can deter cut-ins. CACC may also improve safety, especially if combined with collision warning or mitigation systems, but CACC alone is not primarily a safety system.

The primary motivation for the development of CACC is to reduce traffic congestion by improving highway capacity and throughput and attenuating traffic flow disturbances. The class of CACC systems utilizing V2V communication could allow the mean following time gap to be reduced from about 1.4 seconds when driving manually to on the order of 0.6 seconds when using CACC (1), resulting in an increase in highway lane capacity. Several California PATH highway traffic simulations (2, 3, 4) showed that autonomous ACC alone, even at high market penetrations, had little effect on lane capacity, and recent on-the-road experiments (5) have shown that a stream of autonomous ACC vehicles is string unstable, resulting in a negative impact on lane capacity. However, with the shorter following gaps enabled by CACC systems, lane capacity could be increased from the typical 2200 vehicles per hour to almost 4000 vehicles per hour at 100 percent market penetration (4).

A secondary motivation for the development of V2V CACC is to reduce fuel consumption, because at highway speeds, fuel consumption is significantly influenced by air resistance. However, all of the research on improving fuel efficiency through shorter following distances utilized constant-clearance-following criteria in tightly-coupled platoons, rather than the constant-time-gap-following criteria that would be more likely to be used in a production CACC system. While tightly-coupled platooning can potentially improve fuel economy for both large trucks (6, 7, 8, 9, 10, 11) and passenger vehicles (12, 13), fuel efficiency improvements with CACC using constant-time-gap-following criteria in normal traffic conditions have not yet been demonstrated.

CACC systems utilizing I2V communication, although not the primary focus of this paper, also generally share the motivation of improving highway capacity and throughput. The two most often discussed I2V CACC concepts include variable speed limits for bottleneck capacity enhancement (14, 15) and the arterial coordinated start. In the variable speed limit concept (15), the CACC system cooperates with the infrastructure to reduce the potential for congestion at bottleneck locations by automatically reducing upstream vehicle speeds through the I2V communication of set speed values, reducing speed differentials and allowing the traffic flow to be maintained at peak throughput. In the arterial coordinated start concept, the CACC
vehicles waiting at a red traffic signal would be instructed to begin accelerating in a coordinated fashion once the traffic signal turns green. This coordinated start could allow more vehicles to pass through a congested intersection on a green cycle than manual driving.

The first section of this paper discusses the CACC system characteristics for a range of CACC concepts, placing each within the broader concept of cooperative vehicle following systems. In doing so, distinctions are made between CACC and close-formation platooning and between V2V and I2V CACC systems in terms of functionality and potential benefits to traffic flow. The second section of this paper discusses CACC operational concept alternatives, including strategies for clustering CACC vehicles when the market penetration is low, strategies for effectively dispersing CACC strings of vehicles once they reach their destination, and other operational considerations such as the maximum CACC string length or vehicle ordering within a CACC string.

**CACC SYSTEM CHARACTERISTICS**

Multiple system concepts have been described as CACC, but all CACC variants are a subset of the broader class of automatic vehicle speed control systems. An important distinction must be made between CACC systems and automated vehicle platooning systems, so CACC needs to be defined in that broader context. Since CACC only provides longitudinal control of vehicle motions, while the driver remains responsible for the steering control and monitoring of the driving environment, it represents Level 1 automation on both the SAE (16) and NHTSA (17) scales of automated driving. As described further in the following sections, automated vehicle speed control systems need to be specified in terms of three dimensions to encompass the wide range of these types of systems:

1. The goals the system is intended to serve
2. The sources of information the system relies upon
3. How the system determines the desired following distance

**System Goals and Information Sources**

Automatic speed control may be used to support a variety of goals:

- Improving safety
- Improving traffic flow dynamics by damping disturbances
- Increasing highway capacity through shorter following gaps
- Saving energy and reducing pollutant emissions through aerodynamic drafting
- Improving driver comfort and convenience.

Different speed control systems may be optimized to provide one or more of these benefits, but a system that is optimized to support one of these goals may actually hinder other goals. As an example, a CACC system that is optimized to maintain close vehicle spacing, increasing highway lane capacity, is not likely to maximize fuel efficiency under traffic conditions that require frequent speed changes.

Speed control systems can obtain the information they need for controlling vehicle speed from a multitude of sources, and the available data sources will determine the level of performance that a particular system can achieve. Autonomous control systems depend only on the information that can be remotely sensed by the host vehicle (through lidar, radar, or video
image processing), while cooperative control systems augment the internal sensor information with information from V2V or V2I communication. When there are multiple consecutive autonomous ACC vehicles (without V2V communication), the information about the leader’s motions must be sensed, processed, incorporated into the control, and then responded to by the second vehicle in the stream. Only after the second vehicle starts to react can the third vehicle infer what happened to the first vehicle from the behavior of the second vehicle. In an autonomous ACC, the detection and response delay is cumulative from the leader to the downstream vehicles (except in the rare cases when radar systems can detect motions of a vehicle ahead of its immediate predecessor using ground reflections). If the total delay (from sensor, data processing, control, and actuation) is 1.5 s (for a high performance vehicle), it would take the 4th vehicle 4.5 s to indirectly sense what happened to the lead vehicle. Furthermore, sensor detection errors will be amplified in this consecutive delay process. The accumulated delay and successively amplified detection errors prevent string stability in longer streams of autonomous vehicle following. Small changes in the lead vehicle speed will result in large acceleration and deceleration events further back in the stream. As demonstrated by California PATH, a deceleration of 0.1 g in the lead autonomous ACC car can easily result in an amplification to a deceleration of 0.3 g by the time the 4th car in the stream reacts (5), even with an ACC controller that was designed with stability in mind.

**V2V CACC Variants**

There are potentially a large number of V2V CACC variants because the communicated information may come from a variety of other vehicles, and the data may represent a variety of information about the source vehicles. V2V CACC systems depend on frequent information updates (generally ten times per second), and they depend on the communication reliability to maintain safety and stability at close following distance, requiring high-performance communication systems such as 5.9 GHz DSRC. Relevant vehicles include the leader of a string of vehicles, the immediate predecessor, or possibly the immediate follower, but communicated data can be received from any other vehicle within range. The communicated data should at least include speed, location, acceleration/deceleration, intentions (commanded speeds, accelerations, or decelerations), and performance limitations.

The most basic V2V CACC implementation depends on pairwise sharing of the additional information between a vehicle and its immediate predecessor (18). In this type of system, a CACC following vehicle can receive notification that the preceding vehicle was commanded a new acceleration or braking rate within one communication update interval (100 ms) of the time when its predecessor received that command internally. This allows the following vehicle to start to respond even before the predecessor’s speed has changed measurably, but small communication delays can still accumulate from one vehicle pair to the next. In the earlier example of four CACC vehicles, the communication delay alone to relay a message from the first to fourth vehicle would be on the order of 400-800 ms, assuming minimal processing time, which is much better than the delay of more than 5 seconds relative to the motion of the first vehicle measured in our field experiments with autonomous ACC (5).

More advanced V2V CACC implementations add information from vehicles that are beyond the direct line of sight. Comprehensive preview information about the actions of vehicles further upstream provides additional phase lead to help stabilize the car-following responses of all the following V2V CACC vehicles. They can anticipate speed changes in the way alert, defensive drivers do by looking beyond the immediately preceding vehicle to see what
is happening multiple vehicles ahead. In the earlier example of four CACC vehicles, the communication delay to send a message from the first vehicle to all other vehicles would only be 100 ms, since all of the followers would be listening to the leader directly.

**I2V/V2I CACC Variants**

In I2V/V2I CACC systems, the roadway infrastructure, through its Traffic Management Center (TMC) and roadside devices, provides recommended speeds to the vehicle speed control systems, and the infrastructure-based information could be static or dynamic. Static I2V information would be information that remains the same over a long period of time, such as a posted speed limit or the maximum safe speed for a curve. Dynamic I2V information could include variable speed limits based on changes in weather, road surface, or traffic conditions. Since this information does not change rapidly for highway driving applications (updates on the order of multiple seconds or minutes or longer) it may be provided using a wide range of wireless communication media, not only 5.9 GHz DSRC. Urban applications involving responding to changes in traffic signal status will need the more frequent updates and lower latencies of 5.9 GHz DSRC.

I2V CACC at signalized intersections and along signalized corridors offers a variety of potential benefits that are quite different from the most commonly considered highway applications. The coordinated start is the most straightforward and prominent I2V CACC application discussed because of its simplicity and the potential for a significant increase in intersection throughput. When the traffic signal changes from red to green, all the equipped vehicles in the queue will receive a message about that change, so they will all be able to accelerate from a stop simultaneously, rather than having to wait for the driver ahead of them to respond to the acceleration of the next driver ahead. Note that if the intersection is not equipped with the ability to broadcast its signal phase information, similar coordinated start benefits could be gained with a high market penetration of V2V CACC vehicles following the start-up trajectory of the first equipped vehicle in the queue.

Another promising I2V CACC application is eco-driving or green driving, reducing the number of stops and/or speed variations that vehicles experience along a signalized corridor. The basic concept of eco-driving is an important element in the AERIS Project’s Eco-Signal Operations scenario (19). Early work on AERIS focused on providing advice to the driver about the speed that the driver should travel, but later work includes the concept of using automated speed control through the I2V CACC to increase accuracy and significantly reduce driver workload and distraction.

I2V CACC can also be synergistic with Multi-Modal Intelligent Traffic Signal Systems (MMITSS) through the communication of the signal status information to the equipped vehicles so that they respond more consistently and predictably to the signal control. This is likely to have the largest influence in general intelligent signal applications, where the I2V CACC can support improvements in traffic flow efficiency and throughput as well as energy and environment by making most effective use of the available green time. When I2V CACC reaches a high market penetration, the signal control strategies can be refined based on assumptions about more consistent vehicle responses to the traffic signals.

**Gap Regulation Strategies**

Many different vehicle-follower speed control strategies have been proposed over the years, based on a wide variety of feedback control approaches, applying data from different
combinations of other vehicles (20). It is not necessary to review all of the strategies in detail because the large majority of these feedback structures are purely theoretical and have only been designed and evaluated in computer analyses and simulations. Only a handful have been implemented experimentally and tested on full-scale vehicles to prove how well they can work under realistic conditions based on the limitations imposed by real-world measurement noise and delays.

### Constant Clearance or Constant Distance Gap (CDG)

Most automated vehicle control projects discussing platooning have emphasized a very close coupling between vehicles to maximize highway capacity and/or to reduce aerodynamic drag, and all of these projects have employed a constant-clearance car-following discipline. In this discipline, the separation between vehicles remains constant, and does not change as the vehicle speed changes. With this tight control, the vehicle occupants experience the perception of a mechanical linkage between the vehicles, and this type of control can only achieve stability when the communication received by each vehicle includes the behavior of the platoon leader or the first vehicle in the sequence (21).

When the primary goals include increasing lane throughput and reducing aerodynamic drag by drafting, this discipline offers performance advantages, but constant-clearance following is more difficult to achieve, requiring a more formal platoon architecture. The platoon leader must be identified to all of the followers, interruptions in the communication are more serious from a safety standpoint, and large gaps must be ensured ahead of the platoon leader to minimize the likelihood that the platoon leader will need to execute an emergency braking maneuver (which could potentially lead to low-delta-v impacts among the followers within the platoon). In fact, these systems should not even be labeled as CACC systems, but should instead be classified separately as tightly-coupled platoons (or closely-coupled platoons).

### Constant Time Gap (CTG)

Constant-time-gap vehicle following most closely represents the way human drivers normally drive at highway speeds, so commercially available ACC systems follow this discipline. In this discipline, the distance between vehicles is proportional to their speed (plus a small fixed offset distance), so that a doubling of speed leads to an approximate doubling of the clearance gap between the vehicles. The time gap criterion is described in terms of the time between when the rear bumper of the leading vehicle and the front bumper of the following vehicle pass a fixed location on the roadway (measured in seconds). This is often erroneously described as “headway” or “time headway”, but headway has traditionally been defined as the time from front bumper to front bumper. Additionally, since CACC does not require close coupling, the authors of this paper have refrained from referring to a sequence of CACC vehicles as a platoon, preferring instead to refer to the sequence as a CACC string.

### Constant-Safety-Factor Criterion

The constant-safety-factor criterion was used as the separation criterion between platoons in the National Automated Highway Systems Consortium studies of the throughput that could be achieved using closely-coupled platoons (22). This discipline was chosen as a way of guaranteeing that even the most severe incidents would not involve more than one platoon, rather, they would be confined to a single platoon. With the very close constant-clearance-distance separations, severe incidents requiring very hard braking could, in some cases, result in
relatively low-speed crashes within the platoon. When these severe incidents were hypothesized, the worst-case (hardest) deceleration by the last vehicle in the platoon was estimated, and the most dangerous condition resulted when the leading vehicle in the next platoon had limited braking capability. Thus, the minimum distance between platoons was set by factoring in the weakest acceptable braking by the lead vehicle of the following platoon, such that a crash between vehicles in different platoons could be avoided. The constant-safety-factor criterion produces an inter-platoon separation proportional to the square of the cruising speed.

CACC OPERATIONAL CONCEPT ALTERNATIVES

For passenger vehicles, most discussions about CACC assume ad hoc coupling of equipped vehicles, and some studies have made the distinction between CACC market penetration and DSRC market penetration (2, 3, 4). A CACC equipped vehicle does not necessarily need to be following another CACC equipped vehicle to get the benefits of the system, rather it must only be following a DSRC equipped vehicle. For commercial trucks, there has been considerably more research into the question of how vehicle coupling could occur beyond ad hoc coupling (23, 24, 25, 26, 27, 28, 29), but it should be noted that all the commercial truck studies have been focused on close-formation platooning rather than on CACC.

The following section discusses the CACC operational concept alternatives that have been described in the literature or further conceived. These include CACC vehicle clustering and string formation strategies (including incentive and support strategies), string dissolution strategies, and the potential roles for I2V CACC. Even with ad hoc coupling, strategies can be employed to increase the density of CACC and DSRC equipped vehicles in certain lanes, such as managed lanes, but there has only been limited published research on how this could be accomplished or what effects it will ultimately yield (30).

Vehicle Clustering Strategies

Ad Hoc Clustering

Most of the existing studies of CACC have relied on ad-hoc clustering of vehicles, which is the simplest to implement and to simulate. Vehicles arrive in random sequence and do not deliberately seek out other similarly equipped vehicles, so the probability of driving behind another suitably equipped vehicle is directly related to the market penetration of equipped vehicles. At low market penetrations, the increases in throughput are negligible because the probability of consecutive vehicles being equipped is negligible. However, if NHTSA mandates that all new vehicles should at least be equipped with a DSRC Vehicle Awareness Device (VAD), or a healthy market for after-market DSRC systems develops, then the market penetration of potential leader vehicles grows rapidly.

Local Coordination

Moving beyond ad-hoc clustering, local coordination could be employed to help cluster CACC capable vehicles. Equipped vehicles, or streams of vehicles, already on the highway and within a certain distance of each other, could be instructed to speed up or slow down to facilitate clustering. This approach was discussed in the SARTRE project (25, 26) and in the current COMPANION project led by Scania (28). If local coordination requires speeding up or slowing down to bring vehicle clusters together, then the CACC vehicle drivers must expect sufficient
benefit from the system to outweigh the inconvenience cost of the coordination; otherwise, they have no incentive to actively seek out other equipped vehicles with which to cluster. Similarly to the ad hoc clustering strategy, the first vehicle in the CACC string does not necessarily need to be CACC-capable, just DSRC equipped, but if the lead vehicle is simply a passive participant, then the coordination process may become more difficult.

The biggest challenges to local coordination are determining all the vehicles’ relative positions with sufficient accuracy to know which is the correct target with which CACC coupling can be initiated (immediately ahead and in the same lane) and communicating that information to the driver. At lower market penetrations, the driver will likely need to execute a lane-change maneuver to join with that target vehicle, especially when the speeds of the vehicles have been adjusted to facilitate the coupling. This requirement leads to a surprisingly difficult issue once we account for the need to protect the privacy of the target lead vehicle owner or operator. Even though each vehicle will broadcast its location information frequently, it is not simple to associate those locations with the correct lanes and to convey that information to a driver in an easily understood way, especially without producing excessive distraction. This is particularly challenging in locations where lanes are added and dropped along the highway, especially since those lane additions and subtractions can happen on both the left and right sides of the roadway. Several possibilities are under consideration:

- Infrastructure lane identification could include some form of unique lane markings that would allow a vision system to identify in what lane the vehicle is traveling.
- Infrastructure lane identification could be RFID based, possibly from overhead gantries or from RFID chips embedded in the pavement or lane dividers.
- Vehicle-based lane identification could be possible with GPS, IMU, camera, and lane-accurate mapping. It’s possible that the vehicle could make the lane determination based on high-accuracy positioning and digital maps (much more accurate than today’s maps), but that would also require everyone to use the same maps, which would have to be updated in real time for all infrastructure changes. This poses technical, institutional, and economic challenges.
- Vehicle-based confirmation of following an equipped vehicle could be possible with visual or infrared camera-visible marking. One potential way to identify other equipped vehicles is to add some rear-facing line of sight marking, perhaps an IR beacon. Each DSRC equipped car could have this redundant communication mechanism that simply broadcasts the same identifier used in the DSRC messages (avoiding privacy concerns). The CACC following vehicles would be equipped with an IR camera, and they would be able to match the IR beacon broadcast by the lead vehicle with the DSRC message IDs received. This would require some technology development and refinement, as well as suitable standards.
- Driver visual confirmation is another possible strategy, based on the driver visually confirming aspects of the appearance of the broadcasting target vehicle that would be contained in the broadcast data stream. There would be significant privacy concerns, since the DSRC standards avoid broadcasting identifying information about the vehicle. Even if these could be overcome with some opt-in selection, there are still problems with drivers’ ability to recognize vehicle make, model, and color attributes, and license plate numbers cannot be read from a long enough distance.
Finally, in the local coordination strategy (and subsequently, the global coordination strategy), a coordination system will need to instruct drivers to take some specific actions to couple with other vehicles. The coordination system will need to instruct some drivers to speed up or slow down to allow all the enabled vehicles to connect. Additionally, lane changes will be required for some drivers, and the in-vehicle system will need to inform the driver when and where to do those lane changes, without giving any false sense of security about the safety of those lane changes (e.g., the coordination system may not be able to detect an unequipped vehicle that is interfering with a lane change). While lane changes will still need to be done manually by the driver, the speed changes could be automatic (similar to I2V CACC), whereby the coordination sets the CACC set speed automatically. However, the automatic adjustment of vehicle speeds will still need to be explained to the driver through the in-vehicle system, so that the sudden increase or decrease in speed is not disconcerting.

**Global Coordination**

Global coordination involves advance planning to coordinate vehicles traveling from similar origins to similar destinations before the vehicles enter the highway (27, 29). Vehicle routes and speeds can be adjusted to time their arrivals at the highway entry points so that they are able to couple together from the start. This concept poses a significant logistical challenge, especially given the uncertainties in traffic conditions and in the time that each vehicle takes to arrive at its intended entry point. Those uncertainties will require the addition of contingency margins to the scheduling, introducing additional travel time costs. This also requires more extensive long-range communication and a back-office coordination functionality that would not be needed in the ad hoc or local coordination cases. This added overhead is only likely to be justifiable based on the added benefits of CACC driving in special cases, such as long-haul trucking, lengthy commute trips on highly congested highways, or long-distance passenger car trips when the market penetration is so low that the chances of finding other equipped vehicles are very low in the absence of global coordination.

Global coordination could be implemented in different ways depending on whether the vehicles will be coupled on the entrance ramp before entering the highway or the vehicles will enter the highway individually and then be coupled “on the fly” similarly to the local coordination case. If the coordinated vehicles are grouped before entering the highway, entrance ramps are likely to require extra lanes to park the CACC equipped vehicles until enough have gathered to cluster together. However, it is hard to imagine that the incremental benefits of CACC driving would be sufficient to justify waits on the order of several minutes unless the trips are very long or the fuel savings really significant. If the vehicles enter the freeway individually, then the global coordination case would suffer from the same problems as the local coordination case. Once on the highway, some vehicles would need to speed up or slow down to form a CACC string and their drivers would face the challenges of knowing what maneuvers they need to make to find their partners.

**Incentive Strategies**

When the market penetration of equipped vehicles is low, it will be important to make it as easy as possible for the CACC vehicles to connect with each other to gain the benefits of CACC operation, but not all vehicles and drivers will benefit equally from CACC coupling. In particular, the driver of the first vehicle in the string does not benefit from a shorter gap to deter cut-ins or a crisper response to maneuvers by preceding vehicles, nor does that vehicle save as
much energy from aerodynamic drag as the followers. One strategy explored in the SARTRE project was to use transfer payments from the following vehicles to the leading vehicle as an incentive for that vehicle/driver to act as the leader (31), but some questions remain open such as size of those payments based on the relative benefits to leaders and followers, willingness of the followers to pay, and willingness of the leaders to lead in the absence of payments.

A second strategy involves the use of managed lanes to consolidate CACC-equipped vehicles. The best current example of special-purpose lanes that could serve as an analogy for CACC-friendly lanes is HOT (High Occupancy-Toll) lanes. In many urban areas, the HOV (High Occupancy Vehicle) lanes have been under-utilized, so transportation agencies have expanded access to those lanes by allowing clean-air hybrid or electric vehicles into the lanes and by allowing single-occupant vehicles into the lanes provided that they pay a toll. Access to the HOT lanes could be extended to CACC-equipped vehicles and/or vehicles with DSRC VADs. A financial incentive could be offered through a reduced toll, based on the fact that CACC enables the lane to accommodate a higher traffic throughput. Since traffic simulations (4) showed that CACC vehicles would occupy half as much lane space as conventionally driven vehicles, an argument can be made that these vehicles should only pay half the toll.

Finally, analogous to the current system of preferential access for HOTs at some metered highway on-ramps, there could be a queuing lane at the ramp meter that lets CACC enabled cars queue up and then lets the CACC string onto the highway all at once. However, once these vehicles get on the highway, there’s no guarantee that their drivers will all choose the same lane or even be able to stay clustered when merging onto the highway. To work most effectively, this strategy may need to be implemented on an entrance ramp that directly accesses the HOT lane. The concept of direct access ramps to and from the HOT lane needs to be simulated and evaluated anyway because it may be necessary to avoid creating congestion in the general purpose lanes when the traffic volume or speed in the HOT lane is substantially more than the traffic volume or speed in the adjacent general purpose lanes.

Additional Operational Considerations

Length Limits for CACC Strings

There are a number of reasons, such as safety, performance limitations, and integration with unequipped vehicles, why limits must be placed on the number of vehicles that will be allowed in CACC strings. One upper limit that could be placed on length is based on the range of the wireless V2V communication system, assuming that all CACC following vehicles will require direct communication from the lead vehicle in the string. However, with 5.9 GHz DSRC communication technology providing at least 300 m of communication range (except where large trucks occlude the line of sight between vehicles), this limitation is not likely to be the binding constraint. The maximum length could also be established based on the number of vehicles or on the distance between the first and last vehicle based on string stability.

For the CACC systems in which all following vehicles obtain reference data from the first vehicle, the durations of the transport delays in the responses of the following vehicles impose some string stability constraints (32), but through careful design of the vehicle control and actuation systems these delays can be kept small enough to enable string lengths up to 10 to 20 vehicles. However, for the CACC systems that couple pairwise, relaying communication between consecutive vehicles, the string length threshold above which stability is lost is likely to be shorter. The most serious limitation on the length of CACC strings is expected to arise from a
need to provide sufficient lane-changing gaps in multi-lane highway environments, especially when the gaps between the CACC vehicles in the string are short enough to deter most cut-in lane changes. These inter-string gaps will be needed to allow unequipped or uncoupled vehicles to merge between consecutive CACC strings when moving to their desired lane or when working around incidents that block a lane.

*Clustering Vehicles Within a CACC String*

There are operational questions regarding how to cluster vehicles within a CACC string. The simplest rule would be based on time of arrival, whereby vehicles joining the string always join at the rear. However, if heavy and light vehicles are allowed to coexist within the same CACC string, there will be additional considerations regarding both string position and maximum string length. For safety reasons, any mixed string of vehicles will require the heavy vehicles to be in front and the light vehicles in the rear; however, this restriction will result in additional implementation problems since most drivers prefer not to be stuck closely following a heavy truck due to the impossibility of seeing around the truck and issues with road debris and spray kicked up by the truck tires. Additionally, with strings of mixed vehicles, the limits on the total number of vehicles in the string would need to be adjusted since the total length of the string will be longer with fewer vehicles (trucks being much longer than passenger cars). The mixed-vehicle-class strings will not be pursued further in this study because of these concerns.

A second clustering strategy is to group vehicles by destination. The maneuvering required for vehicles joining and leaving CACC strings could be reduced if the vehicles were clustered by common destinations from the start. This would reduce the amount of accelerating and decelerating for joining and splitting maneuvers and would enable the vehicles to maintain a more nearly constant speed for improved fuel economy and smoother traffic flow. On the other hand, this will impose delays on some of the vehicles that will have to wait for additional vehicles to show up heading to their common destination, and could require significant staging facilities for vehicles to await the arrival of their peers.

**CACC String Dissolution Strategies**

The dissolution of CACC strings as the vehicles approach their destination needs to be considered with as much care as the formation of the CACC strings, because if done badly, this could potentially create new traffic problems. Unfortunately, there has been very little research on CACC dissolution strategies. When the vehicles are coupled using CACC they can drive at shorter gaps than they would using ACC, so it would be undesirable to have entire strings of CACC vehicles simultaneously switch to ACC, instantly creating the need for larger separations. The most efficient action is for the departing driver to do a simple lane change in the direction of the off-ramp. The vehicle that was behind the departing vehicle in the original lane can then simply close the gap to its new preceding vehicle, and the length of the string decreases by one.

However, if the driver of the departing vehicle is not comfortable with making the lane change while still under CACC control, especially if speed adjustments are needed to merge into a limited gap in the adjacent lane, the driver will need to deactivate the CACC function by tapping on the brakes before changing lanes. The departing vehicle would thereby create a split in the CACC string, and the departing vehicle would become the manually driven leader of the string of CACC vehicles following it until it moves out of the lane. Once the departing vehicle completes the lane change, the vehicle that was behind it must decide if it closes what may be a long gap to rejoin the former CACC string or becomes the leader of a new CACC string.
Another string dissolution concern is determining how multiple consecutive vehicles within a CACC string leave at the same exit. It would be most space efficient for them to remain coupled as a CACC string while doing their lane changing and exiting maneuvers, but it is probably going to be difficult for the drivers of those vehicles to do a fully-synchronized lane change. They would have to find a gap in the adjacent lane long enough to accommodate all of their vehicles, and manually executing the lane change in very close coordination, even with lateral guidance assistance, may be asking too much of drivers. Furthermore, if a substantial fraction or number of drivers intend to depart at one exit or destination (such as the one serving the football stadium just before game time), it may not be possible to accommodate all of them at the same exit. In this case, some vehicles will need to be directed to exit the lane earlier or be directed to second-choice nearby exits to spread the burden of accommodating them out in space and time. The direction could come from variable message signs, I2V communication messages, or infrastructure changes around the event arena (direct exits from the CACC lane or making the CACC lane limited access, forcing the vehicles in that lane to bypass the main event exit and use an alternate exit with less traffic).

CONCLUSIONS

This paper has introduced a range of CACC concepts, while placing CACC within the broader context of cooperative vehicle following systems. This is important because CACC must be distinguished from close-formation platooning systems, which impose more daunting technical challenges and are likely to be harder to operate in close proximity to unequipped vehicles on general-purpose highway lanes. Furthermore, this paper makes a distinction between V2V and I2V CACC concepts so that future discussions of CACC can be more precise and readily understood. While the V2V CACC functionality appears to produce the greatest benefits on limited-access highways, the I2V CACC functionality is likely to be more beneficial on urban and suburban signalized arterials.

Most research on ACC and CACC deals with the very local vehicle-following behavior and its impact on traffic flow capacity and dynamics. However, for CACC to truly be effective, it is important to consider higher layer coordination among vehicles to facilitate clustering of equipped vehicle into CACC strings and to manage the dissolution of these strings as the vehicles approach their destinations. This clustering may be done ad-hoc or by local or global coordination strategies, and each coordination strategy brings technical challenges that have yet to be completely resolved. While this paper introduces the relevant concepts and operating issues associated with CACC systems, our future research will assess the potential benefits of each operating concept over a range of operating conditions and market penetrations. The operating concepts will be studied in more detail using simulations to assess the advantages and disadvantages of alternative strategies.

ACKNOWLEDGMENT

This research was supported by the Federal Highway Administration’s Exploratory Advanced Research Program under cooperative agreement DTFH61-13-H-00013, with cost sharing by the State of California Transportation Agency, Department of Transportation (Caltrans). The contents of this paper reflect the views of the authors, who are responsible for the facts and
accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the State of California.

REFERENCES


