OPERATIONAL CONCEPTS FOR TRUCK COOPERATIVE ADAPTIVE CRUISE CONTROL (CACC) MANEUVERS

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Submission date: 1 August 2015

Number of words including abstract (226) and references (721)	6220
Number of tables and figures (4) x250	1000
Total	7220

ABSTRACT

Cooperative adaptive cruise control (CACC) has been loosely defined in recent literature to represent a wide variety of vehicle-following control concepts, and when discussing trucks, CACC is often used synonymously with platooning. This paper discusses the similarities and differences between CACC and platooning, and it provides a more precise functional description of CACC operations for trucks. CACC operations include not only the steady-state cruising mode of CACC operation but also the maneuvers that need to be done to join vehicles together using CACC and to separate them when a vehicle needs to leave a CACC string or the string is interrupted by a cut-in maneuver by a non-cooperative vehicle. The CACC maneuvers are described using activity diagrams that specify the sequence of actions that need to be taken by each driver and each vehicle (and its CACC software) and the information that needs to be exchanged among them. These precise definitions of information exchange can be used to specify the V2V messages that need to be exchanged among vehicles to implement CACC control and the driver-vehicle interface displays and controls that will be needed. The paper also addresses practical considerations in CACC operation such as maximum lengths for strings of CACC trucks, strategies for sequencing the trucks in CACC strings and higher-level strategies for clustering CACC-capable trucks, ranging from ad-hoc to local and global coordination.

INTRODUCTION

The concept of truck platooning for improved fuel efficiency has been the focus of many research projects over the years, and a strong business case has been made for truck platooning at all levels of automation (*1*). At highway speeds, fuel consumption is significantly influenced by aerodynamic drag, and the shorter following gaps that can be maintained with automated speed control can significantly impact fuel economy for large trucks. Research at the California PATH Program and in other projects around the world, such as CHAUFFEUR, SARTRE, Energy ITS, and COMPANION, have demonstrated energy savings potentially as high as 15% to 25% (*2, 3, 4, 5, 6, 7*). The fuel savings alone will result in dramatic operating cost savings for truck fleets and significantly reduce the dependence on petroleum for transportation, while the shorter following gaps and enhanced traffic flow stability will increase roadway capacity, especially in areas with high truck throughput such as drayage operations near ports and rail connections.

The aforementioned truck platooning projects have emphasized a very tight coupling and constant clearance distance between the platoon members. The majority of the truck platooning studies have considered and tested gaps between trucks as small as 3 m to 10 m at highway speeds (equating to 0.1 s to 0.3 s at 65 mph). These short following gaps are likely to require the implementation of dedicated truck lanes and automation of both speed and steering control on the trucks. The dedicated lanes would be required for safety because trucks following at such close distances will leave very little opportunity for other traffic to change lanes across the platoons, and the platoons will have difficulties in responding safely to emergency conditions created by bad behaviors of drivers of other vehicles. Automated steering will be required for truck platoon systems that are operated at very short gaps because driver forward vision will be highly limited, and manual steering with poor visibility of the forward road will result in a higher workload for the driver and earlier onset of fatigue. Furthermore, lateral offsets between trucks arising from manual steering inaccuracy will create additional drag, reducing the potential fuel savings that could otherwise be achieved. Thus, automated truck platooning should represent at least SAE Level 2 automation (*8*) if it is to be operated at such short gaps that manual steering is not practical.

Limited vehicle speed automation has already been commercially deployed in some trucks using Adaptive Cruise Control (ACC) systems, but the performance of these systems is limited to longer following gaps than would be required for truck platooning due to both sensor and vehicle response delays, and they maintain constant time gaps rather than constant clearance distance gaps between consecutive vehicles. In the near term, Cooperative Adaptive Cruise Control (CACC) provides a good compromise in terms of performance and implementation. In recent years, CACC has been used loosely to describe different functions and capabilities (*10*), but CACC is fundamentally automated vehicle following and speed control with a cooperative element based on Vehicle-to-Vehicle (V2V) and/or Infrastructure-to-Vehicle (I2V) communication. This communication reduces sensor processing delays, thereby enabling shorter following gaps while reducing string instability. With CACC, only truck speed control will be automated, while the drivers will still be responsible for most of the dynamic driving task including actively steering the vehicle, monitoring roadway and traffic conditions, and intervening when events occur that cannot be handled by the CACC system, so CACC represents SAE Level 1 automation (*8, 9*). To highlight the distinction between automated truck platooning and CACC, a group of CACC equipped vehicles is referred to as a CACC string, rather than as a platoon.

The literature to date, as cited in this paper, has only considered the operating concepts for truck platooning and CACC systems in broad strokes and generally at the strategic level, rather than the operational level. As an example, while the literature discusses general concepts that could be employed to facilitate CACC string formation using *ad hoc*, local, or global coordination, very little prior research has been done to define how string formation would work from the driver's point of view under any of these strategies.

The goal of this paper is to define the basic operating concepts for truck CACC operations. This paper first discusses the key differences between CACC operations and automated truck platooning. Then the discussion focuses on the primary new contribution of this paper, which is definition of truck CACC operational concepts, including coordination strategies and maneuvers, with a particular focus on the drivers' roles and responsibilities. Other operational considerations such as the maximum CACC string length and vehicle sequencing within a CACC string are also discussed.

CACC STRING VERSUS TRUCK PLATOONING SYSTEM CHARACTERISTICS

This paper explains that there are three important distinctions to be made between CACC strings and automated truck platooning systems. From the driver's perspective, the primary difference is that truck platooning has generally included both lateral and longitudinal control, while CACC provides only longitudinal control, leaving the driver responsible for active steering control and monitoring of the driving environment. In fact, one major assumption that drove many of the operating concept decisions detailed in this paper is that CACC could be implemented on vehicles with no lane tracking or mapping capabilities. Thus, the first difference between CACC and truck platooning is that CACC only represents Level 1 automation on both the SAE (*8*) and NHTSA (*9*) scales of driving automation, while platooning generally represents at least a Level 2 automation system (also on both scales).

As described in a previous paper, although CACC has been used to describe multiple system concepts (*10*), each CACC concept uses a combination of automated vehicle following and speed control plus a cooperative element, such as Vehicle-to-Vehicle (V2V) communication about the forward vehicle(s) and/or Infrastructure-to-Vehicle (I2V) communication about traffic further ahead. Although both CACC and platooning are subsets of the broader class of automated vehicle speed control systems using V2V communication, the second important distinction is that CACC and platooning generally differ in their vehicle-following control strategies. Many vehicle-following speed control strategies have been proposed over the years, based on a wide variety of feedback control approaches and applying data from different combinations of vehicles (*11*), but only a few have been implemented for platooning or CACC.

All of the truck platooning projects reviewed in this paper have emphasized a very close coupling between vehicles employing a constant-distance-gap (CDG) strategy within the platoon and a constant-safety-factor strategy between successive platoons (*12*). The CDG discipline maintains a constant separation between vehicles, regardless of vehicle speed, and the tight control achieved using this strategy gives the perception of a mechanical linkage between the vehicles. However, stability can only be achieved using communication to share real-time data about the behavior of all the vehicles in the platoon (*13*), and interruptions in communication require relaxing of the CDG strategy. Additionally, with such short following distances between trucks, emergency braking maneuvers could potentially lead to low-speed impacts among the followers, especially if different loading and braking performance characteristics between trucks are not factored in. A constant-safety-factor strategy between platoons sets the minimum distance such that the weakest acceptable braking by the lead vehicle of the following platoon is enough to avoid a crash between the platoons. The constant-safety-factor criterion produces an inter-platoon separation proportional to the square of the cruising speed.

In contrast, both commercial ACC systems and CACC research projects have typically employed a constant-time-gap (CTG) vehicle following strategy, since this more closely represents how people normally drive at highway speeds. Using a CTG strategy, 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 or distance gap between the vehicles.

The presentation bt Le Vine et al (14) was about discharge characteristics of passenger cars at an intersection. The authors suggested a "defensive driving" strategy, which means "driving-to-protect-oneself-from-causing-a-crash" rather than 'cooperative' behavior. From our viewpoint, there is no conflict between those two objectives. In fact, real-time cooperative controls among all the vehicles can significant enhance safety or "protect-oneself". This can be achieved by using the upper bound for the CTG.

The presentation of Lu et al (15) contained the latest results on truck CACC system development and preliminary test results. It include overall system hardware structure, software structure, following strategy, control design and implementation, and field test at low speed. The vehicle following strategy included all possible CACC following scenarios in real traffic:

- There is another vehicle in front of the leader (ACC)
- There is no other vehicle in front of the leader (CC)
- Leader vehicle drive manually
- Leader vehicle drive automatically

Those scenarios have designed and implemented on trucks and preliminarily tested. Note that even if the leader vehicle is driven manually, it can still pass information to its followers. Such information is still very important from a control viewpoint: it is more accurate with much less time delay than what the followers obtained through remote sensor such as video camera, radar or lidar.

The CTG strategy has been implemented with all vehicle-followers listening directly to the lead vehicle (16), and and its immediate predecessor (17). CACC studies conducted with passenger vehicles (16,*18*) have been tested at time gaps in the range of 0.6 s at 65 mph (~30 m/s), equating to a 17.5 m gap between vehicles, without any lane keeping automation or assistance. At the shorter CACC following gaps, the surrounding traffic (unequipped vehicles) was still able to maneuver between the electronically coupled vehicles when needed, creating unequipped vehicle cut-in and cut-out scenarios that need to be considered for CACC strings, but are unlikely under CDG platooning, when the following distances are much shorter.

The third important distinction between CACC and platooning lies in the degree of formality, centralization, and hierarchical control expected in the procedures and maneuvers. Truck platooning research has generally assumed more formal procedures and hierarchical control when forming, joining, or departing a platoon because the close CDG spacing is not tolerant to sudden changes made by any particular vehicle. As an example, in the SARTRE concept, a driver intending to join a platoon would need to request the desired maneuver and wait for approval and further instructions from the lead vehicle before initiating any maneuvers. Conversely, since CACC relies on the driver for active roadway monitoring and steering, CACC can be implemented using less formal procedures and decentralized control. In fact, since the driver could, at any moment and without prior notification to the lead vehicle, decide to join or leave the CACC string simply by executing a lane change, CACC cannot rely on centralized control and more formal string formation and departure procedures.

TRUCK CACC OPERATIONAL CONCEPTS

CACC String Formation and Join Maneuvers

Coordination Strategies

The first challenge in proposing a vision for CACC operations is string formation. Three coordination strategies that have been described in the literature that could apply to CACC string formation (*10*): *ad hoc* clustering, local coordination, and global coordination. CACC for passenger vehicles will probably rely on ad-hoc clustering, since coupling only occurs once the vehicles happen to be following each other on the highway because there is no coordination or maneuvering to locate and follow other equipped vehicles. However, given the specific trucking goal of increased fuel efficiency and given the large performance differences between passenger cars and trucks, CACC-equipped trucks will want to be paired with other CACC-equipped (or at least communication-enabled) trucks, pointing toward the use of local or global coordination strategies. Local coordination attempts to actively match nearby equipped vehicles to promote the formation of CACC strings. Equipped trucks that are already on the highway and within a certain distance of each other could be instructed to speed up, slow down, or change lanes to facilitate coupling (19). Global coordination adjusts the departure times, routes, and/or vehicle speeds before entering the highway, so that the equipped trucks can be coordinated to arrive simultaneously at highway entrance points and maximize the time spent travelling in a CACC string once the trucks have entered the highway (20). Once formed, CACC strings will need to rely on a low latency, short range communication medium such as DSRC, but forming a CACC string of trucks using local or global coordination could use longer range communications, especially at low market penetrations of equipped trucks.

Truck Sequencing Strategies

Lead truck assignment and truck sequence within a CACC string could be based on a number of different considerations including initial position, destination, truck loading, performance, aerodynamics, and driver preference. Dictating string sequence by initial truck position provides for the least complicated set of maneuvers during the coordination phase of the string formation. Sequencing the trucks by destination would keep the core of the string intact for the maximum amount of time possible, with the rear trucks successively departing as they reach their destinations, but sequencing by destination requires more complicated join maneuvers that may negate efficiency gains from the ordering effect.

Truck loading and performance sequencing also relates to safety in the event of a hard braking maneuver and efficiency on hilly terrains. In both cases, the worst performing trucks should be at the front of the string to be sure that the string can safely stop and that it stays together on positive grades. Finally, some drivers may have a preference for leader or follower position, which could be taken into account during the local coordination phase of the string formation, but given the *ad-hoc* nature of CACC, a follower can become a leader of a new shorter CACC string at any moment, either after a cut-in or when the current leader departs the string. Thus, any attempt at formally sequencing the trucks will be temporary at best. However, if truck performance information is communicated, the system can still employ strategies such as increasing the minimum allowable following time gap or decreasing the overall string performance to maintain safety at the expense of increased fuel consumption.

Length Limits for CACC Strings

The physical limit on CACC string length is likely to be about eight trucks based on the 300 m range of the 5.9 GHz DSRC V2V communication systems to ensure that all the platoon members are within the range of the platoon leader to minimize the latency for receiving messages from the leader. The estimate of a maximum of eight trucks is based on typical 73 ft (22.25 m) tractor-trailer combinations at a 0.6 s time gap (17.4 m spacing at 65 mph), keeping the total length of the string under 300 m. However, the communication range will not be the binding constraint because of other considerations. Reports from the Netherlands and from the SARTRE project suggested much lower limits, on the order of two to three trucks, out of concern about impeding the lane changing opportunities for the surrounding traffic (*1,21*) and whether guardrails and other infrastructure would be able to survive an impact from multiple successive trucks in a platoon (22). The lane capacity kinematic analyses by the National Automated Highway Systems Consortium suggested that the main capacity increases are accomplished by the time a platoon reaches three or four trucks in length, and additional capacity increases for longer platoons are relatively minor while the operational complexities and disadvantages grow as the platoons get longer (23).

CACC Join Maneuver

The procedure for CACC string formation needs to consider the roles and responsibilities of drivers in both the leader and follower positions, the implications of the vehicle clustering strategy, and the minimum sensing capability that will be required of a CACC-equipped vehicle. The driver roles and responsibilities differ between CACC and truck platooning. As discussed in the SARTRE project, it was postulated that platooning imposed additional responsibilities on the lead truck driver for monitoring both the automation and the road ahead while the following drivers completely disengage from the dynamic driving task (21). In CACC, all the drivers need to remain engaged in the dynamic driving task and ready to take over as the string leader. Furthermore, since the CACC string drivers are already engaged directly in control of the vehicle steering, a CACC system is both reliant on and subservient to the driver. If a driver wishes to leave a CACC string without notification, the system cannot prevent it and may not be able to instantly detect it without requiring lane tracking as part of the CACC system.

To illustrate the string formation procedure, an activity diagram has been developed and is proposed in Figure 1. The activity diagram is a useful tool to illustrate a timeline, with the occurrences of decisions, actions, and CACC information and communication requirements. In each activity diagram, there are two entities that perform activities (either a driver or the system on the trucks) as identified on the left side of the diagram and along the timeline as represented by blue dashed lines. To read the diagram, the boxes on the dashed lines extending to the right of the driver and vehicle icons describe the sequence of activities performed by those entities, with time flowing from left to right. The activities on the driver line correspond to driver decisions and actions, while the ones on the truck line correspond to algorithms that must be implemented as part of the CACC system. The boxes falling between the dashed entity lines on the diagram represent the information that is passed between these entities, either via the V2V communication between the trucks or the DVI between the driver and the truck. One of the conclusions from this exercise is that the SAE J2735 Basic Safety Message is not sufficient for CACC messaging, but must be supplemented with some additional data elements. The possibility of micropayments is included in the activity diagram as a means for followers to compensate the leader for the disparity in fuel consumption benefits between vehicle positions. Although shown in this diagram, the micropayments are not a technical necessity for CACC.

A number of system assumptions, prerequisites, and guiding principles were used in constructing the activity diagram. First, CACC is proposed as an extension of ACC, and when CACC is enabled, the system will automatically engage whenever conditions permit. However, even if the CACC is disabled, the ACC will still function normally. The driver may enable or disable the CACC, configure a preference for leader or follower, and adjust the set speed and the gap settings in both ACC and CACC mode. The second a prerequisite for the system design was that both the *ad hoc* and local coordination scenarios need to be supported, preferably without requiring vastly different procedures. With the procedures proposed in Figure 1, the local coordination phase could be skipped if the two trucks were already following each other in the same lane. Finally, in developing the proposed procedure, the guiding principle was to only require activity by a driver if the driver is being asked to do something specifically different, such as changing speed. As an example, when using local coordination, the following truck driver may need to select a leader or existing string to join, but the leader would only need to confirm the request if he was being asked to slow down or perform some other maneuver to facilitate the join. If the follower is already behind the leader and engages the ACC, then the CACC would automatically engage without requiring confirmation from the leader. The leader would just get a notice that a string was formed and he was the leader.

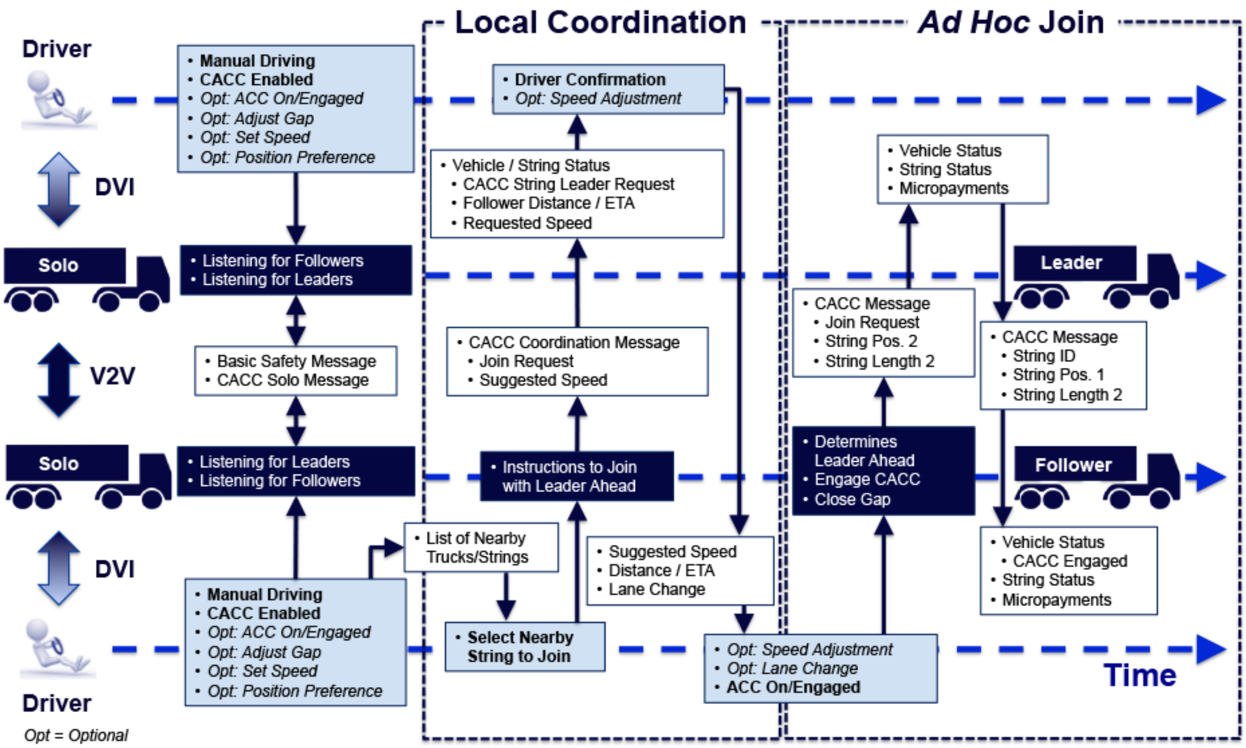

Figure 1. CACC String Formation Activity Diagram.

The activity diagram also illuminates tasks that are allocated to the truck's coordination and CACC systems, and it highlights potential V2V communication requirements. In the concept described here, the CACC coordination messages should be distinctly separate from the CACC operational messages because the two sets of messages may be operating over completely different media. During the coordination phase, a join request needs to be specifically targeted to the lead truck, requesting any specific maneuvers necessary to facilitate the join. The lead truck driver then has the option to accept or decline because the lead truck would likely need to slow down in order for the following truck to catch up; otherwise, the following truck would need to violate the speed limit.

After the trucks are in position to couple, the following truck initiates a join maneuver since only the following truck can know that it is in the correct position with no other vehicles between the two trucks. If both trucks are initially operating as solo trucks, the join request is complicated by the fact that a new string needs to be formed. The following truck needs to specifically request that the lead truck form a string by creating a string ID number, designating itself as the first truck in the string, and suggesting that the overall string length is now two trucks. The following truck would then echo back the new string id, suggest that it is in the second position, and confirm that it thinks that the overall string length is now two trucks. Additional trucks initiating a join into an existing string would then broadcast the existing string's ID, designate their new position within the string, and suggest a new overall string length. All of the other trucks in the string would simply echo back the new string length to confirm that everyone agrees with the organization of the string. In both cases, once the joining truck hears that all the trucks in the string agree on the organization of the string, then it can begin CACC following and close the following gap. After the join maneuver is completed the trucks should end up in steady-state cruising.

CACC Steady-State Cruising

Steady-state cruising is what truck drivers will be doing most of the time while the CACC system is engaged. After a string is formed, the drivers will still be tasked with actively steering their vehicles and monitoring vehicle status and traffic conditions, and steady-state cruising should only be interrupted by split maneuvers. While cruising in a string, drivers should retain control of the trucks' set speed and gap settings, but the CACC system will need to calculate and display the minimum set speed that is required to remain as part of the string. As an example, if the driver of the lead truck in the string decides to increase his set speed from 55 mph to 60 mph, then all the following trucks' drivers need to know that their set speed must be set to 60 mph or greater, or else the lead truck will eventually pull away from the rest of the string. Looking at the issue of gap setting, a driving simulator study in the SARTRE project (24) found that the minimum comfortable following distance ranged from 16.5 to 18 m when travelling between 50 and 75 mph (80 and 120 km/h), equating to a following time gap ranging from 0.5 to 0.8 s. The participants felt that the following distance became unsafe at 7 m, equating to about 0.2 s. Prior on-the-road research, which focused on passenger car CACC, showed that drivers were fairly comfortable at following time gaps down to 0.6 s in traffic (17), but it is possible that such short following time gaps may be less acceptable for truck drivers given the obvious visual occlusion that will be present when following another truck so closely.

CACC String Split Maneuvers

Overview

Starting from steady-state cruising, string split maneuvers will occur in a variety of situations. A string split maneuver will occur whenever any of the following trucks' drivers disengages the CACC system by tapping the brakes or turning the system off, or when any truck driver in the string decides to change lanes. String split maneuvers can also occur when an unequipped vehicle cuts in between the following trucks in the string, or when there is a V2V communication disruption or other system fault. A string split may be temporary, such as during a cut-in, or permanent, such as when a driver decides to leave the string in order to exit the roadway.

Any truck in the CACC string may depart the string at any time, and the effect that the departure has on the string will depend on which truck is exiting. In an ideal departure, the driver of the departing truck will signal their intent to exit the string by activating the turn signal or otherwise indicating so on the DVI. If a driver signals their intent to depart, then any following drivers in the string will be notified of the maneuver through their DVI. In the least disruptive case, the departing truck simply changes lanes, and the following trucks close the gap. However, in some cases, the departing truck may need to revert to manual speed control before changing lanes so that the driver can adjust speed to fit into the available gap in the destination lane. In the case when the departing truck is a middle truck in the CACC string, the string will be temporarily split into two strings, with the departing truck leading the second CACC string under manual control until it fully departs the lane. After the departing truck changes lanes, the trucks that were following it may rejoin the original CACC string and close the gap left by the departing truck, unless they have fallen too far behind the remaining trucks in the string.

Lead Truck Departure Scenario

Figure 2 illustrates the CACC string split maneuver as a result of the lead truck (S1 Leader) changing lanes and leaving the string (String 1). In this scenario, assuming the CACC system doesn’t need to track the lane or know anything about the road geometry, the lead truck will not necessarily know that it has changed lane, especially considering that the driver may or may not use the turn signal before changing lanes. When the lead truck changes lanes, the first follower in String 1 will be the first to detect the loss of the CACC string leader, and the first follower will respond by designating itself as the leader of a new string, String 2. Subsequently, new string 2 leader broadcasts a CACC coordination message that includes a new string ID, its revised position as the new leader, and the current length of new string by its estimation. The other following trucks acknowledge this broadcast by updating their string information to reflect the new string number, their new positions in the string, and confirming the new string length. Within a few V2V update cycles, all of the vehicles in String 2 should be in agreement on the organization of the string, and steady-state cruising should resume uninterrupted. The former String 1 lead truck should still be broadcasting itself as the String 1 leader, even though the truck changed lanes. After an update cycle or two, the String 1 lead truck will realize that it no longer has any followers, and the system will revert to designating itself as a solo truck. Alternatively, if the String 1 lead truck and any followers changed lanes in a coordinated manner, the followers that changed lanes would detect that they are still behind the String 1 leader and renumber themselves accordingly. Within a few update cycles of followers and leaders designating and confirming their assumed string assignment and positions within each string, the members of the two strings will have agreed upon the correct organization for each string.

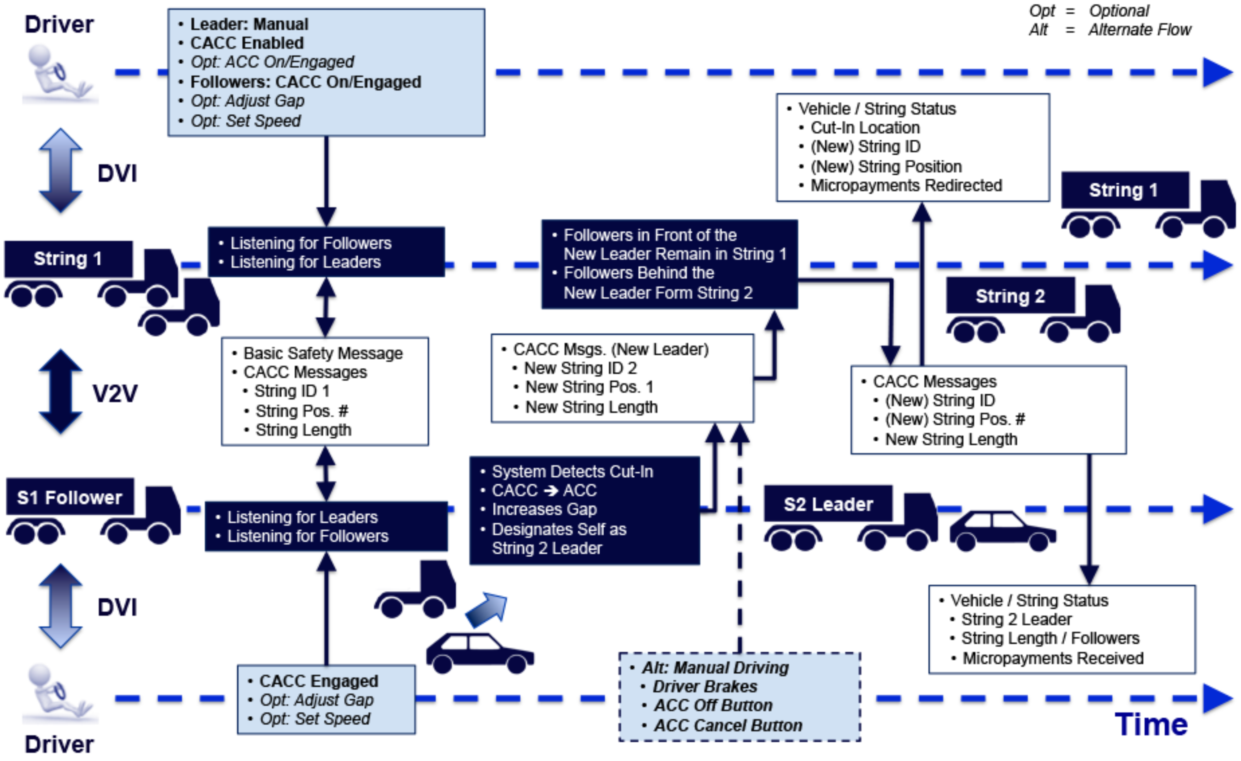

Figure 2. CACC String Split Maneuver – Lead Truck Departs by Lane Change.

Middle or Trailing Trucks Departure Scenarios

Figure 3 illustrates the scenario where the middle truck departs the string by changing lanes. One of the middle trucks String 1, designated as S1 Follower in the activity diagram, initiates a lane change and departs from String 1. While in String 1, the truck would have the CACC system engaged, but once the CACC system detects that the truck has changed lane (by comparing the GPS tracks of itself and the rest of the string and by seeing a change in forward targets from the sensors), the CACC system will transition back into ACC mode, increasing the following gap to any lead vehicles in the new lane and designates itself as a solo truck. The truck in String 1 immediately following the departed truck should also recognize its predecessor's departure through the loss of its forward target, and it will designate its new position within the string and reduce the string length by one when it next broadcasts the CACC coordination message. The gap left by the departing truck would then be automatically closed by all of the following trucks so that steady-state cruising can continue.

There is an alternate flow to the middle truck departing where the middle truck needs to brake before changing lanes. This flow is not depicted in the activity diagram shown in Figure 3, but it is described in Figure 4 which illustrates what happens when an unequipped vehicle cuts into the middle of the string. When the driver of any middle truck in the string brakes for any reason, whether the braking precedes a lane change or is in response to a cut-in or other traffic or roadway reason, the middle truck splits the string and designates itself as the leader of a new string. Any followers would need to switch to listening to the new string leader. Once the middle truck that broke the string leaves the lane, the two strings could remerge, assuming the distance between them had not grown too large.

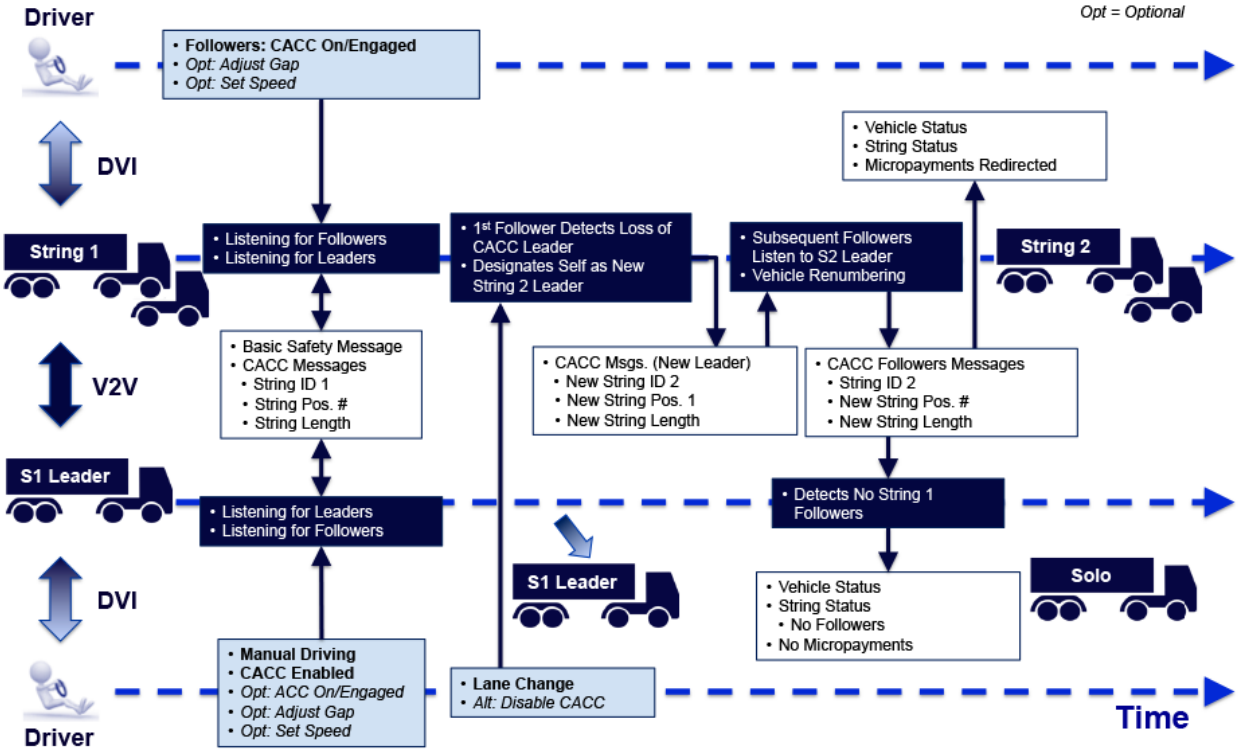

Figure 3. CACC String Split Maneuver – Middle Truck Departs by Lane Change.

An additional scenario that is not depicted is the case where the trailing truck in the string departs. Since the trailing truck in the string has no followers, the string is essentially unaffected by any actions taken by the trailing truck. If the trailing truck brakes or changes lanes, it will simply broadcast that it is no longer part of the string, and the other trucks in the string will acknowledge the departure by decrementing the string length by one.

Middle Truck Braking and Cut-In Scenarios

Both driver braking within the string and cut-ins during CACC operations will be unavoidable, and the CACC system needs to be designed to automatically handle either event by splitting the string into two separate strings. Figure 4 primarily depicts the cut-in scenario, but the flow is just as valid for any situation where a middle truck driver decides to manually brake or otherwise disengage the CACC system. In the cut-in situation, the truck immediately behind the cut-in (designated as S1 Follower in the figure) will detect the cut-in, designate itself the lead truck for the new String 2 (S2 Leader), and revert to an ACC following strategy and a corresponding ACC gap setting. Alternatively, since the driver is still responsible for monitoring for potential cut-ins, the driver may disengage the CACC system through manual braking should the system fail to respond quickly or appropriately. In this case, the driver of the truck directly behind the cut-in would still cause a CACC split to occur and would still be designated as the new lead truck in the string of followers, but the driver would be controlling the lead truck manually. After the unequipped vehicle departs the lane (cut-out), the CACC system can automatically re-join the two split strings and close the gap if the followers have not fallen too far behind.

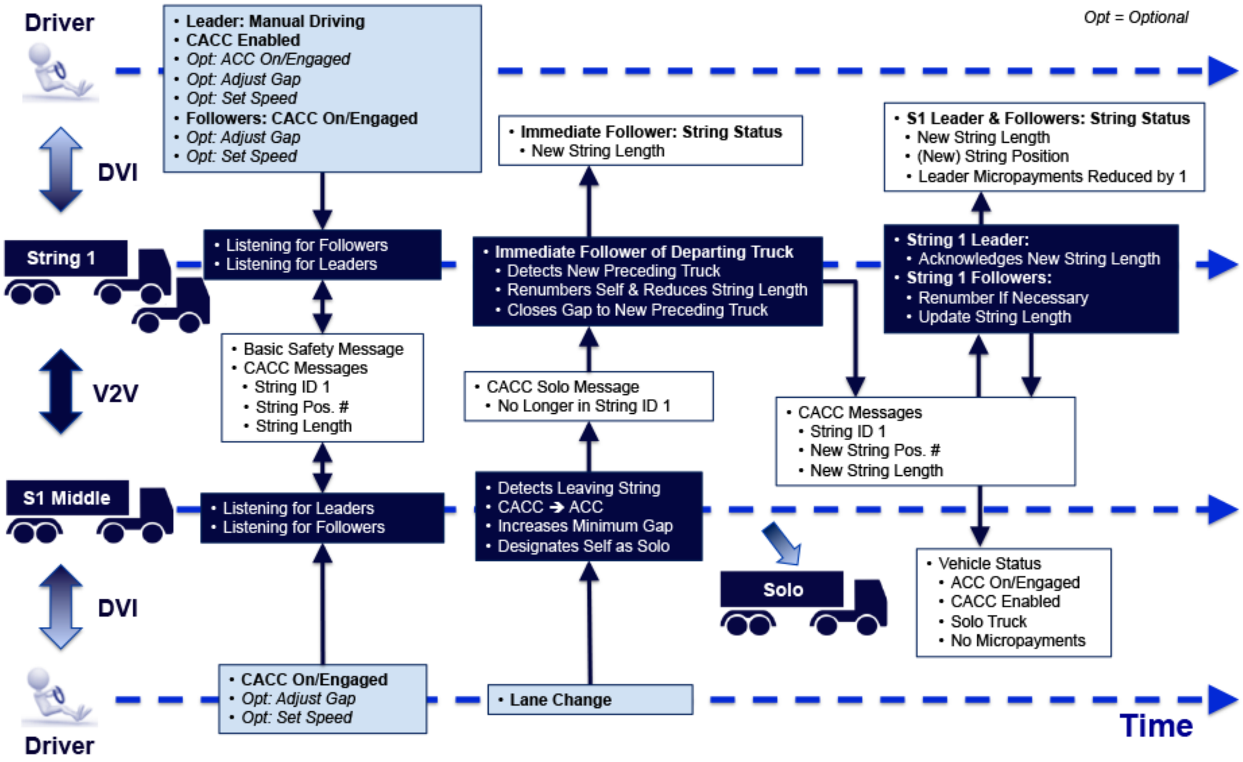

Figure 4. CACC String Split Maneuver After a Cut-In.

CONCLUSIONS

The concept of closely-coupled truck platooning has been the focus of many research projects over the years, and truck platooning has always included automation of both lateral and longitudinal control in the following trucks because of the very close following distances targeted by those prior projects. CACC can be viewed as an intermediate step toward a longer-term vision of trucks operating in closely-coupled automated platoons on both long-haul and short-haul freight corridors. There are several points of distinction between CACC and automated truck platooning, the most important being the formal procedures and hierarchical control associated with the formation, management, and separation of platoons. CACC strings can be implemented using less formal procedures and decentralized control because the driver could, at any moment and without prior notification, decide to leave the CACC string. Keeping this in mind, this paper introduced a set of detailed operating concepts for truck CACC, covering clustering and coordination strategies, string formation, and string split maneuvers. CACC string formation is primarily *ad hoc*, occurring automatically whenever two or more equipped vehicles are directly following, but local coordination can also be used to match similarly equipped trucks and guide them into position for the join maneuver.

The goal of this paper was to define the basic operating concepts for typical truck CACC operations. By using detailed activity diagrams, the roles and responsibilities of the drivers during the different maneuvers such as joining, departing, or splitting a CACC string of trucks can be defined precisely. This is an important step in the development of the driver-vehicle interface because it clarifies the information that needs to be provided to the driver and the decisions by the driver that need to be implemented by the truck systems (and that therefore require driver controls). This precise description of the fundamental maneuvers is also useful for designing the control software and for developing simulation models to accurately represent the behavior of the CACC systems in traffic. However, this does not provide a complete definition of CACC operations since it does not cover the host of atypical situations that will be encountered by some CACC strings including emergency responses and fail-safe procedures in response to equipment and communication failures. Additionally, procedures for dealing with roadway hazards that are visible to the lead truck driver, but not the following truck drivers, is an open topic for further research.

ACKNOWLEDGMENT

This research was supported by the Federal Highway Administration’s Exploratory Advanced Research Program under Cooperative Agreement No. DTFH61-13-R-00011, 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.

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