Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams

Definitions, Literature Review and Operational Concept Alternatives

Steven E. Shladover
Christopher Nowakowski
Xiao-Yun Lu

California PATH Program
Institute of Transportation Studies
University of California, Berkeley

Raymond Hoogendoorn (Section 4.6)
Technical University of Delft

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EXECUTIVE SUMMARY

This report introduces the topic of cooperative adaptive cruise control (CACC) and the research that is planned on that topic in the EARP project, "Using Cooperative ACC to Form High-Performance Vehicle Streams". The motivations for current interest in CACC and the benefits that it can provide to traffic flow and the environment, as well as to individual drivers, are explained in the introduction.

CACC is defined in some detail to try to overcome some of the confusion that has arisen based on recent over-use of this term. The 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. A further distinction is made between CACC, using constant-time-gap vehicle following, and tightly-coupled vehicle platoons, using constant-clearance vehicle following. The CACC systems can be implemented based on a variety of feedback structures, which may be as minimal as pairwise communication between adjacent vehicles, while the tightly-coupled platoons require communication from the first vehicle to all the followers. The term "CACC string" is used to distinguish the CACC groups of vehicles from the more formally structured "platoons" that use constant-clearance control.

A brief literature review introduces prior research on both CACC and tightly-coupled platoon systems, with an emphasis on references that describe alternative operational concepts. This is not intended as a comprehensive review of all literature about cooperative vehicle following control because that is not the focus of the current project. Rather, the focus is on the concepts for managing the flows of traffic for cooperative vehicle following systems at a higher level.

The central portion of the report is Chapter 4, identifying the operational concepts for managing CACC vehicle maneuvering and traffic flows. This includes approaches for grouping the CACC vehicles, ranging from ad-hoc to centrally coordinated strategies, and the incentives that could be used to facilitate the vehicle clustering, both operational and financial. These are particularly important at low market penetrations, when the CACC vehicles are likely to be widely separated. The dissolution of CACC strings is also discussed, since this needs to be done carefully to avoid adverse traffic impacts.

Although the main focus is on V2V CACC for use on limited access highways, strategies for I2V CACC and for both V2V and I2V CACC on signalized arterials are also considered. Connected Cruise Control (CCC), which has been developed as a driver-advisory transitional strategy to lead toward CACC in the Netherlands, is also discussed.

The report concludes with introduction of example simulation scenarios that could be used to model the effectiveness of CACC strategies on urban and rural limited-access highways and at a signalized arterial, and with discussion of performance measures for evaluation of CACC alternatives.

1   INTRODUCTION

Cooperative Adaptive Cruise Control (CACC) is a term that has been used rather loosely in recent years, such that different people visualize different functions and capabilities when discussing CACC systems. Thus, there are now multiple system concepts that have been described under the CACC label, and the functionalities included in these varied concepts can be quite different from each other. At the heart of each CACC concept is the merging of Adaptive Cruise Control (ACC), a subset of the broader class of automated speed control systems, with a cooperative element, such a Vehicle-to-Vehicle (V2V) or Infrastructure-to-Vehicle (I2V) communication. The V2V communication could provide information about the vehicle or vehicles directly in front of you, and the I2V communication could provide information about traffic further ahead or about current speed restrictions as part of an active traffic management approach.

There are two primary transportation system motivations for the development of CACC. The first motivation is to reduce traffic congestion and the second is to improve fuel efficiency. It may also improve safety, although it is not primarily a safety system. At the individual driver level, CACC can make ACC more attractive and convenient to drivers by providing behavior that is more responsive to preceding vehicle speed changes, that gives an enhanced sense of safety because of its quicker response, and that deters cut-ins at shorter gaps.

At highway speeds, fuel consumption is significantly influenced by air resistance, and the shorter following gaps that can be enabled by CACC can significantly impact fuel economy for both large trucks (California PATH, Browand, et al., 2004; Shladover, et al., 2011; Lu and Shladover, 2011; Scania and the Swedish Research Council, Alam, Gattami, and Johansson, 2010; the Energy ITS project, Tsugawa, et al., 2011; and the SARTRE project, Dávila, 2013) and passenger vehicles (Shida and Nemoto, 2009, and Shida, et al., 2010). However, as described further in Section 2 of this report, it should be noted that all of the research cited above on fuel efficiency at short following gaps has utilized constant-clearance-following criteria, rather than the constant-time-gap-following criteria that would be more likely to be used in a production CACC system. The potential for fuel efficiency improvements with CACC using constant-time-gap-following criteria has not yet been demonstrated.

The second motivation for the development of CACC is to improve highway and roadway capacity and throughput. 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 (Nowakowski, et al., 2010, and Nowakowski, O'Connell, Shladover, and Cody, 2010), resulting in an increase in highway lane capacity. Several California PATH highway traffic simulations (VanderWerf, et al., 2001, 2002, and Su, Shladover, Lu, and Nowakowski, 2011) showed that ACC alone, even at high market penetrations, had little effect on lane capacity, and recent research (Milanés and Shladover, 2014) has even suggested that a stream of ACC vehicles would fail to achieve string stability, resulting in a negative impact on traffic capacity. However, with the shorter following gaps enabled by CACC systems, lane capacity could be increased from the standard 2000 vehicles per

hour to almost 4000 vehicles per hour at 100 percent market penetration. Unlike the experimental work related to fuel efficiency, the simulation work related to the potential CACC impacts on highway capacity has been based on the types of constant-time-gap controllers that would be used in future production CACC system.

CACC systems utilizing I2V communication, although not the primary focus here, also generally share the motivation of improving highway capacity and throughput. In this concept, the CACC system could cooperate with the infrastructure to reduce the potential for congestion at bottleneck locations through the active traffic management technique of speed harmonization. As the vehicles approach areas of congestion, their speed could be automatically reduced by the infrastructure commands, reducing speed differentials and allowing the traffic flow to be maintained at peak throughput. Another, less studied, CACC concept utilizing I2V communication to improve traffic throughput is the arterial coordinated start. In this concept, the CACC vehicles waiting at a traffic signal could 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.

Finally, additional motivations for CACC include comfort, convenience, and customer satisfaction. In a study that introduced CACC to drivers on real roads and in real traffic (Nowakowski, et al., 2010, and Nowakowski, O'Connell, Shladover, and Cody, 2010), drivers reported more satisfaction with the improved CACC performance and shorter time-gap settings (0.6 to 1.1 s) in dense traffic than with the longer standard ACC gap settings (1.1 to 2.2 s). Although a following-time-gap setting of 0.6 s is sometimes perceived to be too short, the drivers from the general public who participated in the PATH CACC field test drove at these shorter time gaps when driving manually without the ACC or CACC system active. As shown in Figure 1.1, almost 80 percent of typical following manually performed by drivers fell into the time-gap ranges offered by CACC and ACC system (from 0.6 to 2.2 s), and 35 percent of the time, the typical following performed manually by drivers fell into the time-gap range that could only be offered by a CACC system (from 0.6 to 1.1 s).
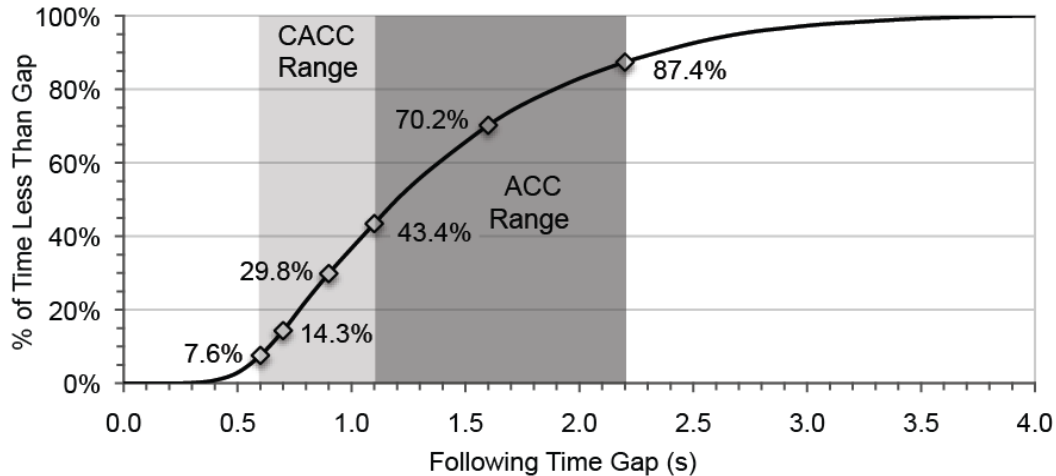
Figure 1.1. Cumulative distribution of vehicle-following time gaps under manual driving.[1]

2   CACC DEFINITIONS

While there are now multiple system concepts that have been described as CACC, all CACC variants are a subset of the broader class of automatic vehicle speed control systems. In reviewing the literature in subsequent sections of this report, there is an important distinction that must be made between CACC systems and automated vehicle platooning systems, so it is important to define CACC in the context of that broader class. Since CACC only provides longitudinal control of vehicle motions, while the driver remains responsible for the steering control, it represents Level 1 automation on both the SAE and NHTSA scales of automated driving. As described further in the following sections, automated vehicle speed control systems need to be specified in terms of four 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. The specific information the system uses as inputs
4. How the system determines the desired following distance

2.1   CACC System Goals

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

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[1] Figure reprinted from Nowakowski, C., Shladover, S.E., Cody, D., Bu, F., O'Connell, J., Spring, J., Dickey, S., and Nelson, D. (2010). *Cooperative Adaptive Cruise Control: Testing Drivers' Choices of Following Distances* (Technical Report for FHWA Exploratory Advanced Research Program Cooperative Agreement DTFH61-07-H-00038). Berkeley, CA: California PATH, Institute of Transportation Studies, University of California, Berkeley.

- Improving safety by making rear-end crashes less likely
- Improving traffic flow dynamics by damping out vehicle-following disturbances
- Increasing highway capacity by enabling closer vehicle following without compromising safety
- Saving energy and reducing pollutant emissions by improving traffic flow dynamics and enabling vehicle following at distances close enough to promote aerodynamic drafting
- Improving comfort and convenience for drivers

The first four goals provide societal benefits beyond the benefits provided to the individual driver, while the fifth goal is entirely a private benefit to the driver. 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 achieve maximum fuel efficiency under traffic conditions that require frequent speed changes.

2.2   CACC Information Sources

Speed control systems can obtain the information they need for controlling vehicle speed from a multitude of sources, and the data sources available 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, while cooperative control systems augment the internal sensor information with additional information that has been communicated from the roadway infrastructure and/or from other vehicles.

2.2.1   *Onboard Sensors*

A variety of internal onboard sensors are needed for doing closed-loop speed control of vehicles. These include the wheel speed sensors as well as brake pressure sensors and internal indicators of brake and accelerator commands and potentially inertial sensors to indicate yaw rate and accelerations. Internal fault indicators are also useful elements of the vehicle's control system.

In addition to the basic internal sensors, automatic speed control systems may also use the following kinds of onboard remote sensors:

- Lidar (laser radar) to detect distance (range) to preceding vehicle or following vehicle
- Radar to detect distance (range) and speed difference (range rate) to preceding vehicle and/or following vehicle
- Video image processing to detect distance (range) to preceding vehicle and/or following vehicle

These sensor systems have all been used in commercially available adaptive cruise control (ACC) systems, and they are also the starting point for CACC systems. Speed control systems that rely entirely upon onboard sensors are **autonomous**, such as **Autonomous ACC** (AACC).

2.2.2 Roadway Infrastructure

In I2V CACC systems, the roadway infrastructure, through its Traffic Management Center (TMC) and roadside devices, may provide recommended speeds to a vehicle speed control systems. These recommended speeds are typically determined based on safety considerations (such as maximum allowable speeds or a maximum recommended speed for a potentially dangerous curve), or the recommended speeds may be based on traffic flow considerations, using the concept of Variable Speed Limits (VSL) to maximize bottleneck throughput or reduce weaving and merging conflicts. The CACC system would then use the communicated recommended speeds as the set speed, which is effectively the maximum speed for the vehicle when it is unimpeded by a lead vehicle. This concept is being tested under the Speed Harmonization project of the FHWA Saxton Transportation Operations Laboratory (Lu, et.al., 2014).

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. Urban applications involving responding to changes in traffic signal status will need more frequent updates and lower latencies.

2.2.3 Other Vehicles

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. Then, 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 delay is cumulative from the leader to the downstream vehicles. 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 begins to react (Milanés, et al., 2014).

Other vehicles may communicate diverse information to enrich the data available to a vehicle's speed control system beyond the data collected by its onboard sensors. This type of V2V CACC is a potentially large category because the information may come from a wide variety of other vehicles, and the data may represent a wide variety of information about the source vehicles. V2V CACC systems depend on very frequent information updates (multiple 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.

The sources of V2V data and type of data that could be provided to a CACC system to be used for vehicle speed control are summarized in Table 2.1.

Table 2.1. CACC data types by data source.

Data Used for Control	Data from Other Vehicles			
	Immediate predecessor	Immediate follower	Platoon Leader	Other Vehicles
Sensed distance (range)	X	X		
Sensed speed difference (range rate)	X	X		
Estimated acceleration/deceleration	X	X		
Communicated data (vehicle speed, location, actual acceleration, commands, faults, performance limits...)	X	X	X	X

Only the data from the immediate predecessor and immediate follower can be sensed directly by remote sensors on the controlled vehicle. The acceleration/deceleration of these other vehicles cannot be sensed directly, but must be estimated from speed difference measurements, a process that is imperfect and subject to time delay and measurement error/noise problems. The autonomous ACC systems are limited to these data sources.

Communicated data can be received from any other vehicle that is within wireless communication range, providing opportunities to get data from many other vehicles and to get a much richer set of data with less time delay and higher accuracy from the immediate predecessor and follower than the data that can be obtained from the remote sensors. The cumulative time delay and successively amplified sensor detection errors have been effectively avoided. This is what enables the performance improvements associated with V2V CACC. The most basic V2V CACC implementation depends on pairwise sharing of the additional information between a vehicle and its immediate predecessor (all the information in Columns 2 and 3 of the table). In this type of system, a CACC following vehicle can receive an acceleration or braking command within one communication update interval (100 ms) of the time when its predecessor receives that command internally, so that it can start to respond even before the predecessor's speed has changed measurably.

It is also possible to add information from vehicles that are beyond the direct line of sight, to provide higher levels of coordination and information about the traffic situation further upstream along the platoon. 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.

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. The 13 combinations that had been proposed in the literature as

of 1995 were reviewed in some detail in Shladover (1995). It is not necessary to review these in any detail because the large majority of these feedback structures are purely theoretical and have only been designed and evaluated in computer analyses and simulations. 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.

2.3   Specific Information Used as Inputs to Speed Control

Based on classical vehicle dynamics and control, there are several obvious kinds of information needed to produce good vehicle speed control performance. Feedback and feedforward control strategies can be designed based on use of many different combinations of information, depending on what can be measured directly or estimated from the available measurements using state observers such as Kalman filters:

- The vehicle's own speed (best derived from wheel speed sensor data, but this can be augmented using other data sources such as GPS positioning)
- Difference between the vehicle's speed and the speeds of its immediate neighbors (best measured directly using Doppler radar, but may be estimated/filtered from lidar range measurements, which would have higher estimation errors and delays due to numerical differentiation)
- Distance to immediate neighbors (measured using lidar or radar or occasionally using video image processing, with additional possible comparison to differences in GPS position estimates)
- The vehicle's own acceleration (best estimated by filtering wheel speed sensor data, but may also be estimated from onboard inertial sensors)
- Difference between the vehicle's own acceleration and acceleration of its immediate neighbors (may be estimated by filtering Doppler radar range rate measurements, but better estimated by comparison of communicated data).

The following additional information is extremely valuable in stabilizing vehicle following behavior and improving safety, but these data can only be obtained by V2V communication in cooperative systems:

- Speed and acceleration of the first vehicle in a multiple-vehicle platoon
- Speed and acceleration commands issued to all preceding vehicles
- Commands (throttle/brake) issued to all preceding vehicles.
- Desired maneuvers
- Fault conditions on all preceding vehicles
- External hazards detected by any preceding vehicles
- Performance limits of any neighboring vehicles (limits in acceleration, braking capabilities and response delays in particular).

For example, the recent PATH CACC implementation on Infiniti M56 cars used a controller that used the communicated actual and commanded (reference) speeds of both the immediately preceding vehicle and the first vehicle in the stream of CACC vehicles. In this implementation,

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any disturbance to the lead vehicle in the stream is known almost immediately by the following vehicles. In contrast, the CACC controller developed by Jeroen Ploeg of TNO and the Technical University of Eindhoven (Ploeg, 2014) focuses primarily on pairwise cooperative car following control, depending on communication of state information from the immediately preceding vehicle to augment the forward ranging sensor data. The controller is based on use of the measured distance and speed difference between the two vehicles and the commanded acceleration of the preceding vehicle (communicated to the follower, along with other information that is useful for fault detection and identification of the correct vehicle sequence). If the communication link is interrupted, this controller can still estimate the actual acceleration of the preceding vehicle based on filtering the range rate measurements, producing reasonably fault-tolerant results.

Ploeg tested situations in which the commanded acceleration of other vehicles further downstream were communicated, but his work generally depended on the pairwise coupling, which means that each successive vehicle in the string adds a response delay equal to the communication update interval. The controller also included a supervisory layer that can adjust the nominal set speed and time gap values to promote improved traffic flow stability and safety. The controller was also designed to allow for future merge coordination control, and it could decide when to switch to autonomous ACC control to accommodate cut-ins by unequipped vehicles.

Practical deployment of CACC systems will depend on the development of standards to govern the data shared by the vehicles and some degree of harmonization of the control strategies as well. One of the challenges in doing this will be obtaining agreement among manufacturers who take substantially different approaches to controlling the speed of their vehicles.

2.4   How the System Determines the Desired Vehicle Following Distance

There are two fundamental vehicle-following disciplines that are employed by most automatic speed control systems, either constant clearance (or spacing) or constant time gap (or headway). In addition, some studies have suggested a constant-safety-factor criterion, in which the spacing between vehicles is proportional to the square of the speed of the follower.

It is also possible that a vehicle may employ multiple types of vehicle following strategies, depending on the operating situation. As an example, one following strategy may be employed between two consecutive CACC vehicles in a string of CACC vehicles, and a different strategy may be employed between the lead vehicle of one CACC string and the last vehicle of a preceding CACC string.

2.4.1   _Constant Time Gap (CTG)_

Constant-time-gap vehicle following most closely represents the way human drivers normally drive at highway speeds. In this discipline, the distance between vehicles is proportional to their speed, so that a doubling of speed leads to a doubling of the clearance gap between the vehicles. The 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 (xx

seconds of time gap). This is often erroneously described as "headway" or "time headway", but headway actually represents the time between the passage of the front bumpers of both vehicles past the same location on the roadway, introducing an error equivalent to the length of the first vehicle.

Although constant-time-gap following works reasonably well at highway speeds, it is not workable at low speeds, because the gap becomes uncomfortably small (and hence unsafe), unless an offset bias is added. Most commercially available ACC systems follow this discipline.

One intrinsic property of constant-time-gap following that is of particular interest to this project is that the length of a CACC string, for a given number of vehicles, will vary proportional to the speed at which the vehicles are traveling. Thus, the physical space on the roadway that is occupied by a string of CACC vehicles is not constant. At higher speeds, the string of vehicles will occupy more space, and at lower speeds, it will occupy less space. Many studies that have assumed constant-clearance following have not had to account for the speed-dependent length of the vehicle strings. Any assessments of the impacts of CACC on traffic will need to account for this in the simulation model, which we plan to do in this project.

2.4.2   *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 case, the separation between vehicles does not change as the speed changes, and the vehicle occupants experience the sensation of a mechanical linkage between the vehicles. Constant-clearance following is more difficult to achieve than constant-time-gap following, and it can only achieve stability through cooperation using V2V communication, and in particular, with the communication of the behavior of the first vehicle in the sequence (often referred to as the platoon leader). However, when the primary goals are increasing lane throughput and reducing aerodynamic drag by drafting, this discipline offers performance advantages.

Because constant-clearance systems depend on receiving V2V information from the platoon leader, and not just from the immediately preceding vehicle, the constant-clearance method requires a more formal platoon feedback architecture, where special status is granted to the leader which then needs to supply its state information to all of the followers. This requirement suggests that these systems should not be labeled as CACC, but should be classified separately as **tightly-coupled platoons** (or **closely-coupled platoons**). Conversely, since CACC does not require such close coupling, the authors of this report have refrained from referring to a sequence of CACC vehicles as a platoon. Instead, a consecutive sequence of CACC vehicles has been referred to as a **CACC string**.

2.4.3   *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. This was chosen as a way of guaranteeing that even the most severe crash 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 that are used within platoons, 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 them could be avoided. The constant-safety-factor criterion produces an inter-platoon separation proportional to the square of the cruising speed.

3   REVIEW OF PRIOR WORK ON CACC CONCEPTS

Prior work on concepts of operation for Cooperative Adaptive Cruise Control (CACC) systems is limited, and in reviewing the literature, there is an important distinction that must be made between CACC systems and automated vehicle platooning systems. Production ACC and experimental CACC system designs are based on a constant-time-gap following criterion (sometimes loosely referred to as constant-headway), and the constant-time-gap criterion is more closely related to the natural vehicle following behaviors seen when drivers manually perform the task. In contrast, the literature discussing automated vehicle platooning generally refers to a controller based on a constant-clearance criterion (also referred to as a constant-spacing or constant-distance criterion). The constant-clearance criterion results in a tighter coupling between the vehicles in the platoon, and while most automated vehicle platooning demonstrations have utilized such a controller, the control design and stabilization challenges are significantly more difficult for this class of controller as explained by Swaroop, et al. (1994).

This section reviews some of the literature on various European and Japanese automated vehicle projects such as CHAUFFEUR, Energy ITS, SARTRE, the Grand Cooperative Driving Challenge, and several other CACC implementation projects. This review is less focused on the technical achievements within each project; rather, it is focused on the concepts of how the systems might work in regards to platoon formation strategies, incentives to promote platoon formation, infrastructure cooperation, and platoon dissolving strategies. While the operational concepts described in these projects were not the primary focus of the research, each project generally did provide some vision or at least context on which the work was based. However, it should be noted that most of the conceptual assumptions described below were based on projects that were primarily focused on commercial truck platooning in order to achieve gains in fuel efficiency and decreased fuel consumption.

3.1   CHAUFFEUR

The European Commission's CHAUFFEUR and CHAUFFEUR2 projects (Benz, et al., 1996, and Fritz, Bonnet, Schiemenz, and Seeberger, 2004), explored the concept of an electronic tow-bar system to couple trucks together on European roads. In the CHAUFFEUR concept, the lead truck would be driven manually, and the following truck or trucks would then be either partially or fully automated. The project included a technical demonstration, estimates of fuel

consumption reduction (Bonnet and Fritz, 2000), and approaches for estimating the costs and benefits of vehicle automation (Baum, et al., 1999, and Baum and Geissler, 2000).

Although the original CHAUFFEUR work is now almost two decades old, the project interviewed fleet and freight operators, professional drivers, and other industry experts to try to determine how to conceptualize such a system in order to gain broader acceptance. Based on the interviews (Benz, et al., 1996), the fleet operators were unsurprisingly concerned with the investment costs and anticipated benefits such as personnel or fuel savings, but they were also concerned about potential organizational changes (such as alerting competitors to their routes or logistics) that might be required to receive the benefits that would be offered by the tow-bar concept. The fleet operators reported that they would be unwilling to adapt their routes simply to allow for coupling with trucks from another company, and they only considered the concept to be viable on longer routes, where the leading and following trucks could swap in order to keep the drivers within their hours of service requirements.

The professional drivers who were interviewed were primarily concerned about safety, but the drivers also noted that their pay (or bonuses) can be tied not only to the number of trips or the amount of freight transported, but also to fuel consumption. Since fuel savings are highly dependent on vehicle position, it could be inferred that the drivers would also be concerned about fairly allocating the fuel savings benefits between the leading and following trucks.

Finally, as part of the original CHAUFFEUR concept, infrastructure involvement was envisioned as potentially necessary in order to create meeting points to promote the coupling of trucks before entering the freeway. However, the project did not appear to go any further in conceptualizing where or how the coupling would occur. The subsequent CHAUFFEUR2 project (Fritz, Bonnet, Schiemenz, and Seeberger, 2004) still assumed that the lead truck was manually driven, but the project emphasized that minimal infrastructure cooperation was needed, relying primarily on vehicle-to-vehicle communication to enable the platoon coupling and decoupling maneuvers. That project made the distinction between fully-automated truck following at short constant-clearance gaps that would only be done in a dedicated truck lane that was physically segregated from general traffic and a CHAUFFEUR-Assistant that would be operated as a driver assistance system like CACC in public mixed traffic, with longer constant-time gaps.

3.2 ENERGY ITS

In 2008, the Japanese Energy ITS project (Tsugawa, Kato, and Aoki, 2011; Aki, et al., 2012; Hashimoto, et al., 2012; Yamabe, et al., 2012; Tsugawa, 2013; and Sugimachi, et al., 2013) began development for the demonstration of an automated four-truck platoon with the goals of energy savings and global warming prevention through ITS technologies. Although the primary goals of the project were centered around measuring and modeling energy and emissions savings (Tsugawa, Kato, and Aoki, 2011, and Tsugawa, 2013), the vehicle development aspects of the project touched on technical and design considerations (Aki, et al., 2012, and Sugimachi, et al., 2013), acceptable following distances (Hashimoto, et al., 2012), and safety in and driver-vehicle interface needs in the context of coordinated maneuvers such as platoon joining and splitting (Yamabe, et al., 2012).

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A much smaller portion of the project focused on conducting industry outreach. From an infrastructure perspective, the project identified concerns over providing the perceived space requirements necessary to assemble and disassemble a platoon and concerns over how to handle vehicles merging from entrance ramps while long platoons were passing. From the industry perspective, freight operators were initially excited by new technologies, but they did not see an industry need for or benefit from platooning (Tsugawa, Kato, and Aoki, 2011). The next steps toward commercialization were not clear at the conclusion of the research project in 2013 because of concerns about the cost of implementing the high level of automation that was demonstrated, which required redundancy of all major components and subsystems.

3.3   SARTRE

From 2009 to 2012, the European Commission funded the Safe Road Trains for the Environment (SARTRE) project, led by Ricardo UK Ltd. and including six additional partners: Idiada and Robotiker-Tecnalia of Spain, Institut for Kraftfahrwesen Aachen (IKA) of Germany, SP Technical Research Institute of Sweden, the Volvo Car Corporation and Volvo Technology of Sweden (Robinson, Chan, and Coelingh, 2010; Jootel, 2012; and Chan, 2012). While most prior CACC and automated vehicle platooning projects focused on either passenger vehicles or heavy trucks, the SARTRE project explicitly set out to study platooning in the mixed heavy and light vehicle case. The majority of the project focused on technical feasibility using currently available technologies (Chan, et al., 2012; Solyom and Coelingh, 2012; Solyom, Coelingh, and Carlsson, 2012; and Bergenhem, Hedin, and Skarin, 2012), safety, and fuel consumption and emissions (Dávila and Nombela, 2011; Dávila, Freixas, and Aramburu, 2013; and Dávila, 2013a). However, the project also included aspects such as commercial viability and infrastructure, policy, and legal impacts (Dávila, 2012, 2013b).

The overall SARTRE concept was based on the premise that the lead vehicle in the platoon would be a heavy vehicle, either a truck or bus, and driven by a professional driver who has additional training before being qualified as a platoon leader (Bergenhem, Haung, Benmimoun, and Robinson, 2010, and Robinson, Chan, and Coelingh, 2010). The following vehicles in the platoon would then be fully automated, but the drivers of the following vehicles would need to remain available so that they could resume control of their vehicles should the platoon be required to dissolve due to unforeseen circumstances. While platoons could contain a mix of heavy and light vehicles, for safety reasons, heavy vehicles would always occupy positions in the front of the platoon and light vehicles would always occupy positions in the rear of the platoon.

Some of the initial work on the SARTRE concept focused on developing use cases and examining both operational (Robinson, Chan, and Coelingh, 2010) and human-machine interface requirements (Larburu, Sanchez, and Rodriguez, 2010). Early analysis suggested that 15 would be the maximum number of vehicles that could be allow in a platoon and that platoon join and split maneuvers would likely need to be allowed from the front, side, or rear of the platoon. In reading the use cases developed for the SARTRE final report (Jootel, 2012), there were additional assumptions noted that had been made about where platoons could operation, such as being restricted to multi-lane roads. However, later work discussed the potential for incentive strategies if platoons were to utilize managed lanes (Brännström, 2013).

As part of the SARTRE concept, there would be some back-office communication and software that would help coordinate platoons and manage payments between platoon followers and platoon leaders to more evenly allocate the benefits of being in the platoon. Qualified platoon leaders would register their willingness to form a platoon, and the back-office software would assist potential following vehicles in locating the appropriate platoon to join. As described in (Robinson, Chan, and Coelingh, 2010, and Larburu, Sanchez, and Rodriguez, 2010), the process to join a platoon could be semi-automated. Thus, the vehicle might take over speed control first to position the vehicle at the right location in the platoon, but the driver would then need to perform the lane change before the automated steering would take over. However, the concept of how a platoon join maneuver might take place is likely related to earlier automation technology decisions. In the SARTRE implementation, the vehicles had limited lane position sensing capability, and lateral control was basically achieved by following the positioning "breadcrumbs' of the manually driven lead vehicle.

In addition to the technical work on vehicle platooning, the SARTRE project explored various models for commercializing such pay-as-you-go or subscription models, and the work explored concepts on how government agencies could provide incentives to increase the sale of equipped vehicles and compensate for the overhead of finding other equipped vehicles in order to form a platoon (Brännström, 2013). The discussion of incentive strategies included providing benefits such as free access to a carpool lane or free parking to encourage the initial sales of equipped vehicles in order to get a critical number of equipped vehicles out on the road quickly. Unfortunately, the SARTRE business case analysis did not go into further details about exactly how platoons would form, other than the earlier reference to some form of communication and back-office software that would help drivers to find and join platoons.

Finally, the SARTRE project examined the potential impacts that platooning might have on infrastructure requirements through outreach efforts to infrastructure owners and operators (Dávila, 2012). However, it should be pointed out that the SARTRE concept was based on the premise that minimal roadside infrastructure would be required (Robinson, Chan, and Coelingh, 2010), so it is likely that the project was presented to the infrastructure owners and operators with the caveat that very little infrastructure should be needed. After experiencing a SARTRE platooning demonstration, the primary comments from infrastructure owners and operators centered on freeway entrance/exit ramps and length of the acceleration/deceleration lanes. With a five vehicle platoon including two heavy trucks driving in the right lane of a highway, the overall length of the platoon could make it difficult for other vehicles to merge onto the highway without having to cut into the platoon and longer acceleration lanes might alleviate some of the pressure on the merging vehicles. Similarly, longer deceleration lanes could make it easier for exiting vehicles to avoid crossing through a platoon. Safety concerns were also reported, such as the potential need to redesign crash barriers which might not provide protection against multiple, closely spaced strikes, such as could occur with a platoon, and toll plazas were noted as locations where the infrastructure would need to be redesigned to support the higher throughput offered by platoons.

3.4 Grand Cooperative Driving Challenge (GCDC)

In 2011, multiple CACC implementations were built and tested as part of the Grand Cooperative Driving Challenge (GCDC) held in Helmond, Netherlands (van Nune, et al., 2012). The GCDC was an international competition that was inspired by the U.S. DARPA Challenges, and the event was organized by TNO and the High–Tech Automotive Systems program, with sponsorship from the local and regional governments near the competition site. Nine teams comprised of 11 universities and partners participated in the competition. Each team built their own CACC vehicle, and the entries included both cars and trucks, each with their own speed control system. Contestants were judged not only on how well their own vehicle performed, but on how well their vehicle cooperated with the rest of the vehicles in the platoon through V2V communication (Shladover, 2012a, 2012b).

The challenge vehicles were staged through two scenarios, one representing urban traffic conditions, and the other representing highway traffic conditions. In each run of each test scenario, vehicle order was swapped, so that no vehicle had a distinct advantage over another. While the highway challenge scenario was typical of other CACC implementations, the urban challenge scenario was of particular interest to this literature review. The GCDC urban challenge scenario was, effectively, one of the first implementations that demonstrated an I2V CACC system with the coordinated traffic signal start function.

The GCDC urban scenario was presented at two consecutive traffic signals. The objective of the challenge was twofold. First, the downstream platoon of vehicles was waiting at a red traffic signal. Once the signal turned green, the platoon needed to maximize throughput at the signal by communicating and accelerating in a coordinated manner. Second, the upstream platoon, which had gotten a green traffic signal earlier, would be approaching the downstream platoon that was still waiting at the red traffic signal. The event was timed such that the downstream platoon would not have fully accelerated to its cruising speed by the time the upstream platoon reached it. Thus, the upstream platoon needed to join the tail end of the downstream platoon, demonstrating cooperative inter-platoon behavior (van Nune, et al., 2012).

3.5 COMPANION

In 2013, the European Commission announced funding for a three-year truck platooning project, COMPANION, to be led by Scania, a Swedish truck manufacturer, including partners from Volkswagen Group Research, Stockholm's Royal Institute of Technology (KTH), Oldenburger Institut für Informatik (OFFIS) in Germany, IDIADA Automotive Technology in Spain, Science & Corporation (S&T) in the Netherlands, and the Spanish haulage company Transportes Cerezuela. Prior truck platooning research performed in partnership between Scania and KTH examined the potential fuel reduction that might be offered through platooning (Alam, Gattami, and Johansson, 2010) and potential vehicle control issues that might arise from the ordering of trucks within a platoon (Liang, Alam, and Gattami, 2011). The COMPANION project will culminate with a demonstration in Spain in 2016, and of particular interest, this new project will focus on how information can be presented to drivers to facilitate forming platoons. As an example, the system could suggest that the driver either speed up to catch up with a platoon or slow down to join a platoon approaching from behind.

Three papers from previous projects in partnership between KTH and Scania (Larson, Krammer, Liang, and Johansson, 2013; Liang, Mårtensson, and Johansson, 2013; and Larson, Liang, and Johasson, 2014) examined the potential benefits of coordinating vehicle maneuvers to facilitate the platoon formation. Two of the papers (Larson, Krammer, Liang, and Johansson, 2013, and Larson, Liang, and Johasson, 2014) examined the concept in which infrastructure-based controllers would be placed at key points in the road network to minimally adjust the routing and timing of the platoon-enabled vehicles to allow these vehicles to converge and form a platoon. In this concept, some of the adjustments to the vehicle routes were made before the vehicles entered the highway, but platoon-enabled vehicles were also allowed some limited ability to speed up to catch up to other vehicles or platoons. The overall fuel savings using this concept was highly dependent on the market penetration of equipped vehicles, with a maximum achievable savings of around 9 percent, but the study's simulations found that fuel savings on the order of 5 percent could be achieved with just over a thousand platoon-capable vehicles participating in the road network, which covered most of the German Autobahns (Larson, Krammer, Liang, and Johansson, 2013).

In the second paper (Larson, Liang, and Johasson, 2014), the authors expanded on the development of a distributed network of infrastructure controllers for coordinating platoon-capable vehicles, and they examined real-world data on the movements of 7500 trucks over 24 hours to estimate the potential for platooning opportunities. A simulation built on these parameters showed that system wide, up to a 9 percent fuel savings could be gained by coordinating all trucks into platoons before they reached the freeways, rather than having each truck individually take the shortest route to their destination. Based on the real-world data of truck movements and placing a maximum radius of 5 km on the vehicle coordination (i.e., vehicle pairs initially over 5 km apart would not be routed together), a system-wide fuel savings of 1.2 percent was achievable. The authors did not that in some initial discussions with the trucking industry, the industry was skeptical about the notion of individual trucks slowing down to facilitate the formation of platoons.

The last paper (Liang, Mårtensson, and Johansson, 2013) examined the potential benefits of a less route-coordinated approach, where vehicles that were already on the same highway would be given instructions to increase their speed in order to catch up to another equipped vehicle and form a platoon. Although the catch-up vehicle will initially consume more fuel, an overall fuel savings of 7 percent could be achieved based on a 10 km (6 mi) starting distance apart, a speed delta of 10 km/h (6 mph), and an overall trip length of 350 km (217 mi). The nominal lead vehicle and platoon speed was 80 km/h (50 mph), and the overall trip length was limited by European requirements that drivers stop for a break every 4.5 hours. However, the fuel savings calculations were highly sensitive to the vehicle speed assumptions. Still, the results were promising.

3.6   Toyota Fuel-Efficient CACC Research

Researchers from Toyota Motor Corporation in Japan (Shida and Nemoto, 2009, and Shida, et al., 2010), developed and tested short, constant clearance gap, passenger vehicle platoons with a CACC controller that was optimized to maximize fuel efficiency and minimize CO_2 emissions. The experimental work tested a three car platoon at constant spacings between 10 m and 30 m,

demonstrating that the CACC controller attenuated lead vehicle acceleration and deceleration disturbances, rather than amplifying those disturbances. Fuel savings for the following vehicles ranged from 6 to 10 percent as the spacing decreased from 30 m to 10 m. While the published research focused on the development of a constant clearance gap CACC controller, the authors have noted that current development work is focused on a more production-favorable constant-time-gap CACC controller.

3.7   FHWA Office of Safety R&D Project on CACC

A project funded by the Office of Safety Research and Development, FHWA, identified human factors issues research questions related to the development and implementation of CACC systems (Jones and Philips, 2013, and Jones, 2013). The reports analysis included both V2V and I2V CACC concepts, and although the bulk of the report focused on identifying human factors related issues, the reports did provide some description of the CACC concepts that were considered.

The V2V CACC concept focused on freeway driving at shorter time gaps to achieve gains in roadway capacity and throughput. However, specifically mentioned in the report was the possibility of using restricted or managed lane access as a means to incentivize V2V CACC use, allowing those lanes to achieve a higher penetration of CACC vehicle streams than the actual market penetration of these systems at any given point in time. The authors point out that the use of managed lanes may have drawbacks, since these lanes may not already exist in the locations where they would benefit the traffic system the most, and it may be difficult to build or convert general use lanes to managed lanes in the locations where these lanes would do the most to benefit the entire system. Furthermore, there could be potential human factors issues with enforcement of CACC equipped vehicles in managed lanes, since the enforcement officers would have no way of knowing which vehicles would be allowed in that lane. Several potential solutions were proposed including a dynamic external light to indicate that vehicle is CACC equipped and the CACC is actively engaged and the potential to use automated enforcement checkpoints that would monitor a vehicles' DSRC message broadcasts.

The described I2V CACC concept was based on using CACC to improve traffic flow through arterial intersections. By combining I2V broadcasts about the traffic signal state and V2V broadcasts between vehicles, the speed of the CACC stream of vehicles could be optimized when approaching a traffic signal, allowing all of the vehicles in the CACC stream to clear the intersection in the shortest amount of time.

3.8   INFLO Project Concept of Operations

The INFLO Project (Intelligent Network Flow Optimization) is one of the Dynamic Mobility Applications projects under the U.S. DOT Connected Vehicles program. This project includes three applications that are intended to improve highway traffic flow: (1) end-of-queue warning (Q-WARN), (2) dynamic speed harmonization (SPD-HARM), and (3) CACC. In this project, the dynamic speed harmonization application could include an I2V CACC system, since part of the concept allows for I2V communication as a means of lowering the vehicle's set speed in advance of traffic congestion. The CACC application discussed in INFLO more closely

represents the V2V CACC concept. Although all three applications were given equal consideration at the start of the project, later efforts focused on the queue warning and the speed harmonization, rather than CACC.

The INFLO Concept of Operations included a CACC concept primarily applicable to freeway conditions, using V2V communication to enable shorter following time gaps and smooth traffic flow, while improving fuel economy and increasing lane capacity and throughput. As part of the CACC concept of operations development in the INFLO project, stakeholder feedback was gathered. The stakeholder discussions revealed that the perceived benefits of the CACC concept were dependent on how closely tied the CACC system was with the dynamic speed harmonization concept (Mahmassani, Rakha, Hubbard, and Lukasik, 2012a).

Later reports (Mahmassani, Rakha, Hubbard, and Lukasik, 2012b, 2012c) stressed that CACC will need to function in a mixed environment, with both equipped and unequipped vehicles allowing for cut-ins by unequipped vehicles, and the project also identified potential needs for a degraded mode of operation in the event of communication failures. The INFLO CACC concept assumed that CACC would be an opt-in service, and the project categorized CACC as a near-term concept that would utilize either shared managed or even dedicated lanes to form ad-hoc CACC vehicle streams (Mahmassani, Rakha, Hubbard, and Lukasik, 2012c, 2012d). While in the managed lanes, V2V CACC was envisioned as being complimentary to the I2V speed harmonization application. Although individual drivers may control their own gap setting, the maximum speeds of the CACC vehicle streams would be set by the infrastructure to optimize traffic flow and prevent traffic congestion from forming at bottleneck locations.

3.9 Saxton Transportation Operations Laboratory Simulation of Near-Term CACC Operations

The FHWA Saxton Transportation Operations Laboratory (STOL) is responsible for a simulation study that is investigating the impacts that near-term CACC operations could have on traffic. To remain within the near-term time scale and stay within the current comfort zone of the vehicle industry, that project is only considering limited functionality for its CACC evaluation cases:

- Time gaps within the same range as current autonomous ACC systems (not less than 1.0 seconds).
- Pair-wise communication between consecutive equipped vehicles, but not including communication or coordination with vehicles at longer range.

The higher-level coordination issues and more aggressive performance (shorter gaps, coordination within platoons) are not being considered in that project, which limits the overlap in scope between that project and this new project.

4 DEFINING CACC OPERATIONAL CONCEPT ALTERNATIVES

For passenger vehicles, the California PATH studies investigating potential CACC lane capacity improvements have generally assumed an *ad hoc* coupling of equipped vehicles, and the PATH studies have made a distinction between CACC market penetration and DSRC market penetration because a CACC equipped vehicle can take advantage of the system as long as it's following a DSRC equipped vehicle, even if that vehicle does not have the CACC option itself. Thus, if a CACC equipped vehicle was following a DSRC equipped vehicle, then the shorter following gaps offered by the CACC system would be available to the following vehicle. Conversely, if a CACC equipped vehicle was following a vehicle that was not DSRC equipped, then the CACC system would revert to the following gaps that would normally be available to an ACC equipped vehicle. However, 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 (Ferlis, 2008). These topics will be explored in detail in the later portions of this project.

For commercial trucks, there has been considerably more research into the question of how vehicle coupling could occur beyond *ad hoc* coupling, but all of the commercial truck studies have been focused on close-formation platooning, rather than on CACC. Starting with the European Commission's CHAUFFEUR project in the mid 1990s, several truck automation projects have engaged fleet operators, truck drivers, and infrastructure owner/operators to get preliminary feedback on the industry's needs, desires, and willingness to change in order to accommodate various cooperative vehicle following concepts of operations.

The following section discusses the different CACC operational concept alternatives that have been described in the literature or further conceived in this project. The operational concept alternatives discussed include CACC vehicle clustering and string formation strategies (including incentive and support strategies), string dissolution strategies, potential roles for I2V CACC, the connected cruise control as a transitional strategy, and arterial CACC strategies. Each section includes discussion about the relevant or important factors that will need to be modeled in a simulation of that strategy.

4.1 Vehicle Clustering Strategies

One of the most important influences on the performance of cooperative vehicle following systems such as CACC is the effectiveness of the strategies that are used to cluster the vehicles together so that they can take advantage of V2V cooperation. This is particularly important at low market penetrations, where the probability is not high that the equipped vehicles will find each other in an *ad hoc* manner.

4.1.1 *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. For purposes of assessing ad-hoc clustering in simulation, it is necessary to consider the following distinct classes of vehicle:

- Manually driven, with no ACC, CACC, or DSRC technology.

- Manually driven, but equipped with a DSRC Vehicle Awareness Device (VAD) that enables it to act as the leader for following vehicles equipped with CACC.

- Equipped with conventional ACC, but no DSRC radio, so it can do autonomous ACC driving, but not CACC.

- Equipped with ACC and DSRC, so that it is fully capable of CACC operation in either a leading or following role. However, if it is following a vehicle without the DSRC VAD, then it can only do autonomous ACC driving.

Ad hoc vehicle clustering was previously studied in PATH's simulations of a single-lane highway scenario for ACC and CACC. At low market penetrations, the increases in throughput are negligible because the probability of consecutive equipped vehicles is negligible. However, if NHTSA mandates that all new vehicles should at least be equipped with a DSRC VAD, or a healthy market for after-market DSRC systems develops then the market penetration of potential leader vehicles grows rapidly.

Although this scenario was studied previously, it needs to be revisited in the current project for a couple of reasons:

(a) The previous simulation study was for a single lane highway because an adequate lane-changing model was not available to represent the multi-lane scenario.

(b) The autonomous ACC model was unrealistically optimistic about the string stability limitations of autonomous ACC driving. This needs to be updated with the newer models (for both AACC and CACC) that PATH developed based on its experimental data for those systems. The updated model will show serious string stability problems for strings of more than three consecutive AACC vehicles, producing an uncomfortable ride for people in subsequent vehicles. This means that drivers will be deterred from using AACC behind a string of three consecutive other AACC vehicles, so the simulation model will have to exclude that option.

4.1.2   *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 freeway 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 and in the current COMPANION project lead by Scania. However, both of those projects are heavily focused on truck platooning and the resulting gains in fuel efficiency which would offset the increased overhead in the local coordination approach. There are many practical details to consider in determining how this could actually work in practice, and those details need to be defined

explicitly before the effectiveness of the local coordination strategies can be assessed in simulation.

CACC vehicle drivers must expect to benefit from using their CACC systems when clustered with other CACC vehicles, otherwise, they have no incentive to actively seek out other equipped vehicles with which to cluster. Additionally, the first vehicle in the CACC string does not necessarily need to be CACC-capable (it could just have a DSRC VAD), so it is more likely to be a passive participant in the coordination process, unless there is a financial incentive for its driver to collect followers (such incentives are discussed in Section 4.2).

Some of the detailed questions about local coordination strategies that need to be defined and then simulated include:

- Should the coordination strategies include both acceleration and deceleration of vehicles to find "partners", or should either acceleration or deceleration be favored?
    - Are there specific conditions that would tend to favor acceleration or deceleration as the coordination maneuver?

- What limits should be applied to the speed differences and the durations of the speed change maneuvers that vehicles use to connect with other vehicles?

- Is any higher level of coordination needed with the target vehicle to initiate a local coordination maneuver? If one vehicle is expending effort to catch up and connect with another, but the target vehicle is about to reach its destination and exit the highway, then that maneuver will have been a wasted effort and should have been avoided.

- How should the costs and benefits of the active local coordination maneuvers be evaluated when deciding to suggest vehicle couplings? Do the cost and benefit estimates need to consider every vehicle involved in the maneuver to make sure that they will all gain some net benefit?

- Must all drivers "opt in" to forming a cluster with others CACC vehicles, or do only the following CACC vehicles need to "opt in." Additionally, could a manually driven lead vehicle with DSRC lead a CACC stream without the driver being informed or taking any conscious action?

- What rules should apply to mixing vehicle types (light vs. heavy-duty) within CACC clusters?
    - Should CACC clusters with mixed vehicle types be prohibited?
    - Should CACC clusters with mixed vehicle types be permitted if the heavy vehicles are at the front, as was done in the SARTRE project?

- How should the limits on length of vehicle clusters be defined? Criteria other than the V2V communication range need to be considered, because range alone could produce excessively long clusters.
    - Should clusters be limited to specific numbers of vehicles or specific distances?
    - Should cluster length limits be fixed under all conditions or adjusted based on traffic conditions?

- o How should cluster length limits be adapted to suit different kinds of environments? (E.g., an urban highway with closely-spaced interchanges and frequent entering and exiting traffic may require different limits than intercity highways with less frequent interchanges and vehicle arrivals and departures.)

- Can the local coordination be accomplished entirely on a peer-to-peer communication basis, or will it require some local infrastructure intelligence as well? If the latter, who is going to provide the back-end communication and server for local coordination? At low market penetrations, the communication requirements for local coordination will exceed the range of DSRC alone, and additional V2I DSRC or cellular communication will be required. Both of these options will require some back-office server to identify, track, and recognize potential coupling opportunities among the equipped vehicles. Furthermore, the back-office could be either publicly or privately owned and operated.

Perhaps the biggest challenge to local coordination is determining how the vehicle driver will know which of the vehicles ahead of him or her is the correct target with which CACC coupling can be initiated. 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 may not be so simple to convey that information to a driver in an easily understood way, especially without producing excessive distraction. Possible concepts for accomplishing this include the following:

- The system could provide a top-view schematic display of the local traffic in the instrument panel or on a head-up display, continuously showing the driver the relative position of their own vehicle and the target vehicle as a maneuvering aid. Unfortunately, this solution would be visually intensive and raises concerns about the potential for distraction.

- The system could provide the driver with a more simplified display indicating whether the target vehicle is in the same lane or a lane to the left or right of the current lane, as well as its distance ahead of or behind the current vehicle position. This concept is challenging because of the difficulty of identifying the lane number on highways, especially where lanes are added and dropped at multiple locations, introducing potential confusion about which is the correct lane.

- The system could provide step-by-step guidance instructions to the driver, advising him or her (1) when to accelerate or decelerate and (2) when to change lanes to the left or right to get behind and couple with the target vehicle. This concept raises safety concerns related to the potential interference that can be caused by unequipped vehicles in the local area. The system might instruct the driver to change lanes to get behind an equipped vehicle, but the system may have no idea that there is an unequipped vehicle tailgating the target vehicle. Unsafe maneuvers could result if the driver slavishly follows the recommended guidance without checking for the presence of unequipped vehicles.

- The system could provide the driver with details describing the appearance of the target vehicle to aid in finding that vehicle in traffic (e.g., you are looking for a blue Toyota Prius

approaching from behind in the left lane). The appearance could be described in terms of vehicle color, make and model, and/or license plate number, but each of these descriptors has problems. The color, make, and model may not be recognizable to many drivers, especially at night, in poor lighting, or when the vehicle is approaching from behind. Broadcasting the license plate numbers does not seem promising, aside from serious privacy concerns, simply because these cannot be read by most drivers unless they are already following the vehicle at a very short distance.

- The system could illuminate an external light on the vehicle(s) that are communicating. The light could be illuminated continuously on any DSRC equipped vehicle (supporting *ad-hoc* coupling), or the light could be configured to only illuminate on the last vehicle in the string of CACC vehicles to indicate that coupling with that vehicle is possible. Although this concept is appealing from the technical perspective, our interactions with the California Highway Patrol regarding the possibility of such external illumination on automated vehicles indicated that there are likely to be legal problems. The external illumination is strictly regulated and different colors of lighting have different significance for law enforcement in different states, so they strongly recommend against special external illumination.

The concepts and issues discussed above need to be developed further in the next stage of this project to determine the best way of promoting vehicle coupling. Fortunately, determining the specifics of how coupling would occur is not on the critical path for developing the simulations of traffic impacts because the traffic impacts should be unaffected by the specific method used to get the vehicles into the correct relative alignment.

4.1.3 *Global Coordination*

Global coordination involves advance planning to coordinate vehicles traveling from similar origins to similar destinations before the vehicles get on the highway. Vehicle routes and speeds may be adjusted to time their arrivals to the highway entry points so that they are able to couple themselves together right from the start. This concept poses a significant logistical challenge, especially given the uncertainties in traffic conditions and the time that it will take each vehicle 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 in terms of 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.

The 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 whether the vehicles will enter the highway individually and then be coupled "on the fly" similarly to the local coordination case:

(a) Grouping at the entrance ramp requires an extra lane or parking lot for the vehicles to gather before entering the highway. If any vehicles traveling in the same direction can be clustered

together, space is only needed for two separate queues (one for each direction). However, if the vehicles need to be grouped by destination, the number of queues (and queuing locations) would have to correspond to the number of distinct destinations to be served. This could potentially be much more burdensome in terms of space required and waiting time needed to accumulate the vehicles before departure. It is hard to imagine that the incremental benefits of CACC driving would be sufficient to justify waits of more than 5 to 10 minutes unless the trips are very long or the fuel savings really significant, but this can be evaluated in simulations of representative conditions.

(b) If the vehicles are to be grouped "on the fly", then there is no queuing at entrances, but the vehicles will need to find each other once they have merged onto the highway. The "on the fly" concept is not necessarily easy given the uncertainties in arrival times and traffic conditions, even with the benefit of pre-trip coordination. The likelihood of successful grouping "on the fly" can be evaluated in simulations for a range of traffic conditions and uncertainties in arrival times at the highway entrances. Additionally, the problem of finding the correct "other" vehicle to couple with on the highway that was already explained in Section 4.1.2 also applies here.

An implementation of the global coordination concept has been evaluated in simulation by researchers from Scania for a trucking scenario using the German Autobahn network. The results of that study are specific to the constraints of that network, the truck scheduling and traffic patterns, and the European laws on truck driver hours of service requirements, so it is hard to know exactly how transferable the results would be to the U.S. trucking environment.

Some of the issues that need to be evaluated in simulations in this project regarding the global coordination schemes include the following:

- How much does each global coordination scheme increase the probability that vehicles can find CACC partners for their trips, compared to local coordination or ad-hoc, as a function of market penetration?

- How long a wait is likely to be needed to provide a high probability of success in connecting with a CACC partner vehicle for each variation of the global coordination concept?

- How does the incremental cost of the added wait compare with the fuel savings from CACC driving, and where are the cross-over points that define the ratios between acceptable wait time and total trip time?

- What is the trade-off between the added cost of building queuing locations at the on-ramp and the reduced uncertainty in the ability of the vehicles to connect with their CACC peers?

- How much additional complexity is introduced if the vehicles need to be grouped in a specific sequence, such as basing the order on vehicle performance or mass? This type of ordering may become important when dealing with trucks that have vastly different performance characteristics.

4.1.4   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. While this issue only becomes a practical problem once the market penetration of equipped vehicles reaches a sufficiently large fraction, nevertheless, CACC string length limitations need consideration. One upper limit that could be placed on length is based on the range of the wireless V2V communication system, assuming that 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. Rather, the string length will need to be limited based on other considerations, such as traffic flow, to allow sufficiently frequent and large enough gaps to facilitate lane change maneuvers around the CACC strings.

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 string length should not be limited by stability considerations. However, for the CACC systems that couple pairwise, relaying communication between consecutive vehicles, there may be a string length threshold above which the performance loses stability. Simulations will be needed to determine how much the hop-to-hop communication delay from each vehicle pair to the next diminishes the string stability and to determine if string stability will dictate a maximum number of vehicles that can couple pairwise in a CACC string.

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 may block a lane. Sufficient gaps between CACC strings will also be essential for accommodating vehicles that are entering or exiting the highway, especially in the immediate vicinity of on and off ramps where those lane change maneuvers become urgent. Traffic simulations need to be conducted for a variety of traffic densities and lane-changing percentages to determine which conditions provide the maximum throughput. With minimal lane changing, the longest strings of CACC vehicles will maximize throughput, but as the lane changing becomes more frequent, more space will have to be allocated for the large gaps between CACC strings, allowing lane changing to be accomplished more easily without cutting through and breaking up a string of coupled CACC vehicles.

Finally, if heavy and light vehicles are allowed to coexist within the same CACC string, there could be additional considerations governing the maximum length of these strings. Limits could be placed on the total number of vehicles in the string, the total length of the string (trucks will be much longer than passenger cars), or on the total number of vehicles allowed from each vehicle class (light duty vs. heavy duty vehicles). 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 may pose 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.

4.1.5 *Clustering 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 facilities for vehicles to await the arrival of their peers. The relative costs and benefits need to be assessed for several traffic scenarios, with different diversity of destinations, market penetrations, travel speeds and categories of vehicles, to identify when this may be beneficial.

4.2 Incentive Strategies to Promote CACC Clustering

In the early days of CACC implementation, 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. Not all vehicles and drivers will benefit equally from being coupled together using CACC. In particular, the driver of the first vehicle in the string does not gain the benefit of a shorter gap to deter cut-ins or a crisper response to maneuvers by preceding vehicles, nor does that vehicle stand to save as much energy from aerodynamic drag as the followers. This means that it would be useful to consider transfer payments from the following vehicles to the leading vehicle as an incentive for that vehicle/driver to act as the leader. The V2V communication system could be the mechanism for implementing this through electronic payments (analogous to electronic toll collection transactions). The open question revolves around the 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. Experiments need to be conducted with CACC test vehicles at a variety of speeds, gap settings and string lengths to determine the level of aerodynamic drag savings that can be achieved at reduced CACC gaps compared to conventional ACC gaps, to help quantify the energy savings. The driver preferences regarding other benefits or disbenefits will have to be determined based on human factors experiments with test drivers from the general public. If a payment scheme is to be implemented, it will be necessary to define clearly when the CACC mode of operation starts and ends so that the payments can be made proportional to the time or distance in CACC operations.

In addition to compensating for the different benefits provided by using CACC in different string positions, it will be more important to offer incentives that increase the concentration of CACC and DSRC equipped vehicles to promote clustering and ultimately, coupling of equipped vehicles in the same lane. Some potential incentive strategies to accomplish this goal are discussed in the subsequent sections.

4.2.1   HOT Lane Usage

The best current example of special-purpose lanes that could serve as an analogy for CACC-friendly lanes is the HOT lanes (high occupancy-toll lanes). In many urban areas, the HOV lanes have been traditionally 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 lane provided that they pay a toll. The HOT lane strategy results in higher throughput for the highway as a whole, while generating revenue as well.

One incentive strategy is to allow access to the HOT lanes to be extended to CACC-equipped vehicles and vehicles with DSRC VADs (that could serve as the lead vehicles for CACC followers). A financial incentive could be offered to them through a reduced toll, based on the fact that CACC enables the lane to accommodate a higher traffic throughput. The traffic simulations by PATH (Su et.al 2011) showed that CACC at 100% market penetration could nearly double the capacity of a highway lane. Based on this, one can argue that the CACC vehicles and their leaders occupy half as much of the lane space as conventionally driven vehicles, so they should only pay half the toll.

Several aspects of the HOT lane access incentive scenario will need to be developed more completely and evaluated in simulation:

- Does the impact of the incentive strategy depend on whether the HOT lane access is continuously available, as it is for the HOT lanes in the San Francisco Bay Area, versus roadway designs where access is only available at specific weaving sections every few miles, as is more typical in the Los Angeles area? The HOT lane design has traffic flow and safety implications, especially as the volumes of entering and exiting vehicles increase. Continuous access has been shown to provide higher safety because merging conflicts are not as tightly concentrated (Jang et.al., 2009). Continuous access should also be less disruptive to traffic in the general-purpose lanes for the same reason (Du et.al. 2013), and continuous access would facilitate local coordination to promote vehicle coupling. HOT lanes with fixed access points (and a single lane) will be more constrained in coupling of equipped vehicles because the vehicles would need to be in the correct order and coupled before reaching the HOT lane entrance. Both alternatives will need to be simulated to estimate their effects on traffic flow.

- Are trucks allowed in the HOT lanes, or is this a light vehicle only strategy?

- Should the same incentives be offered to vehicles with the full CACC capability and vehicles that only have the DSRC VAD, or should the VAD vehicles receive less of an incentive? What if the DSRC VAD was a prerequisite to HOT lane access for all vehicles (currently, an electronic toll tag is a prerequisite for HOT lane access)?

- The HOT lane will generally be moving faster than the general purpose lanes due to the traffic congestion in those lanes, so the CACC strings in the HOT lane will be passing the equipped vehicles that are waiting to merge into the HOT lane at a reduced price. How would additional vehicles join a CACC string? Using local coordination, could equipped vehicle drivers be prompted to change lanes into the HOT lane in front of or behind a current CACC string? If the HOT lane is moving quickly relative to the general purpose lanes, and unequipped vehicles are following the CACC string, it may be difficult for a vehicle to merge

into the HOT lane behind the CACC string without causing a safety hazard. Alternatively, the CACC string could slow down to allow a new leader to merge into the HOT lane in front of the CACC string. Are there other scenarios that need to be identified and simulated?

- Should we always assume the HOT lane to be the left-most lane of the highway, or are there advantages to considering other lanes? The left-most lane has the least potential interference from the entering and exiting traffic in the right-most lane, and also has the possibility of its own separate left-side entrance and exit ramps where appropriate. However, in the absence of such special ramps, the vehicles that travel in the left-most lane also need to make more lane changes during their trip than they would if they were using a different lane closer to the access and egress ramps.

4.2.2   *Entrance Ramp Meter Queuing Lanes*

Analogous to the current system of preferential access for HOVs 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 cluster onto the roadway all at once. However, once these vehicles get on the roadway, there's no real guarantee that their drivers will all chose the same lane or even be able to stay behind each other when merging onto the highway. To work, this strategy may need to be implemented on an entrance ramp that goes directly onto 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.

4.3   Support Strategies For Vehicle Clustering

4.3.1   *Queuing Areas for Vehicle Clustering*

This strategy was mentioned as a possibility in CHAUFFEUR, and may well be necessary for the global coordination strategy that was proposed by the researchers at Scania in the COMPANION project. Attempting to time the arrival of several trucks via surface streets to a highway entrance ramp could be difficult given the surface street traffic variability. It may only be possible to time the arrivals with an accuracy in the range of 5-10 minutes. In free-flow traffic conditions at full highway speed, a 5-10 minute differential would probably result in too much distance between vehicles (5 to 10 miles) to make the eventual fuel efficiency gains worth the expenditure of energy needed to close the 5 to 10 mile gap between vehicles by accelerating the second vehicle.. The downside of the queuing area concept is of course the challenge of finding space near the entrance ramps and the cost of constructing the queuing areas.

This strategy could be combined with the entrance ramp metering light incentive or the HOT lane incentive. If the HOT lane has discrete entrance points, consists of a single lane, and a vehicle only gets the toll reduction if it is already coupled with others, then it could be worth waiting a few minutes to find other vehicles to link with before getting on the highway. However, limiting the toll reduction to vehicles that are already electronically coupled is likely to be an undesirable limitation on the discount and could act as a deterrent to potential customers.

4.3.2 Additional Vehicle Clustering Support Strategies

Since affordable GPS units can't guarantee lane-level positioning accuracy, there may need to be some support, either infrastructure or vehicle-based, to make sure that equipped vehicles are able to efficiently cluster with each other. If a CACC vehicle starts to follow an unequipped vehicle (unequipped with DSRC), then the CACC vehicle must revert to a longer following distance and an ACC controller.

One of the main technical challenges is getting the vehicles to know, in real time, which lane they are occupying on a multi-lane highway, so that they can communicate the lane number to other vehicles, ensuring that they are electronically coupled only with other vehicles in the same lane, and not with vehicles in other lanes. 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. There are not yet any low-cost and robust means for positively identifying lane number, but the possibilities include the following:

- Infrastructure lane identification could include some form of unique lane markings that would allow a visual system to identify in what lane the vehicle is travelling.

- 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 (getting around any 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 could be a possible strategy. The strategy would depend on the driver to visually confirm 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, driver actions will be required to couple with other vehicles, such as speed reductions/increases or lane changes. In the local and global coordination strategies, drivers will need to take some specific actions to couple with other vehicles. The coordination will need to tell some drivers to speed up or slow down in order to allow all the enabled vehicles to connect. Additionally, there could be lane changes required, and the system will have 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 (for example, not being able to detect an unequipped vehicle that is going to get in the way of a safe lane change). Speed changes could be done similar to VSL or I2V CACC, whereby the coordination sets the CACC set speed automatically, but lane changes will need to be done manually. For the automatic adjustment of vehicle speeds, the system will still need to interact with the driver to explain why the speed has been adjusted so that this is not disconcerting.

4.4 CACC Vehicle 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. 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 between them. The following should be considered in development of vehicle string dissolution strategies:

(a) When a vehicle in a CACC string approaches its destination and needs to leave, the most efficient action is for the driver to do a simple lane change in the direction of the off-ramp. As soon as that vehicle has left its lane, it will no longer be coupled to the other vehicles in its original lane, although it could still couple behind an equipped vehicle in its new lane. The vehicle that was behind it in the original lane can then simply close the gap to its new preceding vehicle, closing up the gap in the middle of the CACC string. In this way, the length of the string does not need to increase, rather it will actually shorten.

(b) Depending on local traffic conditions and, in particular, if the CACC strings are longer than ideal for the current traffic conditions, the local traffic management system could recommend that the gap left by the departing vehicle not be filled. The vehicle that was behind the departing one could become the leader of a second, shorter string comprised of the additional CACC vehicles that were originally following it. The inter-CACC-string gap would then be at least the length of an ACC gap, or it could be made longer if it serves traffic management purposes well.

(c) If the driver of the departing vehicle is not comfortable with making the lane change while still under CACC control, s/he could de-activate the (C)ACC function by tapping on the brakes before doing the lane change. 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 behind it. Once the departing vehicle completes the lane change, the vehicle that was behind it now becomes the leader of the CACC string that was split off by the departing vehicle.

(d) If several consecutive vehicles within a CACC string are leaving 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. While this strategy would make the most effective use of the available road space and would minimize longitudinal traffic disturbances, 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 they would then have to manually execute the lane change in very close coordination, which is not easy to do unless they have sophisticated lateral guidance assistance.

(e) 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 may 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).

This is particularly going to be needed if drivers feel the need to step on the brakes before they do a lane change, because that causes each vehicle to occupy more space than it would while remaining under CACC control. For example, if 10 consecutive CACC vehicles are driving at a 0.6 s time gap (18 m clearance) at 30 m/s speed (67 mph) and each vehicle is 5 m long, that string of CACC vehicles occupies 5 x 10 + 18 x 9 = 212 m. If those drivers want to follow at a 1.0 s time gap (30 m clearance) under manual control, the same string of vehicles now needs to occupy 5 x 10 + 30 x 9 = 320 m. Under congested traffic conditions, the additional 108 m of length for this vehicle string may not be available, but even if it is available, the last vehicle in the string will have to decelerate significantly to increase its distance behind the leader. Allowing an average of 10 seconds for this maneuver to be completed would require the tenth vehicle to slow down to 8.4 m/s (about 19 mph) within the 10 seconds, for an average deceleration rate of 2.16 m/s/s (about 0.2 g), which would represent a substantial disturbance for the following traffic.

4.5   Infrastructure-To-Vehicle (I2V) CACC Concepts

Although I2V CACC is one of the major categories of CACC, it is not the primary focus of this project. That concept is being addressed in the STOL Laboratory Speed Harmonization project, in which recommended speed limits are communicated to the test vehicles' I2V CACC systems, with the set speeds selected to maximize bottleneck throughput based on traffic condition data measured along the congested region upstream of the bottleneck. The underlying theory of variable speed limits (VSL) and variable speed advisories (VSA) has been studied extensively in other projects, especially in several European countries and Australia, but in most cases that has been based on display of the set speed values to the drivers (on roadway-mounted changeable message signs or on in-vehicle displays provided with I2V data), with the drivers actually choosing the speed of travel.

Extension of the I2V CACC beyond adjusting the set speed, to include adjusting the vehicle following-gap setting, is a newer idea that is currently being explored in the Netherlands. This has the potential to further contribute to traffic flow stability and throughput if it can be applied correctly, but there are safety and driver acceptance concerns about commanding a time gap setting shorter than the setting chosen by the driver. For these reasons, it will probably be necessary to limit the I2V modifications to increasing the gap setting beyond the setting chosen by the driver. This concept will be evaluated in simulation in this project to determine the extent to which it may be able to improve traffic flow.

4.6   Connected Cruise Control as a Transitional Strategy

Since adaptive cruise control is still a relatively rare option on vehicles in the U.S. and its cost has not yet declined because of expensive ranging sensors, it is worth considering intermediate developments that can pave the way toward ACC and CACC on a wider range of vehicles at lower cost. This has been considered in the Netherlands in the Connected Cruise Control (CCC) development work. The CCC system uses an in-vehicle system as well as a traffic center. The system is aimed at the improvement of traffic flow efficiency without negatively affecting traffic safety. The system is advisory to the driver rather than implementing vehicle control actions directly.

The in-car devices provide floating-car (probe) data to the traffic management center, which also has access to inductive loop detector data. Both data sources are used for traffic state prediction. From the predicted traffic state, the advice algorithm generates an advice which is send to the in-car device and communicated to the driver through an HMI.

The advice is provided upstream in order for the drivers to respond to situations they are not able to perceive themselves at that stage. This effectively extends their response range beyond the line of sight to between 1 and 2 kilometers downstream, allowing the driver to perform strategic maneuvers.

The system performs an update every minute. As the systems aims at providing advice in case of crucial situations, the information density is relatively low. Currently, the system provides the driver with the following advice:

- Change lanes to left or right, keep lane
- Drive at provided speed
- Adapt speed to the left / right hand lane
- Yield for merging traffic from left / right hand lane
- Maintain a short but safe headway

The first two types of advice are quantitative, while the other three have a more qualitative nature. With regard to the headway advice, a qualitative advice was preferred as research has shown that drivers are not able to maintain a quantitative headway.

As was mentioned before the system makes use of traffic state prediction. In the context of the traffic state prediction, the extended generalized Treiber-Helbing filter is used as this is an efficient filter capable of short-term prediction and real-time use.

The advice algorithm provides advice based on the traffic state prediction. The algorithm consists of four different steps, namely:

1. Infrastructural properties: infrastructural properties are assigned to different cells, such as 'end lane', 'end section' and 'split section.'

2. Advice principles: in this step different advice principles are used to independently generate advice regions. (e.g., acceleration advice principle, distribution advice principle, spillback advice principle). The advice is triggered based on characteristics of the traffic state, such as high or low speeds.

3. Advice filtering: this step entails the filtering of the different advice regions, as these may overlap. In this context use is made of simple prioritizing.

4. User selection: in this step users are assigned to the different advices.

4.7 CACC in the Signalized Arterial Traffic Environment

The signalized arterial environment is so different from the limited-access highway environment that it is necessary to think about CACC in significantly different terms. The most important differences between the arterial and highway environments that affect possible CACC usage include the following:

- Arterials have much lower speeds with more stop-and-go maneuvers, so aerodynamic drag savings from drafting are no longer a serious consideration.
- Generally, vehicles travelling on arterials do so in much shorter trips, with very limited steady-state cruising, making the smoothness of the vehicle-following dynamics less important to overall traffic flow.
- Arterials generally have fewer lanes traveling in each direction, especially after accounting for turning lanes, making it much more difficult to designate any specific lane for CACC preferential access as a means of concentrating the CACC vehicles in a preferred lane.
- The traffic signals are the dominant influence on arterial traffic flow dynamics and capacity.

Considering the differences described above, I2V CACC will be more important on arterials than V2V CACC, whereas V2V CACC will be more important for limited-access highways. Because of the potential safety benefits from I2V intersection collision avoidance applications, public agencies will be motivated to deploy DSRC RSEs at major signalized intersections, and these could easily become the mechanism for distributing I2V CACC messages.

4.7.1 _Infrastructure-to-Vehicle (I2V) CACC at Signalized Intersections_

The DSRC RSEs at the intersections will at least be broadcasting signal phase and timing (SPaT) messages at intervals of 100 ms. The SPaT messages can be used to support three types of I2V CACC applications: coordinated start after a signal change, eco-driving, and intelligent traffic signal control.

4.7.1.1 Coordinated Start when the Signal Phase Changes from Red to Green.

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 driver ahead of him or her. However, the coordinated start only works when consecutive vehicles can form a CACC string. Any unequipped vehicle drivers will remain unaware of the SPaT information, and they will only be able to start accelerating after they see the preceding vehicle accelerating. Since the start-up delays at signals are a substantial constraint on intersection capacity today, this has the potential to significantly increase the throughput of equipped intersections once the CACC vehicle market penetration grows past a critical level.

Some additional research will be needed to produce realistic input values for simulations to estimate the traffic impacts of this application. In particular, experiments with a set of I2V CACC vehicles are needed to show how quickly the start-up can be done using real vehicles. This could be implemented using the CACC test vehicles and smart intersection of the STOL Laboratory at FHWA – TFHRC.

The benefits of the coordinated start I2V CACC application can be estimated based on studies of a single signalized intersection, but there are additional potential benefits to be gained when the coordinated start is implemented in a corridor with consecutive equipped intersections. The specific corridor applications and benefits are reserved for discussion in the subsequent sections of this report. For the single intersection, the throughput needs to be evaluated compared to a conventional baseline case as a function of market penetration of CACC vehicles and as a function of the length of the green phase. It is natural to expect the largest advantages for the shortest green phases (when the start-up transient is a substantial fraction of the total phase duration), and indeed, this form of I2V CACC, when available at high market penetration rates, could eventually enable municipalities to obtain higher intersection throughput with shorter signal cycles, reducing delay times substantially. Its effectiveness at low market penetration rates is likely to be limited because of the difficulty of clustering the equipped vehicles in the same lane.

4.7.1.2 Eco-Driving Along a Signalized Corridor

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, but that scenario is focused more on providing advice to the driver about the speed that s/he should travel under the assumption that the driver is controlling the vehicle speed continuously. However, applying that speed control through the I2V CACC can make it a lot more accurate and can significantly relieve driver workload and distraction. The effectiveness of this scenario will depend heavily on market penetration, since unequipped vehicles would not be able to receive the eco-driving speed advice and would not know what speed profile they should be following to save energy.

This application is somewhat beyond the originally anticipated scope for this project, so it is not clear how much attention it will be possible to devote to it during the remainder of the project. Studying it in simulation will require a signalized corridor simulation case study with multiple consecutive signalized intersections.

4.7.1.3 Multi-Modal Intelligent Traffic Signal System (MMITSS) Applications Enhanced by I2V CACC

The Multi-Modal Intelligent Traffic Signal System (MMITSS) project is developing a family of intersection signal control applications based on connected vehicle technology. The emphasis in MMITSS is on use of connected vehicle data (mainly communicated V2I rather than I2V) to influence the traffic signal control for several applications:

- General intelligent traffic signal control (ISIG) to improve efficiency, throughput, energy and environment
- Pedestrian crossing enhancements to support the needs of impaired pedestrians who need longer crossing times
- Signal priority provided at multiple levels for emergency, transit, and freight vehicles.

The connection between MMITSS and I2V CACC is in 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 the ISIG applications, where the I2V CACC can support the energy and environmental goals already mentioned in Section 4.7.1.2, but also the traffic flow efficiency and throughput goals can be supported by making most effective use of the available green time. When I2V CACC reaches a high market penetration, the ISIG control strategies can be refined based on assumptions about more consistent vehicle responses to the traffic signals. In the meantime, MMITSS may be able to support I2V CACC by making small adjustments to the signal timing to ensure that CACC strings are not broken by signal phase changes, allowing all of the vehicles in the string to pass through the intersection before changing the phase to red.

4.7.2 *Vehicle-to-Vehicle (V2V) CACC at Signalized Intersections*

The only significant benefit of V2V CACC in the signalized intersection environment is likely to be related to the coordinated start of vehicles that have been stopped at a signal that is changing from red to green. In this case, even if the signal is not equipped to broadcast its signal phase and timing data as an I2V message, the first equipped vehicle in the queue can broadcast its state information so that any equipped vehicles following behind can accelerate in a synchronized fashion. As with the other V2V CACC applications, this will depend on having a continuous

string of CACC vehicles. Any unequipped vehicles in the middle break the string. At a high market penetration, the V2V CACC should enable a much quicker clearance of the queue at the signal, comparable to the queue clearance with the I2V CACC at the signal, increasing the intersection throughput or facilitating the selection of shorter signal cycles without sacrificing throughput.

5   SIMULATION ENVIRONMENTS FOR EVALUATION OF CACC

The evaluations of CACC performance and impacts need to be done for a variety of operating environments so that the effects of differences in the operating environments can be understood. Three basic simulation environments have been identified at this stage to represent substantially distinct types of operations:

- Urban freeway with closely-spaced interchanges and normally heavy traffic
- Intercity (rural) freeway with widely-spaced interchanges and normally lighter traffic
- Urban corridor with signalized intersections

Networks have already been created for two of these environments in previous projects, representing specific locations in California, while the third (the rural freeway) needs to be created for use in this project.

The urban freeway corridor can be used to represent a variety of high-density traffic scenarios, and since the chosen urban freeway already has and HOV lane, this can easily be turned into an HOT lane for simulation studies. The intercity freeway corridor can be used to represent the lower-density traffic scenarios, including longer trip lengths and less maneuvering (lane changing) to accommodate entering and exiting traffic flows. This could also emulate the operations of an urban express lane with only limited access points. The urban corridor is needed to represent the effects at signalized intersections, especially for the eco-driving applications and for estimating the potential to increase throughput by reducing start-up delays.

5.1   Urban Freeway at High Density (California SR-99 south of Sacramento)

A microscopic freeway traffic model for California SR-99 NB between Elk Grove and the intersection with SR-50 (about 13 miles long) in Sacramento, CA, has been built and preliminarily calibrated (Lu, Chen, and Shladover, 2014).
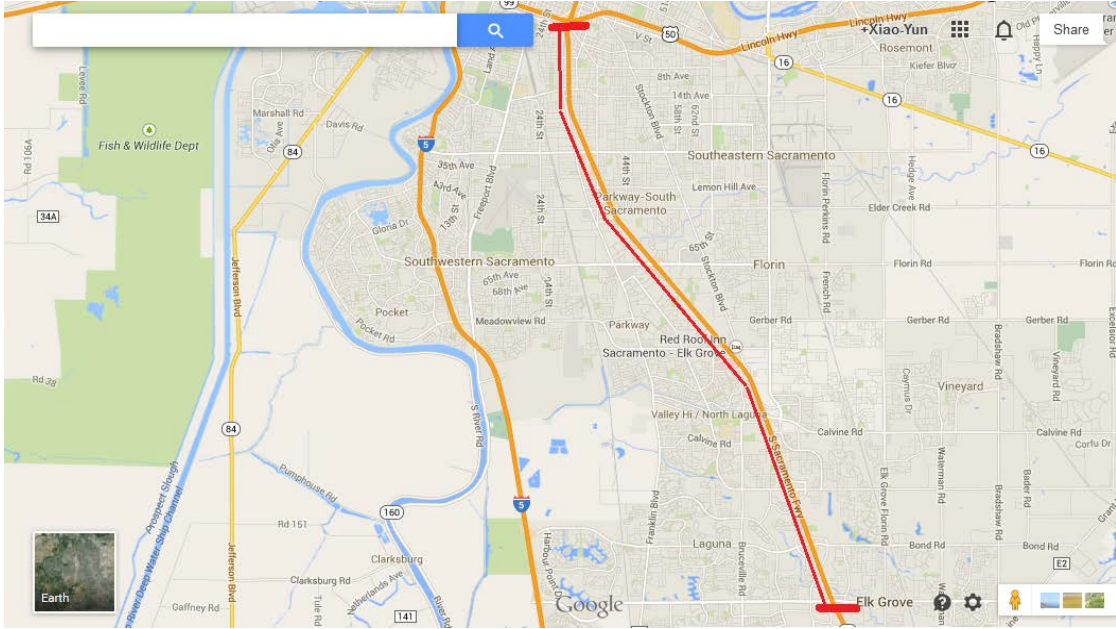
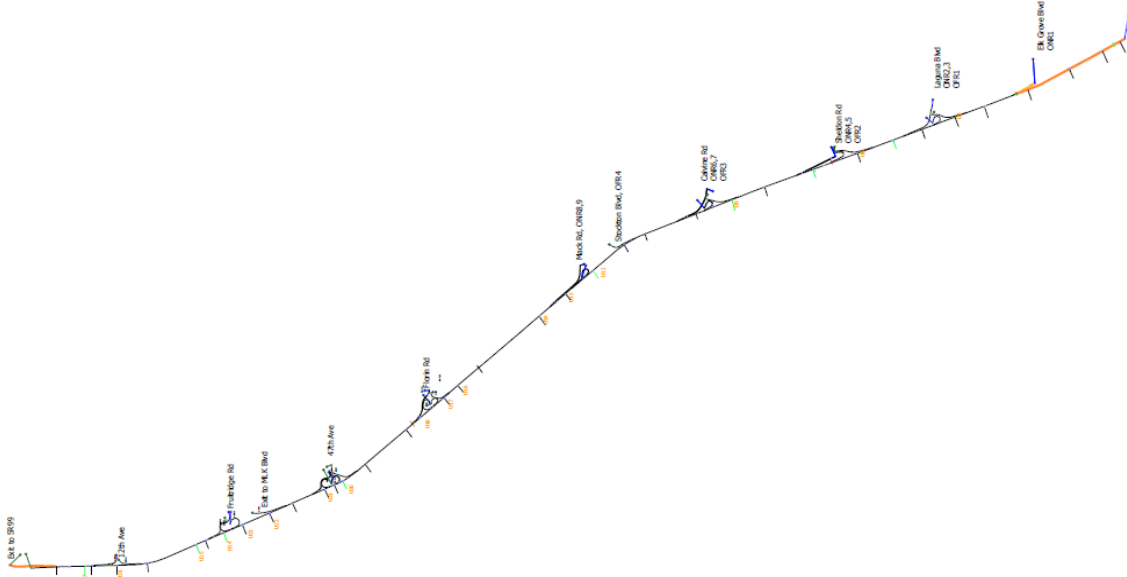Figure 5.1. Road geometry of SR-99 (between two red bars).

Figure 5.2. Aimsun network model of SR-99.

This freeway corridor has the following characteristics:

- One HOV lane
- The maximum and minimum number of mainline lanes are 5 and 2
- 16 onramps, and most onramps with more than one lane have an HOV bypass lane
- Onramp geometries are representative in geometry and number of lanes (maximum 3)

- Two bottlenecks in AM peak traffic, which sometimes combine into one, therefore causes significant congestion
- 12 off-ramps
- Demands from some onramps are very high and therefore have significant impacts on mainline traffic

This model could be used for CACC simulation as an urban freeway network model.

5.2   Rural Freeway Network

This network has not been created yet, but a good candidate site for this scenario is California SR-99 between Modesto and Merced, in the agricultural Central Valley of California. This freeway has three lanes of traffic in each direction for 30 miles and two lanes in each direction for 8 miles, with interchanges to local rural roads, handling relatively small volumes of entering and exiting traffic, at an average spacing of about 2 miles. The majority of the traffic volume is long-distance mainline traffic, so that it displays a distinctly different pattern of traffic from the urban section of SR-99 described in Section 5.1.

This network will be useful for simulating CACC usage under lighter traffic volumes and in traffic patterns dominated by through traffic, with very low volumes of entering and exiting traffic at the interchanges, making a distinct contrast with the urban freeway scenario.
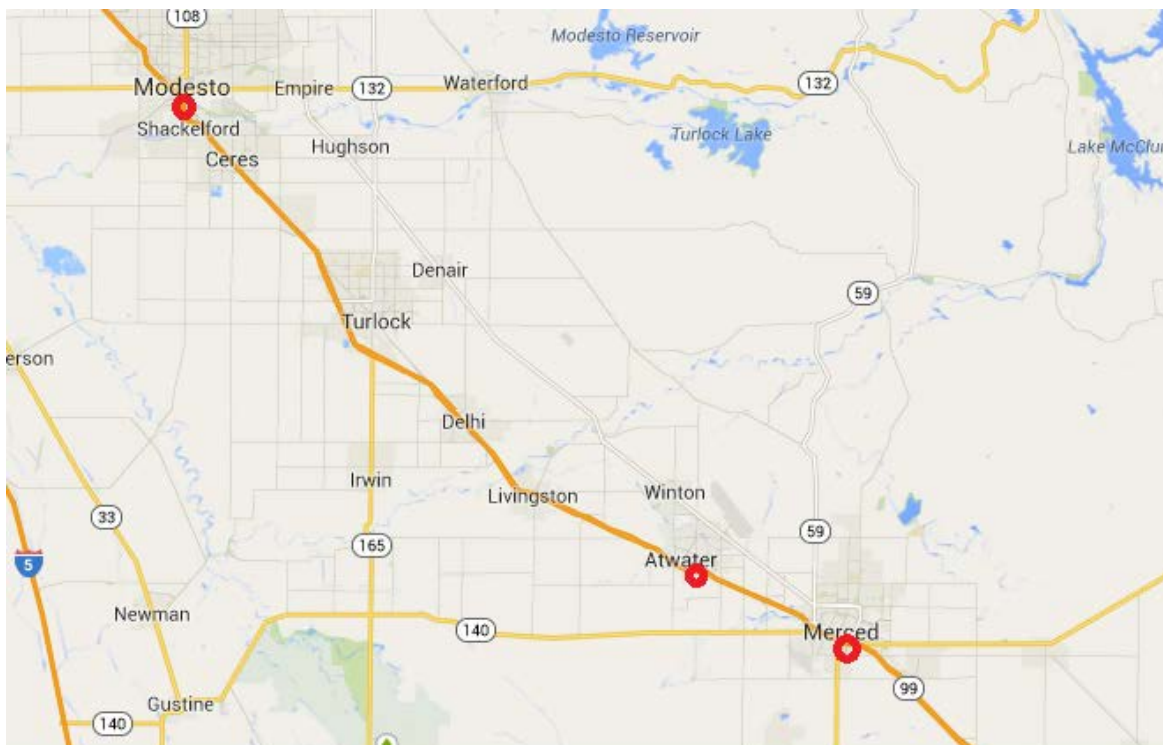

Figure 5.3. Google map of SR-99 rural freeway.
(Three lanes per direction from Modesto to Atwater and two lanes from Atwater to Merced.)

5.3 Urban Arterial with Signalized Intersection

This scenario is necessary to evaluate CACC string traffic behavior/impacts on arterial roads and at signalized intersections, particularly as it affects the start-up transition after the traffic signal transitions from red to green. Both the I2V and V2V implementations of CACC can be compared for capacity and travel time improvements. The preferred location is along El Camino Real in Palo Alto and Mountain View, CA, since this high-volume arterial has already been modeled in detail by PATH using VISSIM for several previous projects. The signals in this corridor are actuated but coordinated to provide a progression, which makes it suitable for evaluation of more advanced I2V concepts to reduce stops and speed changes.
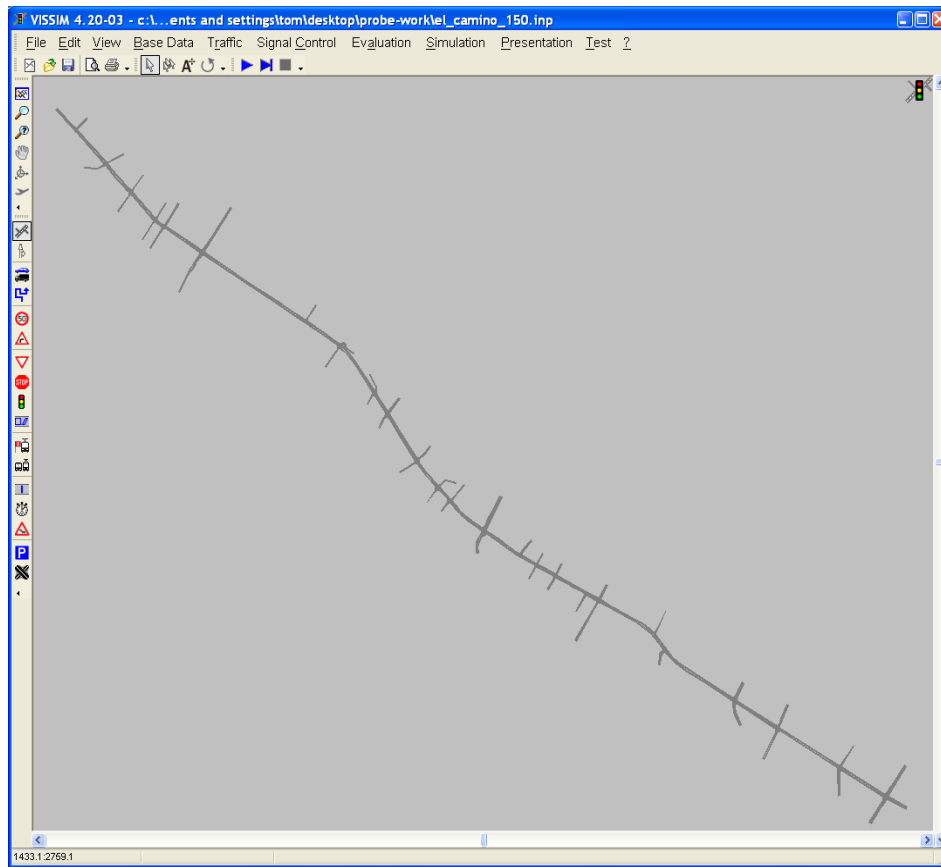

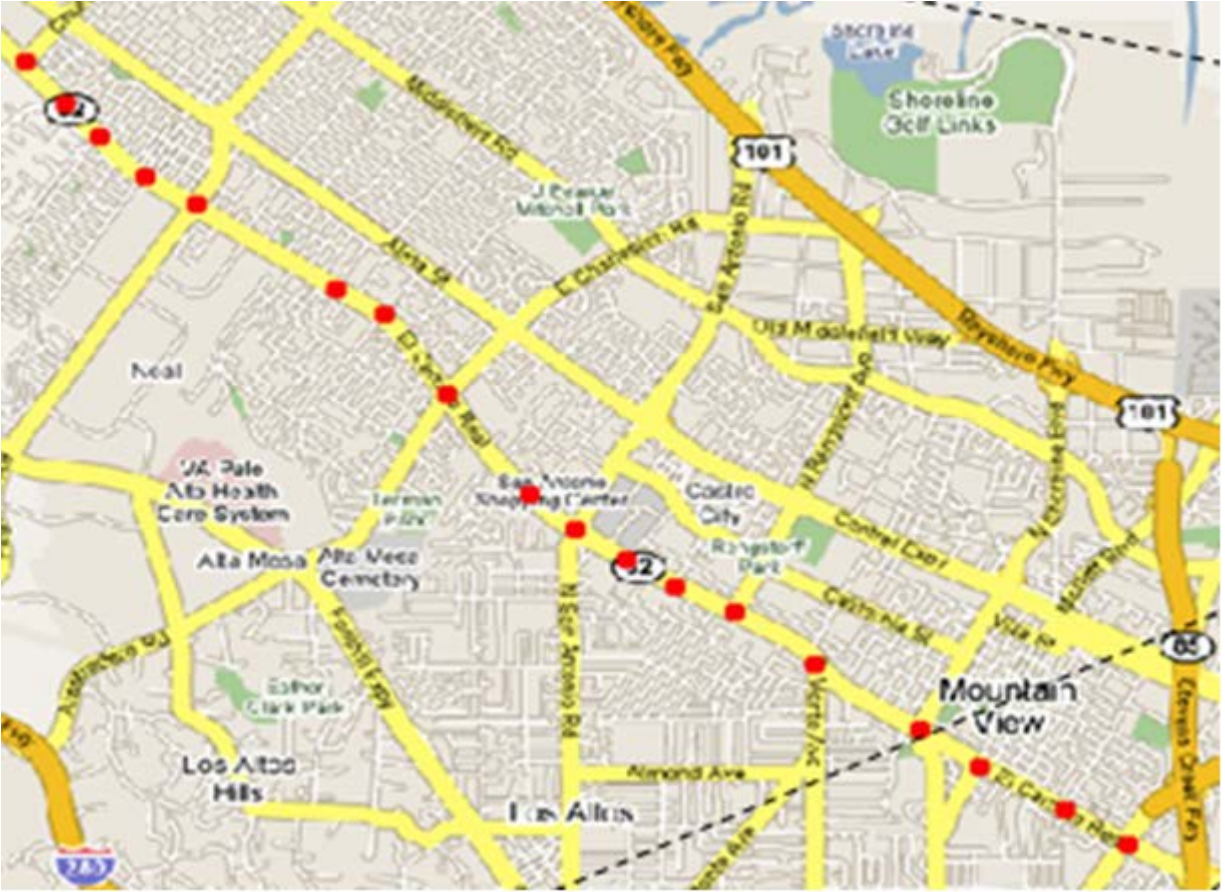Fig. 5.4 VISSIM Network Representation of El Camino Real in Palo Alto and Mountain View, CA

Fig. 5.5 Map of El Camino Real in Palo Alto and Mountain View, CA, with Red Dots Indicating Locations of Signalized Intersections Included in VISSIM Model

6   PERFORMANCE MEASURES

The concepts for managing CACC vehicle strings need to be evaluated based on a variety of criteria so that the trade-offs among different dimensions of performance can be well understood. The simulation experiments will be designed to cover a wide range of operating conditions so that the conditions in which the alternative concepts show relative advantages and disadvantages can be determined. The baseline cases will be the extreme cases of no CACC or all CACC vehicles so that the full range of potential effects can be understood, and then intermediate cases will be chosen carefully to illustrate the trends in performance.

In addition to the three basic simulation scenarios identified in Section 5, these condition variations are expected to include:

- Traffic volume per lane
- Market penetrations of CACC, ACC, CCC, and V2V-only vehicles
- Volumes of entering and exiting traffic at freeway interchanges

- Percentage of heavy trucks in traffic stream
- Availability of I2V speed control/advisory information

The performance measures to use in comparing alternatives need to reflect the important system-level transportation performance attributes as well as the attributes that will be of interest to individual vehicle operators. The attribute that is most difficult to represent is safety. This is particularly challenging in the context of CACC because the vehicle spacing control is being done automatically rather than by drivers. The traditional surrogate safety measures used in traffic simulation studies are not valid here because those are implicitly founded on assumptions about driver responses to longitudinal disturbances, but those driver responses are largely irrelevant when considering ACC and CACC control. We have doubts that it will be feasible to define meaningful surrogate safety measures for evaluating CACC alternatives.

The basic performance measures for freeway applications that we expect to apply include the following:

- Total Travel Time (TTT)
- Total Travel Distance (TTD)
- Total delay (TD)
- Speed Variation
- Total Number of Stops
- Number of lane changes
- Energy consumption
- Criteria pollutant emissions

These will be estimated at the aggregate level for the entire highway section, but also need to be disaggregated so that the measures for the equipped vehicles and the unequipped vehicles can be distinguished from each other, to determine how much additional benefit the equipped vehicles may gain.

For the most important cases, it is also necessary to determine the maximum throughput that can be achieved on the simulated highway section. This involves making successive simulation runs at increasing traffic volumes until the traffic flow breaks down when the maximum achievable throughput has been exceeded.

The basic performance measures for signalized intersection applications that we expect to apply include the following:

- Cycle failures
- Average queue length
- Total Number of stops
- Average travel time
- Upper tail percentiles of travel time distribution
- Energy consumption

- Criteria pollutant emissions

One of the most interesting opportunities for improving signalized intersection operations through use of CACC is by enabling the vehicles queued at a red signal to start up simultaneously when the phase changes to green. This could significantly increase the capacity of the intersection, so that potential capacity increase needs to be measured. Similar to the freeway cases, this can be simulated by running a series of simulated cases at increasing demand levels to determine which demand level leads to unbounded spillback, thereby exceeding the intersection capacity. Note that the signal phase change information could be obtained directly from the traffic signal using I2V communication to all the queued vehicles or it could be conveyed by V2V communication from the first queued vehicle to all the following vehicles. The differences in traffic performance measures between these two alternatives should be negligible in practice because the driver of the first queued vehicle still needs to verify that there is no crossing traffic in the intersection before proceeding into the intersection, but the V2V case does not require installation of any roadside equipment.

It will also be interesting to understand the contributions that CACC can make toward eco-driving in a signalized arterial environment, particularly with I2V communication of signal phase and timing information, but that is more relevant to the scope of the AERIS project than to this project.

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