Vehicle-to-Infrastructure Program Cooperative Adaptive Cruise Control

Final Report

www.its.dot.gov/index/htm
Final Report – March 31, 2015
FHWA-JPO-16-257

U.S. Department of Transportation
Federal Highway Administration

Produced by Crash Avoidance Metrics Partners LLC in response to Cooperative Agreement Number DTFH6114H00002

U.S. Department of Transportation
Federal Highway Administration

Notice

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The U.S. Government is not endorsing any manufacturers, products, or services cited herein and any trade name that may appear in the work has been included only because it is essential to the contents of the work.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-JPO-16-257	(Remove; Insert Information Here or leave blank)	(Remove; Insert Information Here or leave blank)

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
Cooperative Adaptive Cruise Control (CACC) Final Report	**5. Report Date** March 31, 2015 **6. Performing Organization Code** (Remove; Insert Information Here or leave blank)

7. Author(s)	8. Performing Organization Report No.
Parikh, J., Abuchaar, O., Haidar, E., Kailas, A., Krishnan, H., Nakajima, H., Maile, M., Meier, J., Rajab, S., Sharrab, Y., Siko, S., Thompson, J., Yamamoto, M., and Deering, R.	(Remove; Insert Information Here or leave blank)

9. Performing Organization Name And Address	10. Work Unit No. (TRAIS) / 11. Contract or Grant No.
Crash Avoidance Metrics Partners LLC on behalf of the Vehicle-to-Infrastructure Consortium 27220 Haggerty Road, Suite D-1 Farmington Hills, MI 48331	**10. Work Unit No. (TRAIS)** (Remove; Insert Information Here or leave blank) **11. Contract or Grant No.** DTFH6114H00002

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered / 14. Sponsoring Agency Code
FHWA Headquarters 1200 New Jersey Avenue, SE West Building Washington, DC 20590	**13. Type of Report and Period Covered** Final Report August 1, 2014 through February 28, 2015 **14. Sponsoring Agency Code** (Remove; Insert Information Here or leave blank)

15. Supplementary Notes

(Remove; Insert Information Here or leave blank)

16. Abstract

This report documents the work completed by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium during the project titled "Cooperative Adaptive Cruise Control (CACC)." Participating companies in the V2I Consortium were FCA US LLC, Ford, General Motors, Hyundai-Kia, Honda, Mazda, Mercedes-Benz, Nissan, Subaru, Volvo Truck, and VW/Audi. The objectives of CACC are to investigate extension of Adaptive Cruise Control systems for longitudinal control using V2V/V2I communication to coordinate a string of vehicles to improve traffic flow. The purpose of the CACC Project was to consider the feasibility of implementing CACC using Dedicated Short Range Communication (DSRC) and to frame the future research work needed to move the concept toward potential implementation. From a literature review of past and on-going CACC work, a broad, high-level research plan was developed to identify the potential benefits, opportunities, safety issues, technical gaps, and challenges in deploying CACC systems. In addition, a more focused set of recommendations assessing the potential for production implementation of CACC in future vehicles were developed along with prototype and small-scale test plans for a follow-on research project to explore implementation issues in a structured fashion.

17. Key Words	18. Distribution Statement
(Remove; Insert Information Here or leave blank)	(Remove; Insert Information Here or leave blank)

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
(Remove; Insert Information Here or leave blank)	(Remove; Insert Information Here or leave blank)	**51**	(Remove; Insert

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Table of Contents

List of Figures

List of Tables

Executive Summary

This report presents the Final Summary Report for the Cooperative Adaptive Cruise Control (CACC) Project under the Vehicle-to-Infrastructure (V2I) Program. The report covers the period from project inception on August 1, 2014 through February 28, 2015.

The objectives of CACC are to extend the performance of Adaptive Cruise Control (ACC) systems and to dynamically and automatically coordinate a string of vehicles in order to improve traffic flow. Additionally, it is theorized that if traffic flow can be maintained while reducing headways among vehicles, improved fuel economy (or energy savings) and reductions in emissions will result [1].

The CACC Project was initiated to consider the feasibility of implementing this concept utilizing Dedicated Short Range Communication (DSRC) and to frame the future research work needed to move the concept toward potential implementation.

The project consisted of three main technical tasks to address the following objectives in sequence:

1. Develop a broad, high-level research plan to identify the potential benefits, opportunities, safety issues, technical gaps and challenges involved in deploying CACC systems
2. Develop a more focused set of recommendations assessing the potential for production implementation of CACC in future vehicles
3. Define prototype and small-scale test plans for a follow-on research project to explore the focused set of implementation issues in a structured fashion

High-Level Research Plan

In order to develop the high-level research plan, a review of prior literature and ongoing research on CACC-related activities was conducted. An examination of issues relevant to CACC revealed a broad spectrum of unanswered research questions. A plan and timeline to explore these questions were developed which framed the work in three phases:

- Preliminary research to examine two key questions:
    - What are the potential benefits of CACC systems based on adding vehicle to vehicle/infrastructure communication to current production ACC systems?
    - What are the issues related to CACC systems reducing the headway gap between vehicles below current production ACC systems?
- A focused research project to assess the viability of enhancing production ACC systems by adding Vehicle-to-Vehicle (V2V) communication
- Additional research to assess the efficacy of utilizing V2V/ Vehicle-to-Infrastructure (V2I) communication to implement CACC

Assessing the Potential for Production Implementation

To provide more focus to the high-level research plan previously developed, an analysis was performed to explore the utility of implementing CACC functionality utilizing DSRC-based communication in conjunction with current production ACC systems. By beginning to delineate the potential benefits and performance issues associated with this approach, more specific issues were identified to focus on in future research plans. Anticipated benefits of adding DSRC communication to ACC include possible flow stabilization and reductions in headway resulting from improved information exchange between vehicles.

The results of this analysis:

- Provide a preliminary assessment of possible extension(s) of production ACC systems functionality utilizing V2V communication
- Provide a working definition of CACC systems for use in future research
- Identify a proposed framework for prototyping a reference CACC implementation
- Conduct a hazard analysis of the reference CACC system

A preliminary hazard analysis indicates the need to explore transitions into and out of CACC control, as well as the implications of CACC system faults during close-coupled following conditions. Moving forward, it will be more informative to assess potential benefits and performance issues associated with CACC by developing and evaluating a reference implementation. Doing so may make the perceived benefits of DSRC-enabled CACC more tangible by demonstrating its performance in the operational context of close-coupled platoons of vehicles.

A focused research effort is recommended to:

- Gather data for production ACC systems in operational scenarios with and without V2V communication to establish the baseline performance differences for the two ACC configurations
- Explore CACC system safety and establishing reference scenarios using the System-Theoretic Process Analysis (STPA)
- Design and test CACC controller algorithms using simulation and Hardware-in-the-Loop (HIL) testing to provide a reference CACC implementation for use in controlled prototype vehicle testing
- Conduct preliminary vehicle-level testing in controlled scenarios to validate simulation and HIL testing

Prototype and Small-Scale Test Plans

The viability and efficacy issues identified in the high-level research plan can be assessed by conducting the recommended research in two sequential phases:

Phase 1:

- Conduct exploratory tests to collect data from a reference ACC system implementations concurrently with V2V communication to compare the results and to establish baseline performance
- Establish a simulation platform to develop and test different CACC algorithms
- Develop a concept CACC system specification and conduct a hazard analysis

Phase 2:

- Perform hardware and software implementation of CACC algorithms using HIL simulations followed by integration and testing on a small fleet of vehicles

The details of this framework will be provided in a separate project proposal document for Federal Highway Administration (FHWA) consideration.

1 Introduction

This report describes the work completed in the Cooperative Adaptive Cruise Control (CACC) Project. The period covered by the report is from August 1, 2014 through February 28, 2015. The project is being conducted by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium. The participating companies in the V2I Consortium are FCA US LLC, Ford, General Motors, Hyundai-Kia, Honda, Mazda, Mercedes-Benz, Nissan, Subaru, Volvo Truck, and VW/Audi. The project is sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH611H0002, Work Order 0002.

1.1 Project Description

The FHWA is engaged in assessing applications that realize the full potential of connected vehicles, travelers and infrastructure to enhance current operational practices and transform future surface transportation systems management through connected vehicle research. CACC is an application that uses longitudinal control to potentially improve drivers' safety and convenience. When used in conjunction with supporting technologies and programs, CACC may also substantially reduce the congestion typically found on most urban freeways. The CACC system regulates inter-vehicle distances in a vehicle string, utilizing information exchanged between vehicles through wireless communication and on-board sensor measurements.

The purpose of the CACC Project is three fold: 1) assess the technical feasibility of the CACC system and develop recommendations for further research; 2) explore the utility of implementing CACC functionality utilizing Dedicated Short Range Communication (DSRC)-based communication in conjunction with current production Adaptive Cruise Control (ACC) systems; 3) develop a plan for prototyping and conducting a small-scale test of CACC.

1.2 Objectives of CACC System

The goal of Cooperative Adaptive Cruise Control (CACC) is to expand the performance of ACC systems and to dynamically and automatically coordinate the longitudinal spacing of individual vehicles within a string of vehicles in order to improve traffic flow. Additionally, it is theorized that if traffic flow can be maintained while reducing headways among vehicles, improved fuel economy and reductions in emissions will result [1].

1.3 Organization of the Report

The report is organized in three main sections. Section 2 of the report presents a summary of the activities that occurred within each active task during the project from August 1, 2014 to February 28, 2015. The task descriptions in this section are intended to provide an overview only. Further details of Task 2, Task 3 and Task 4 are described in Section 3, Section 4 and Section 5 respectively.

2 Summary of Project Activities

This section summarizes the three tasks for the project.

2.1 Task 1 – Technical Project Management

The goal of this task was to provide technical oversight to ensure the project achieves its objectives within the time frame and resources allocated for the effort. The scope of the technical project management activities includes:

- Technical and administrative leadership over all aspects of the CACC project
- Tracking of costs, milestones and deliverables
- Coordination and project progress reporting with the Government Task Manager (GTM) and other related U.S. Department of Transportation (USDOT) organizations
- Risk identification and management throughout the project
- Development of material for quarterly status reports
- Providing technical progress and accomplishments for the current quarter
- Planning for the next quarter and variances from the current work plan, including planned corrective actions to issues encountered during project execution

To support these activities a project plan was developed including a risk management plan that outlined the risks associated with project execution and plans to mitigate. A bi-weekly conference call was set up to coordinate and provide project progress to the FHWA and the GTM.

2.2 Task 2 – Develop Research Plan

The purpose of this task was to assess the technical feasibility of prototyping a CACC system by identifying technical challenges, safety issues and research gaps. Taking an evolutionary approach based on radar-based production ACC systems, the approach taken to address the following topics is discussed in this task and incorporated into the high-level research plan.

- Potential extension of production ACC using vehicle-to-vehicle (V2V) communication
- V2V communication and standards for CACC
- CACC vehicles for platooning
- Overarching functional and operational safety of CACC system

2.3 Task 3 – Assessing the Potential for Production Implementation

The purpose of this task was to assess the potential for developing CACC systems for future production vehicles. Considering CACC as an extension of current ACC systems complemented with V2V communication, the task developed the following:

- A preliminary look at possible enhancements of production ACC systems by adding Vehicle-to-Vehicle (V2V) communication systems
- A working definition of CACC systems for use in future research
- A preliminary investigation of the use of System-Theoretic Process Analysis (STPA) to conduct a preliminary hazard analysis for CACC systems
- A proposed framework for prototyping a reference CACC implementation as a near-term research project

2.4 Task 4 – Develop Prototype and Small-Scale Test Plans

The purpose to this task was to develop a plan for testing a prototype CACC system and conducting a small-scale test fleet. The outline of a follow-on research project was developed to conduct this work in two sequential phases totaling 32 months of effort. The plan focuses on the development, implementation, and testing of a prototype CACC system to explore traffic flow, throughput and potential safety issues resulting from operating a coordinated string of vehicles.

3 Task 2 – Development of Research Plan

The focus of this task was to develop a research plan that identifies technical and safety issues, knowledge and information gaps, deployment challenges, and provides recommendations for the next steps in developing a CACC system. Task 2 featured the formulation of initial research questions, a literature review, and an assessment of unanswered research questions and the preparation of a research plan.

3.1 Initial Research Questions

To frame the topics of interest in potentially developing and deploying CACC systems, a list of research questions was prepared for preliminary consideration. The original list of questions included in the Statement of Work (SOW) for the project was refined during the early stages of the task execution through internal discussions within the technical team and with the FHWA project team. The resulting list of initial research questions was divided into four areas to facilitate discussions, provide a structure for conducting the literature review, and an organization for the research plan. The initial research areas and questions are presented below:

Potential extension of production ACC using V2V communication

Considering radar-based production ACC systems augmented with DSRC-based V2V/V2I communication and messages, by taking an evolutionary approach:

- Can V2V communication enhance performance of production ACC systems?
- Can V2V communication help reduce the minimum headway gap in ACC? If reduced headway operation is feasible, can it lead to improved traffic flow?
- What are the safety and driver comfort concerns in reducing the headway gap?
- How can V2I enhance the performance of CACC and what are the potential methods/techniques for accomplishing V2I?

V2V communication and standards for CACC

- What is the impact of communication delay on system performance and safety?
- What additional effort is needed to make DSRC radios interoperable and to standardize messages specifically for CACC applications?
- What is the impact of DSRC channel saturation on system performance?
- What is the impact of communications security and privacy implementation on system performance?

- Are there other communication schemes and/or media that will enhance the system performance?

CACC vehicles for platooning

For the development of the research plan, a vehicle platoon is defined as a group or convoy of vehicles moving in a longitudinal formation under longitudinal control. The grouped vehicles are driven on a limited access roadway in a managed or dedicated lane.

- What is the process of joining and leaving a platoon?
- What are the necessary positioning requirements for safe platooning?
- What is the maximum platoon size that can be achieved while maintaining safe and reliable operation?
- What are the impacts on a platoon due to loss of communication and/or positioning data in various driving environments?
- Can a platoon be ad-hoc (randomly formed) or is coordination (managed by a platoon leader) required? What are the challenges to either implementation?
- What are the criteria for forming, managing and dissolving a platoon in ad-hoc and coordinated formations?
- What are the considerations for managing a coordinated platoon when the platoon leader changes lanes or leaves the platoon?

Overarching functional and operational safety of CACC systems

- How will a CACC system recover if there is a hardware or software failure so that a vehicle does not enter a conflict zone with other vehicles, pedestrians or objects?
- Even if the system were operating as designed, are conflict scenarios possible?
- Is a new system architecture needed to ensure that safety requirements are met?
- How can self-diagnostics and the concepts of graceful degradation and fail-safe operation be implemented?

3.2 Literature Review

Twenty-six publications relevant to the initial research questions identified in the previous subsection were reviewed. A bibliography of these publications is provided in Appendix B. The purpose of the literature review was to aid in identifying technical and safety issues, gaps in information, and challenges regarding development of CACC systems. The publications reviewed consisted of ongoing advanced research activities on CACC by the USDOT, the SAfe Road TRains for the Environment (SARTRE) Project (funded by the European Commission) and various academic institutions. The concept of a string of vehicles as a platoon and associated issues in string stability and scalability predominated the research findings. Resolution of the identified platooning issues using wireless communication was also discussed. Table 3-1 maps the publications reviewed against the following three broad categories:

- CACC for vehicle platooning
- Human-Machine Interface (HMI) / Driver Vehicle Interface (DVI) for vehicle platooning
- V2V communication for the CACC application

Table 3-1: Categorization of Reviewed Literature

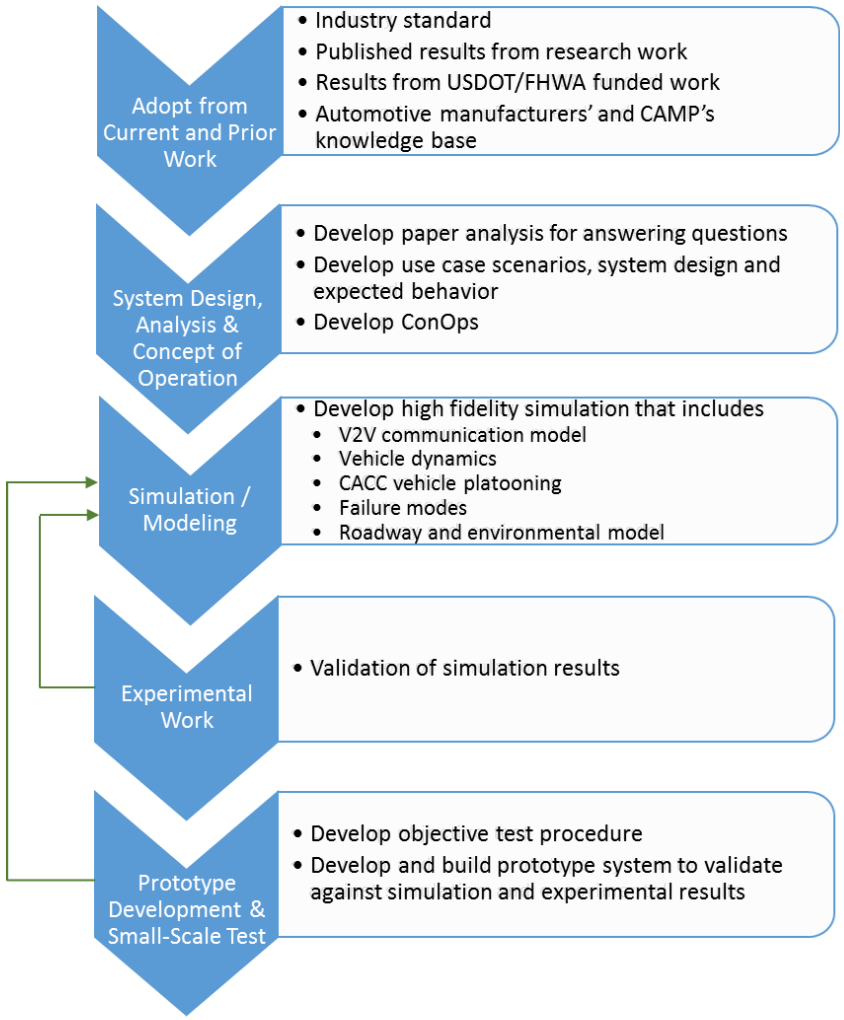
	Publication Number																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
CACC for Vehicle Platooning																										
General Concepts	X																X								X	
String Stability & Scalability			X		X		X								X				X	X			X			
Formation, Joining, Leaving and Size				X		X						X														
Impact on Traffic Flow																					X	X		X		
SARTRE Project									X	X	X															
HMI / DVI for Platooning		X														X		X								X
V2V Communication for CACC								X				X	X	X			X									
Safety and/or Reliability																										

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium

As shown in Table 3-1, 19 of the 26 publications reviewed focused on some aspect of CACC platooning. These 19 publications described the general concept of platooning, platoon string stability and scalability, platoon formation and platoon management, including platoon joining and leaving. Four of the 19 publications addressed HMI and DVI issues for platooning operations. Five publications addressed V2V communication for longitudinal control in the CACC application. None of the publications addressed safety and/or reliability for CACC, suggesting that this would be a fruitful area for future research. The output from the literature review was a list of research questions that should be further addressed in order to fully develop the CACC application. The list represents an interim step in the preparation of the research plan. Further assessments of the research needs, refinement, and preparation of the research plan were then conducted. These efforts are discussed in the next subsection of the report.

3.3 Research Plan Development Approach

To facilitate development of the research plan from the list of research questions discussed in the previous subsection, a process was identified to further assess and characterize the type of research that might be most appropriate for the unanswered research questions. The process is shown in the flowchart in Figure 1. Five primary activities comprised this process and iterative work is provided in some of the steps as indicated by the flow lines on the left side of the figure. A brief description of each step in the process follows Figure 3-1.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium

Figure 3-1: Process Flow Used for Development of Research Plan

- **Adopt from Current and Prior Work:** For the unanswered questions, review and adopt where possible, published results from current or prior activities. New activity may be built upon the previous work.
- **System Design, Analysis and Concept of Operations (ConOps):** In this step, system design and ConOps are developed to gain better insight into the problem space. Additionally, for the developed concept, a Failure Modes and Effects Analysis (FMEA) and hazard analysis will be carried out.
- **Simulation/Modeling:** Performance analysis and characterization are carried out in this step through modeling and simulation. Depending upon the degree of complexity, this step can require a significant timeframe. To help reduce the development time, existing models and simulation (e.g., V2V communication) can be utilized and extended.
- **Experimental Work:** To validate assumptions and simulation results, it may be necessary to develop experimental setups and conduct tests including development of

test plans and use cases specifically for simulation validation. The results of this step can help refine the modeling and simulation activity in the previous step and in the next step.

- **Prototype Development and Small-Scale Test:** The knowledge and information gained during the course of the previous steps will be utilized to define and develop a prototype and small-scale test.

Each unanswered research question identified from the literature review was considered in light of the research approaches depicted in Figure 3-1. The results of this effort are discussed in Subsections 3.4 through 3.7. Each of these subsections presents a summary of the topics identified for the high-level CACC research plan. Each subsection is organized around one of the four major areas discussed in Subsection 3.1. Subsection 3.4 presents the summary of research needed on the feasibility of extending ACC for CACC; Subsection 3.5 discusses research needed on V2V communication for CACC; Subsection 3.6 presents safety research topics for CACC; and Subsection 3.7 summarizes research needs regarding platooning. Within each subsection, a general summary of the research area is presented first, followed by summaries of the specific questions that require further research.

Appendix C shows the estimated timeline for conducting research activities for the unanswered questions within these four major research areas. The timeline for a given activity and sub-activity shown in Appendix C was developed using the steps outlined in Figure 3-1. The reference numbers shown in Appendix C correspond to the material in Subsections 3.4 through 3.7 in which those research topics are discussed.

It was difficult to identify a research timeline for CACC development due to much uncertainty about potential project execution times. Additionally, outcomes of predecessor tasks can dramatically impact the time needed to execute successor tasks. Assumptions, resources, and priorities further affect what work could be executed in parallel or in series. As a result, the timeline presented in Appendix C should be considered as an initial estimate based on a subjective assessment of information available during this task. Further refinements to the timeline may be made as new information becomes available and the general assumptions, priorities, and resource availability are clarified. Additionally, a detailed plan to define prioritization, schedule and full scale dependencies can be better addressed after successful prototype development and small-scale testing as proposed in Section 4.

3.4 Potential Extension of ACC

ACC is an advanced cruise control system that automatically adjusts the speed of the host (i.e., the following) vehicle to maintain time-gap between the host and a preceding vehicle traveling in the same path/trajectory. Vehicle following distance is determined through on-board sensors (e.g., radar, Light Detection and Ranging (LIDAR) or camera) on current production systems. ACC systems can be either full- or partial-speed range. Some full speed range ACC is able to bring a vehicle to a complete stop and resume vehicle speed from a standstill while others require driver input after the vehicle comes to a stop before ACC control resumes. Partial speed range ACC has a minimum speed threshold under which it does not operate.

Table 3-2 provides general performance characteristics of production ACC systems. The characteristics are generic and not specific to any Original Equipment Manufacturer (OEM).

Table 3-2: Generic Performance Characteristics of Production ACC System

Description	Operating Range
Vehicle Speed: Partial Range	30 km/h - 180 km/h
Vehicle Speed: Full Range	0 km/h - 180 km/h
Headway Gap	1 s - 2.5 s
Deceleration	<= 3.0 m/s^2
Acceleration	<= 2.0 m/s^2
Sensing Range	0.5 m - 250 m

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium

The purpose of this research task is to determine whether traditional ACC can be extended through the use of V2V/V2I communication to support a CACC application.

3.4.1 Assess Benefits of V2V Communication for Production ACC Systems

ACC requires the following vehicle to behave in a predictable manner and react to the actions of the preceding vehicle. Longitudinal control is automated in ACC making it critical to accurately maintain the following vehicle's distance/time gap and identify the vehicle's position relative to the preceding vehicle to achieve safety, stability, efficiency, mobility and driving comfort goals.

Vehicle communication using DSRC provides actual vehicle data that can be used by the ACC systems to extend ACC performance through immediate direction of vehicle longitudinal control. Vehicle communication can transmit vehicle data with low latency that may not be readily available from an on-board sensor.

In this subtask, the data elements identified in SAE J2735 will be assessed to determine what aspects of ACC control can be further extended with additional vehicle data. Examples of the types of vehicle data defined in SAE J2735 that are communicated through V2V communication from the vehicle's own systems are:

- Vehicle Dynamics: yaw rate, vehicle speed, acceleration
- Driver Inputs: steering wheel angle, brake input, throttle input
- System Status: turn signal status, wiper status
- Vehicle Position: path history, Global Positioning System (GPS) location

3.4.1.1 Assess Performance, Safety and Reliability of CACC with V2V/V2I Communication

V2V/V2I communication has several advantages over typical sensors. Unique properties of V2V/V2I communications include:

- Increased Range

  When a sensor-based ACC system currently has no target, but is heading towards a slower vehicle, the system can only react when the vehicle is within sensor range and a plausibility check has taken place. With extended sensing range this check could happen earlier and may lead to a smoother deceleration.

- Vehicle Path History and Prediction

  An ACC system must keep track of possible control targets in the same and adjoining lanes using only position and speed readings. Path history and predicted path or trajectory information could help to quickly assign these readings to tracked vehicles, therefore helping to reduce response times.

- Wider Field of View

  Vehicles that are not visible to the typical sensor could be detected using V2V communication, and could be directly considered as control targets or used to precondition the sensor recognition, also reducing response times.

In this subtask, the unique properties that V2V/V2I communication can provide to an ACC system will be assessed to determine how CACC potentially benefits from these properties in terms of performance, safety and reliability.

3.4.1.2 How Can V2V Messages Allow for a Reliable Decrease in the Minimum Headway Achievable with ACC?

In typical sensor-based systems, the vehicle will respond to driver or automated control input in a delayed fashion due to system response time, especially from brake system pressurization and the suspension. Latency may also be associated with the sensor's acquiring and processing changes in speed of the preceding vehicle.

V2V communication may reduce system latency because equipped vehicles broadcast information about the system change and status every 100 ms. This reduced latency may support a shorter gap between vehicles that remains acceptable to vehicle occupants. In this subtask, the ability for V2V communication to optimize the headway gap will be assessed. This will include safety requirements for vehicle dynamics, critical functionality, and string stability while maintaining driver expectations for comfort, especially during acceleration and braking.

In summary an evolutionary approach is proposed to determine whether production ACC can be enhanced by adding V2V communication to gather additional vehicle data otherwise not available from on-board sensors of the lead vehicle. In Task 3, preliminary research will be carried out to examine two key questions:

a. What are the benefits of adding V2V communication to current production ACC systems?

b. For CACC, what are the issues related to reducing the headway gap between vehicles beyond the headway gap in current production ACC systems?

The research steps outlined in this subsection represent a potential short-term research project to assess the viability of extending production ACC systems by adding V2V communication. This work is suggested as the next step in the CACC work flow that would follow the current project. Appendix C depicts the proposed timeline for this potential project. The main efforts in the project would be:

- Development of a ConOps and test scenarios
- Analysis of the CACC application through a concept FMEA and safety analysis
- An initial vehicle build and testing of the prototype

After the completion of the proposed short-term project, there would be an opportunity to review and reassess the longer-term, remaining research needs. Depending on the results obtained from the short-term studies, the longer term research plans may need to be modified. The longer term research needs are discussed in Subsections 3.5, 3.6 and 3.7.

3.5 V2V Communication for CACC

CACC is an extension of the ACC concept. In addition to determining the preceding vehicle's position, speed and acceleration through the on-board sensor in ACC, CACC obtains the information from Basic Safety Messages using DSRC V2V communication.

This subsection defines a methodology to investigate communication aspects of the CACC application. V2V communication is a system designed to transmit Basic Safety Messages (BSMs) between vehicles to facilitate operation of in-vehicle safety applications. Vehicles can, with some delay, remotely acquire other vehicles' information via the exchange of BSMs. This in turn can support investigation of CACC wherein a vehicle may obtain position, speed and acceleration/deceleration information, among other data, from the lead vehicle in a platoon to mitigate string instability effects and optimize the headway gap between consecutive vehicles. The goal of this subtask will be to determine the frequency, range and content of the additional messages needed for effective CACC.

3.5.1 Assess V2V Communication Only Method for CACC

V2V communication may or may not have sufficient information to support CACC operation without additional information from on-board sensors. Based on preliminary assessment from prior work, operational safety requirements, and no available fallback mode for communication failure, the V2V Communication Only method for implementing CACC is not considered a viable option and thus outside the research plan.

3.5.2 V2V Communication Message and Transmission Rate

Information required by vehicles for CACC operation needs to be updated at a rate sufficient to maintain correct functionality. Some data relevant to CACC operation may require a more precisely defined update rate than others. This would require formation of V2V communication messages as well as definition of update rates for these messages. Certain assumptions for CACC requirements and platoon management can be made to facilitate work to be performed in this activity. This activity details the research approach to define and validate V2V and V2I messages and the corresponding update rates to be used for CACC applications.

3.5.2.1 Assess Sufficiency and Effectiveness of V2V BSM

The existing V2V communication standards define different messages and data elements that can be exchanged between vehicles. The work performed in this project may possibly benefit from available knowledge and build on it to support CACC applications. Messages or data elements in addition to BSM or extensions to BSM may be needed given that CACC and platoon management operation require unique messages to be disseminated. Steps to perform this subtask are summarized here:

- Define information required for CACC operation based on previous research, work performed in this project or by using findings to make reasonable assumptions
- Review platoon related messages defined in the SAE J2735 and SAE J2945 standards
- Investigate the sufficiency of the BSM and other messages defined in previous V2V standards to implement the CACC application
- Identify absolute minimum data elements for CACC
- Determine if there is a need for additional messages and data elements needed for CACC and platoon management including messages for V2I/I2V
- Define any additional messages for which a need has been determined

3.5.2.2 Assess Communication Latency/Message Loss

A minimum update rate for each message used to support CACC operation can be set according to defined CACC system requirements. Some information may require a more precise update rate to assure operational safety. Other information may have more relaxed update rate requirements as they may be less critical, or a vehicle can make adjustments based on previous V2V communication as well as its on-board sensors. However, it will be noted that not all vehicles will have the same sensory capabilities, thus sensor capabilities need to be clearly defined. Based on aforementioned information, the assessment of communication latency and message loss effects on CACC operation can be performed. Steps required for completing this subtask are:

- Investigate proper update rates for CACC/platooning messages based on system requirements
- Validate defined update rates capability to ensure reliable and safe CACC functionality through simulation and experimental work
- Adjust update rates as deemed necessary based on simulation and/or experimental work results
- Introduce scenarios of possible communication latency, message loss and/or total communication loss
- Assess effects of scenarios defined in the previous step on CACC functionality through simulation and experimental work
- Draw conclusions from simulation and test results on the applicability of defined messages to support CACC and platooning operation

3.5.2.3 Determine Required Minimum Message Transmission Rate

Based on characterization and determined minimum and maximum headway gap values, V2V communication message update rates can be defined and tested. Steps needed to realize this subtask are as follows:

- Investigate and provide recommendations for minimum, maximum and optimal headway gap values based on operational safety and driver expectations for comfort

- Calculate V2V message update rates to guarantee fulfillment of CACC minimum requirements and performance
- Assess system performance at defined message update rates for different headway gaps through simulation and experimental work
- Adjust update rates as deemed necessary based on simulation and/or experimental work results

3.5.3 Communication Protocol for CACC Platoon Discovery and Management

This task studies communication requirements and protocols to support CACC vehicle platoon discovery and management. (The process of platoon formation and management is discussed in Subsection 3.7.) Research conducted in this task will assess the need for a communication protocol to enable platoon formation and management. If deemed necessary, such a protocol will need to be developed and evaluated.

Presently standardized messages and procedures such as BSM, SAE J2735 Annex I and other DSRC messages might provide a partial or full solution to the development of a platoon management protocol. The sufficiency of available messages and procedures as well as the need for further protocol development are assessed in this research. Steps required to perform this subtask are as follows:

- Investigate the need for a platoon management protocol based on information obtained from Subsection 3.7
- Review previous standards, SAE J2735 and SAE J2945, for available data frames and elements that could support platoon management messages
- Assess the need for additional message structures and procedures to realize a platoon management protocol
- Define required message structures and messaging needs if not already available
- Evaluate developed platoon management protocols through simulation and possibly experimental testing
- Introduce necessary changes to platoon management protocols if needed

3.5.4 Assess Impact of Communication Channel Management and Behavior

V2V communications are wireless in nature where several transmitters (vehicles) share the same medium (radio frequency or channel). This suggests that transmitters will contend for medium access, possibly creating congestion and failing to prevent frame collisions in a high-density traffic environment. Wireless links may suffer from other wireless communication effects such as small- and large-scale fading, among other Radio Frequency (RF) propagation effects. Communication performance degradation may occur as a result of these effects. Consequently, wireless channel behavior needs to be characterized so that necessary channel management decisions can be taken (e.g., offloading platoon specific communication to a different channel). This task addresses wireless communication issues and corresponding channel management procedures.

3.5.4.1 Assess Need for Increased Message Transmission Rate and Impact on Processing Requirements and Channel Behavior

Steps required to accomplish research proposed in this subtask are summarized as follows:

- Review previous CAMP project reports on V2V safety communication scalability
- Review literature for findings on DSRC wireless communications problems and channel congestion
- Assess the need for additional channel management procedures based on CACC/platooning message update rates and anticipated channel congestion
- Introduce scenarios wherein wireless communication effects may degrade wireless link performance. These scenarios may include channel congestion, wireless signal propagation effects, loss of GPS signal and tunnel access.
- Evaluate and adopt results from the CAMP Vehicle-to-Vehicle Communication Interoperability (V2V-Interoperability) Project in the context of CACC/platooning performance scenarios introduced in the previous step. This will be done to define needed simulation and experimental work since the V2V-Interoperability Project is addressing scalability and channel congestion for a large number of vehicles. CACC/platoon performance with congested channels might be evaluated through simulation only.
- Adjust message update rates, channel management protocols and/or wireless transmission parameters based on results obtained in the previous step
- Investigate effects of GPS signal loss on CACC/platooning system performance
- Reevaluate CACC/platooning performance using adjusted wireless communication settings
- Draw conclusions from simulation and testing results of CACC/platooning system performance under worst-case conditions
- Maintain coordination with CAMP activities associated with spectrum and /or congestion management

3.5.5 Communication Security

Communication security is vital to ensure safe and reliable CACC system operation. It includes authentication of vehicles to join a certain platoon, the capability of a vehicle to provide control commands to the platoon and protection of the platoon from external malicious behavior. Research of the applicability of current V2V communication security methodology and the possible need for additional security mechanisms will be performed in this task.

3.5.5.1 Assess Sufficiency and Effectiveness of V2V Security Methodology for Platooning

Steps required for completion of this subtask are as follows:

- Review the current security and privacy mechanism implemented in V2V communications standards and related CAMP V2V/V2I security projects

- Assess security requirements for CACC/platooning operations
- Define management of a platoon vehicle with expired/invalid certificates
- Investigate additional security requirements for safe system operation, if such are required
- Assess the effects of a security breach on the CACC/platooning system via assumptions, simulation and experimental work
- Assess via simulation and experimental testing, the potential time delay introduced by security mechanisms implementation and its impact on system performance due to additional processing
- Make necessary recommendations for security mechanisms based on simulation and testing results
- Maintain coordination with CAMP activities associated with security credential management

3.5.6 Assess Needs for Additional Communication Methods

To effectively manage traffic throughput on roadways, recommended platoon speeds and/or headway gap information are critical for effective CACC. Such information can be disseminated by a Traffic Management Center (TMC) for efficient traffic flow. Such information can be received using the DSRC communication through the Road-side Equipment (RSE). However, since the communication range of DSRC is short, a large number of such RSEs are needed to cover longer driving distances. Cellular communication technology offers much greater coverage. Such technology could be utilized effectively (as well as other technologies such as Satellite Radio or Digital Audio Broadcast) to disseminate information from the TMC for efficient CACC operation. This subtask investigates additional communication methods for effective and safe CACC functionality.

To summarize, the questions outlined to assess the efficacy of V2V communication for CACC and vehicle platooning is described in this subsection. Appendix C shows the timeline to carry out research work for V2V communication activities and sub-activities spanning up to 31 months. Though some dependencies exist and are reflected in the timeline, it is possible to conduct several activities in parallel. Additionally, this work can leverage prior and current work conducted at CAMP on V2V communication simulation.

3.6 Safety for CACC

In this task, a critical component of safety for CACC is assessed. The impact of operational safety; an assessment of sensor/communication hardware and software failure and the levels of mitigation needed; and assessment of minimum standards for system requirements, system architecture and functional safety will be investigated. Various platooning scenarios and safety impacts due to general communication failure or positioning information need to be assessed with respect to platoon size and headway gap.

3.6.1 Operational Safety

The impact of operational safety will be assessed in this subtask. Options for mitigating potential safety risks during platooning need to be evaluated in order to identify appropriate requirements or potential redundancies necessary in the system architecture. Assessments of communication and sensor failures of a CACC system need to be conducted and evaluated for platoon safety. Communication or sensor failure will be assessed in the context of possible platoon scenarios such as the platoon splitting, the platoon dissolving, vehicles joining and leaving a platoon, and the case where a vehicle malfunctions while traveling in the platoon. Additionally, possible time limits for vehicles to continue with communication or sensor failure in a platoon will be assessed and determined.

3.6.1.1 Assess Communications and/or Sensor Failure Impact on Platoon Safety

Scenarios under which communication and/or on-board sensor failures and subsequent impact on CACC operation to be assessed in this subtask include the following:

- Develop and assess strategies for mitigating communication and/or sensor failure during normal operation and during exception conditions (e.g., while braking hard). Possible strategies to consider include:
    - Split the platoon at the vehicle node where failure has occurred, dissolve the platoon, and increase the headway gap
    - Transfer control back to the driver, advise the driver to leave the platoon and readjust the remainder of the platoon
- Determine procedures to handle loss of communication and/or sensors during normal operation vs. during exceptions (e.g. while braking hard)
- Through simulation, assess and determine time limits for the vehicle to continue in the platoon with failed communication/sensor
- Propose the need for and implementation of headway gap adjustment for all vehicles in the instance of communication/sensor failure in a platoon

3.6.1.2 Assess Impact of Road and Weather Condition on CACC Platooning

In this subtask, the impact of road and weather conditions will be assessed. Impacts to platoon size, speed and headway gap will be assessed for readjustment. Additionally, guidelines will be developed for forming and operating a platoon under adverse weather and/or road conditions, limited visibility and nighttime driving.

3.6.2 Minimum Performance Requirements

In this subtask minimum system requirements such as V2V communication, communication security and object detection sensors for safe, reliable and robust platooning operation will be defined. This includes determination of minimum communication/sensor requirements for safe operation in joining, maintaining and leaving a platoon. Minimum communication/sensor requirements (coordinated versus ad-hoc platoon) will also be established. Additionally, the impact on a platoon's safe operation when a non-conforming vehicle is in the platoon will be assessed.

3.6.3 System Architecture for Safety

In this subtask, vehicle and infrastructure level system architecture requirements will be identified and evaluated for safety. The following needs will be assessed:

- Infrastructure architecture for Infrastructure-to-Vehicle (I2V) communication, such as placement of RSEs for TMC message dissemination system, for safe and effective operation
- General implications of system architecture (e.g., reliability, fault-tolerance, redundancy)

3.6.4 Functional Safety Requirements

Functional safety requirements (e.g., ISO 26262) of CACC as well as guidelines and the process of disengaging CACC in a platoon will be addressed for transfer of control to the driver in the following steps:

- Develop functional safety requirements
- Develop guidelines and the process of disengaging CACC and transferring vehicle control back to the driver

Questions and the required assessment of overarching safety are outlined in this subsection. The safety impact due to hardware and software failures are discussed. As shown in Appendix C, Timeline for Safety Research, this activity is dependent on other factors and base level analysis of other subsystems (e.g., V2V communication), and the vehicle platooning scenarios, before it can be fully assessed.

3.7 CACC for Vehicle Platooning

For the purpose of Task 2, platoon formation and management are classified in the following two ways:

- Ad-hoc mode: This mode is conceptually similar to the current ACC system in which a vehicle operator, when deciding to follow a vehicle, engages the CACC. The operator selects the desired headway gap. Once engaged, the CACC system takes over the throttle and brake control of the vehicle and follows the preceding vehicle. In addition to the vehicle's own object detection system, the CACC vehicle receives DSRC V2V communication messages from other CACC vehicles. The longitudinal controller uses information from both systems to maintain vehicle speed and headway gap as desired by the vehicle operator. In this mode, there is no coordinated mechanism in place with other CACC vehicles to inform and detect platoon members for targeted (i.e., the same for all vehicles in platoon) headway gap. Also, a vehicle can join or leave the platoon and no coordination is required. When a vehicle joins or leaves a platoon, the rest of the vehicles in the platoon will adjust speed and set the headway gap based on received information from other vehicles and on-board object detection systems.
- Coordinated mode: In this mode of operation, as the name suggests, a leader coordinates platoon formation and management. Generally, a lead vehicle serves to prescribe platoon speed and headway gap between vehicles. In coordinated mode, the platoon joining and leaving processes follow certain protocols and guidelines unlike in ad-hoc mode.

The purpose of this task is to assess technical issues and challenges of forming and managing a platoon of vehicles in CACC.

3.7.1 Vehicle Platoon Sizing

In this subtask, a determination of effective platoon size will be carried out based on conditions and dependencies such as driving and roadway condition, length of travel, communication range, headway gap, safety and reliability of platoon operation.

3.7.2 Platoon Formation and Management

This subtask will determine the process, requirements for communication messages, and message frequency for formation and management of ad-hoc and coordinated platoons. Developing the process to inform members of a platoon being formed includes these steps:

- Assess the process for ad-hoc versus coordinated platoons
- Determine requirements for forming an ad-hoc platoon
- Determine requirements for forming a coordinated platoon
- How can joining and leaving a coordinated platoon be managed through a platoon leader?
- Determine whether the position of each member in a platoon needs to be known by all other members in the platoon for forming and managing the platoon
- Determine requirements for a leader vehicle in a coordinated (managed) platoon

3.7.3 Process of Joining and Leaving a Coordinated Platoon

This subtask will define and develop a process of joining and leaving a coordinated platoon. In this task, it is assumed that a minimum platoon of two vehicles is already formed. The following must be addressed for a coordinated platoon:

- Determine the need for the leader to communicate an acknowledgement / refusal to join the platoon by the leader to the requesting vehicle
- Assess and determine the need for negotiation and the required messages during the joining process such as:
  - Speed of the platoon
  - Required headway gap
  - Joining the platoon at the end, in the middle, or as a new leader (replacing the existing leader)
  - Assigning a new platoon leader when the current platoon leader is leaving the platoon
- Identify various conditions and factors that impact splitting, merging and dissolution to manage platoon size for safety and required performance
- Assess driver acceptance of a closer headway gap as well as the relevant HMI / DVI needs for platooning

To summarize this subsection on CACC for vehicle platooning, an in-depth assessment of many complex scenarios related to coordinated platoons such as forming, managing, joining and leaving as well as the overall operation of a coordinated vehicle platoon is required.

Collectively, the work described in Subsections 3.5, 3.6 and 3.7 comprises a longer-term research project that could be executed as resources permit. As shown in Appendix C, this effort spans 40 months. Refinement of assumptions, priorities and resource estimates could lead to shorter project timelines.

3.8 Summary of Research Plan

In summary, the objective of this task was to prepare a research plan to address the unanswered technical and safety questions, information gaps, and deployment challenges regarding potential future development and deployment of CACC. Four broad topic areas were considered relevant during development of the CACC research plan

- Extension of current production ACC using V2V communication
- V2V communication and standards for CACC
- CACC vehicles for platooning
- Overarching functional and operational safety of the CACC system

A literature review was conducted (see Subsection 3.2) to assess the current body of knowledge about CACC and identify additional research needs. This effort identified a broad spectrum of research questions that have not been addressed. A process for determining an appropriate research methodology for each of the unaddressed research needs was developed (see Subsection 3.3). Each of the identified research needs was considered further using this process. The resulting list of research needs and assessment of the research approach needed to address each were then summarized in Subsection 3.4 through 3.7. A research timeline (see Appendix C) was then identified. The timeline was based on the assumption that resources required to accomplish the outlined tasks will be available in the future. Clarifications of assumptions, priorities and resource availability will facilitate refinements to the timeline in future work.

The research plan proposes follow-on research in three phases:

1) Preliminary research in Task 3 to examine two key questions:
    a. What are the benefits of adding vehicle communication to current production ACC systems?
    b. For CACC, what are the issues related to reducing the headway gap between vehicles beyond the headway gap in current production ACC systems?
2) A potential short-term project of under 18 months to assess the viability of extending current production ACC systems by adding V2V communication (see Subsection 3.4)
3) A potential longer-term project to assess the efficacy of V2V/V2I communication for vehicle platooning of CACC vehicles (see Subsections 3.5, 3.6 and 3.7)

4 Task 3 – Assessing the Potential for Production Implementation

In this task, an approach has been identified for developing the CACC prototype to investigate certain aspects of the feasibility of introducing CACC as an option in future production vehicles. Such aspects include string stability, optimization of headway gap, preliminary hazard analysis and implementation of simulation and a prototype system exploring the technical feasibility of CACC systems.

By defining CACC as an extension of an ACC system complemented with DSRC-based communication links, a natural first step in assessing CACC feasibility is to investigate the potential benefits of this feature under a variety of use cases. Subsequently, it is proposed to analyze potential safety concerns in CACC arising from reducing the minimum headway relative to production ACC systems, as well as broader implications and research gaps associated with the implementation of CACC systems in future vehicles. Task 3 concludes with a set of guidelines for assessing CACC as a short-term follow-on project as previously suggested in Task 2 (Section 3).

4.1 Production ACC Systems

ACC is a driver assistance system that enhances conventional cruise control to automatically adjust the speed of the Host Vehicle (HV) to maintain desired headway time between the host and a preceding vehicle traveling ahead in the same lane. The vehicle speed and following distance are determined with a system of on-board sensors (e.g., radar, LIDAR, or camera).

ACC systems are designed to enhance driving comfort and convenience. Typically, the minimum time headway for current production ACC systems is at least 1.0 *s*. This is consistent with the relevant ISO 15622 [2] standard that specifies a headway gap to be $\tau_{min} \geq 0.8\ s$, which incorporates the driver reaction time for transferring vehicle control back to manual mode. If a shorter optimized gap is found to be technically feasible, standards may need to be changed.

ACC systems are implemented using any one or combination of radar, LIDAR or camera sensors. The ACC system considers the sensor limitations in its design. Modern radar-based object detection sensors have the following typical characteristics:

- Sensor cycle time in the order of 100 *ms* or less [3]
- Wide field-of-view up to 30^0
- Range from 0.5 *m* to 250 *m* with accuracy of ±0.1 *m*
- Relative speed measurement from -75 *m/s* to +60 *m/s* with accuracy of ±0.12 *m/s*

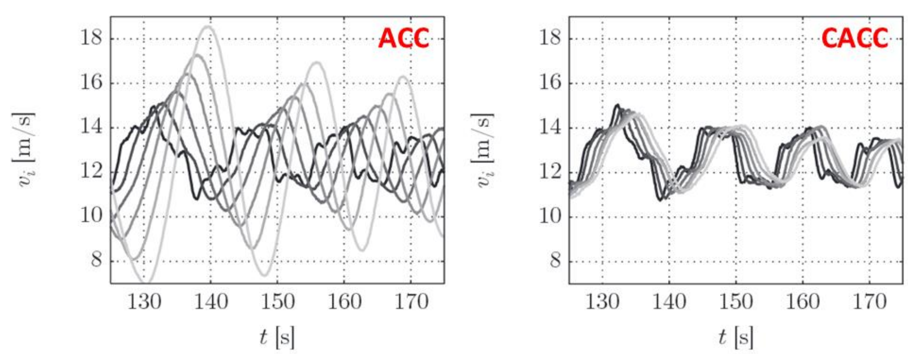
The classification of sensor readings into objects followed by target selection are essential functions of an ACC system. There are several limitations to overcome in a sensor based ACC. For example, a sensor in an ACC system has no perception of road and lane geometry or the traffic conditions on the road. The inability to differentiate between a stopped object in the HV lane and a stationary object such as an overpass may cause the HV to slow down or stop when it may be inappropriate. Another limitation of a sensor-based system is the inability to map the lane of travel of the preceding vehicle relative to the HV's path. For example, when entering or exiting a curved section of roadway, a vehicle in an adjacent lane may be detected as the object of interest and may appear to be in the path of the HV. Such sensor limitations led to development of algorithms that are conservative in behavior [4].

In a string of vehicles with activated ACC systems, braking and/or acceleration by the lead vehicle in response to varying traffic conditions may introduce oscillations in the following vehicle column due to system latencies. Such oscillations become amplified within the string of ACC-activated vehicles resulting in an unstable string. This may lead to a higher accelerations and decelerations among vehicles, causing an unpleasant driving condition or even the phenomenon of phantom traffic jams [4][5].

4.1.1 String Instability

Multiple vehicles in a lane form a string. String instability can be described as a small disturbance at the beginning of the string increasing in magnitude without bound while propagating through the string. A simple braking maneuver by the lead vehicle in the string may induce oscillations due to the delay in response by the following vehicles. For example, a single driver or ACC-activated vehicle responding to a temporary deceleration of the preceding vehicle can trigger a series of reactions in the following vehicles. In a stable string, the oscillations are not amplified as they propagate through the length of the string. A stable string minimizes oscillation caused by accelerations or decelerations, thereby reducing the potential of phantom traffic jams or rear-end collisions.

Headway clearance and system latency are two critical parameters for a stable string. Earlier results are drawn on to explain this statement. Figure 2 shows the oscillatory responses of ACC and CACC systems, each with clearances of 0.7 s [5]. The oscillation is introduced by the first vehicle in a string of six vehicles, each of which is represented by a curve; the black (darkest) and light gray (lightest) curves are the responses of the first and sixth vehicle, respectively. While the oscillations are shown to be amplified in the ACC systems, this is not evidenced in the CACC systems because of the feed-forward input, via DSRC, of the preceding vehicles' acceleration.



Source: © 2014 by J. Ploeg, "Analysis and Design of Controllers for Cooperative and Automated Driving." Used with permission of the author.

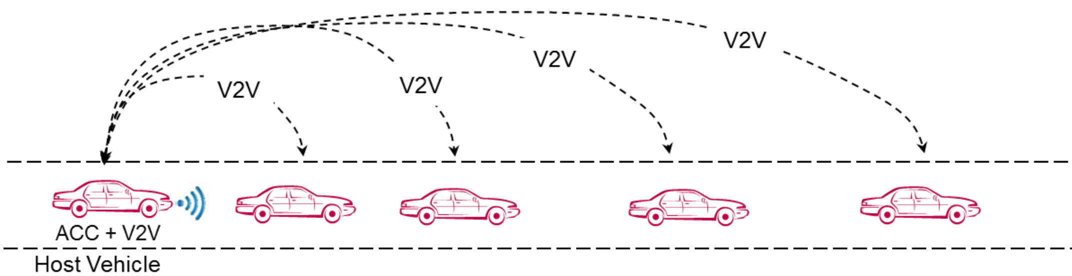
Figure 4-1: Speed Transitions in a String of Six Vehicles with ACC and CACC Systems

4.1.2 V2V Communication with One Vehicle Look-Ahead

Previous research [5] indicates that ACC in combination with V2V communication provide benefits in terms of string stability even in a two-vehicle scenario. However, a state-of-the-art radar sensor may have a faster response time [3], which may have further positive effect with respect to string stability. Therefore, a side-by-side comparison between production ACC systems, *with and without* V2V communications, for a one-vehicle look-ahead is recommended to fully delineate the benefits of V2V communication.

4.1.3 V2V Communication with Multi-Vehicle Look-Ahead

V2V communication provides a forward-looking capability beyond the preceding vehicle wherein the HV equipped with object detection sensor can acquire information from multiple preceding vehicles as shown in Figure 3. This string may include vehicles not equipped with V2V communications capability.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium

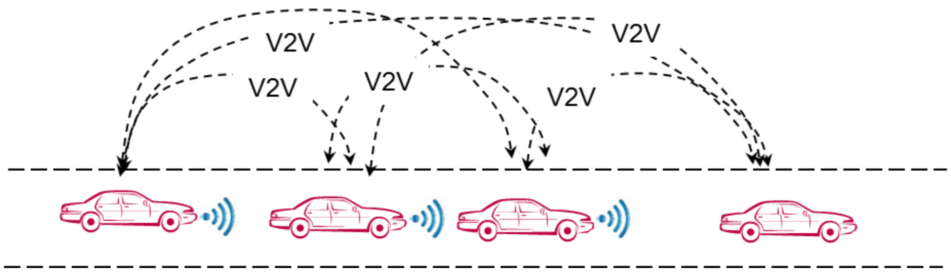
Figure 4-2: V2V Communication with Host Vehicle

In addition to the various vehicle parameters received from the preceding vehicle as defined in the current version of the standardized BSM [6], the look-ahead feature provides additional information to the HV, affording better situation assessment for vehicle longitudinal control. Prior research [7] has shown such a feature mitigates string instability [8] effects. The additional information can be useful to the HV's longitudinal controller in making appropriate speed adjustments.

If this information from the preceding vehicle is not available to the following vehicles, delays in braking and acceleration by the following vehicles based on the lead vehicle status are amplified as it propagates along the string of vehicles. However, if the controllers on the following vehicles receive the lead vehicle status and activate brake/acceleration as soon as they receive a message, string instability effects may be alleviated. Such functionality would enhance driver experience by mitigating unpleasant oscillations that may occur in a traditional ACC system. This is one of the benefits of CACC and is defined formally in the next section.

4.2 Cooperative ACC (CACC)

CACC can be viewed as an extension to the ACC concept that uses V2V and/or I2V communication to provide additional information from preceding vehicles equipped with V2V communication or from an infrastructure device. That is, in addition to determining the immediately preceding vehicle's speed and distance using ACC systems, CACC functionality facilitates obtaining additional information using DSRC-based messages. This allows vehicles to "cooperate" by communicating with each other while in ACC mode as illustrated in Figure 4. The lead vehicle may or may not be equipped with ACC.



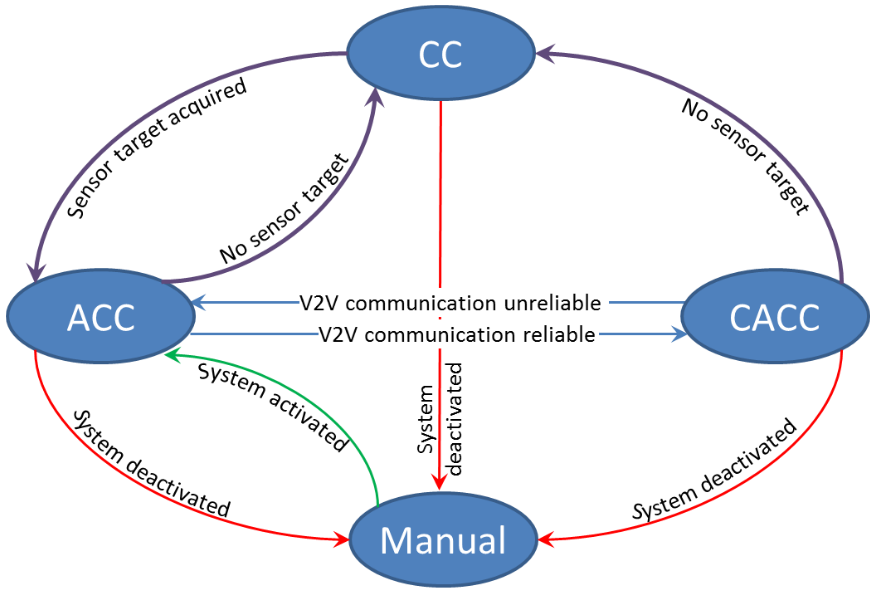
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium

Figure 4-3: CACC Concept

A CACC-equipped vehicle receives DSRC messages from multiple preceding vehicles. This information would then be utilized to enhance the control of the HV brakes and accelerator in the presence of multiple preceding vehicles. This in turn helps mitigate string instability oscillation effects introduced by ACC systems and potentially enhances safety. V2V communication provides the HV controller situational awareness to adapt to certain events ahead of the preceding vehicle. The controller can react to events beyond the sensor range.

4.2.1 State Transitions in a CACC System

The CACC system is presented as an extension of the ACC system. Thus, it can be envisioned that the controller will alternate between ACC and CACC modes without driver action. Figure 5 illustrates very broadly the four states that would exist in a CACC system – Manual, Cruise Control (CC), ACC and CACC.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium

Figure 4-4: CACC State Transition Diagram

The CACC state extends the Manual, CC and ACC functionality. In this state, the HV follows the lead vehicle by utilizing both sensor data and V2V communication input. It should be noted that in this system, the transitions from either Manual or CC to CACC are not considered as they are internal sub-states of the system. Certain communication reliability requirements have to be met with the immediately preceding vehicle before the system can trust and consider the V2V input. Therefore, it is envisioned that when the HV encounters a V2V-enabled vehicle and CACC is activated, the system first enters in the ACC state. In this state, the system continues to receive V2V messages and sensor readings. Once the V2V messages are confirmed and validated, the system transitions to the CACC following state. Under any circumstances, if the communication is not reliable, the system transitions back to the ACC state. Note that additional investigation of communication performance related to communication reliability was identified as part of the longer-term research outlined in the Section 3, Task 2 Research Plan. Similar to an ACC system, the CACC system can be deactivated for manual vehicle control. It should be noted that the CACC system would be similar to a Level 1 [9] automation ACC system where the driver is required to steer the vehicle, maintain situational awareness, and resume manual operation of the vehicle should conditions require it.

As described in Section 3.7, CACC for Vehicle Platooning, in an ad-hoc platoon mode, which is conceptually similar to the current ACC system, the headway gap set by the driver may not altered during the CACC state. However, in case of coordinated or managed platoon mode, the headway gap and the vehicle speed is coordinated by the platoon leader.

4.2.2 CACC Usage Model

Keeping in mind the evolutionary approach to investigating the implementation of CACC functionality in vehicles, the CAMP V2I Consortium members have developed the following usage model for a CACC system.

4.2.2.1 CACC Activation

The CACC system is envisioned to operate in a similar manner to an ACC system. Each individual OEM will define the specific control inputs and HMI for operation of their system. The driver turns on the system, sets (or adjusts) the desired vehicle following gap, and sets the desired maximum vehicle speed similar to the ACC system. When there is no target detected by the on-board sensor, the vehicle is operated in a conventional CC mode as described in Subsection 4.2.1. Upon identifying and acquiring a target vehicle the system switches to the ACC mode, in which it adjusts its speed based on the speed of the target vehicle while following it. Throughout the aforementioned sequence of system transitions, the vehicle continues to receive V2V messages from vehicles within its DSRC range. When the vehicle identifies one or more preceding vehicles with V2V communication and that satisfy possible additional CACC requirements for situations such as transitions into / out of a platoon and failure management, it switches to the CACC mode during which the vehicle controller utilizes inputs from both the object detection on-board sensor and V2V messages from the preceding vehicles.

4.2.2.2 CACC Deactivation

The CACC system can be deactivated by the driver either by switching off the system or by applying the vehicle brakes. Moreover, when the V2V communication link (with the preceding vehicle) is disrupted the CACC system switches to the ACC mode.

4.2.3 Rationale for Reducing Minimum Headway Setting in CACC

As outlined in Intelligent Network Flow Optimization (INFLO) [1], the objective of CACC is to dynamically and automatically coordinate cruise control speeds among platooning vehicles in order to significantly increase traffic throughput. Additionally, if headways among vehicles can be reduced, while maintaining traffic flow, improved fuel economy (or energy savings) may result. CACC demonstration tests have revealed some level of driver acceptance during usage on freeways during their commute to work [10].

4.3 Preliminary Hazard Analysis of CACC

The next research question undertaken in this task is whether the benefits of V2V communication can result in shorter headway in current production ACC systems. The addition of V2V communication to ACC does not automatically imply reduced, safe headway. A comprehensive safety and hazard analysis early in the CACC development process is necessary to identify countermeasures that may be needed during system design and specification.

This step is especially important for scenarios with shorter headways than typical under ACC operation. To identify these additional hazards and to define countermeasures, we propose to conduct an STPA [11]. STPA is a new hazard analysis process that assumes that accidents are caused by component behavior due to inadequate implementation of constraints and not only due to component failures [11]. STPA includes both component and component interaction failures. Causes involving software and human errors which usually involve not failures but inadequate or undesired control actions are also included. The first step in STPA is to identify the undesired control that can lead to hazards. The second step is to determine the potential cause(s) of the undesired control. A partial execution of Step 1 of the STPA is conducted as part of this task for illustrative purposes.

4.3.1 Why STPA?

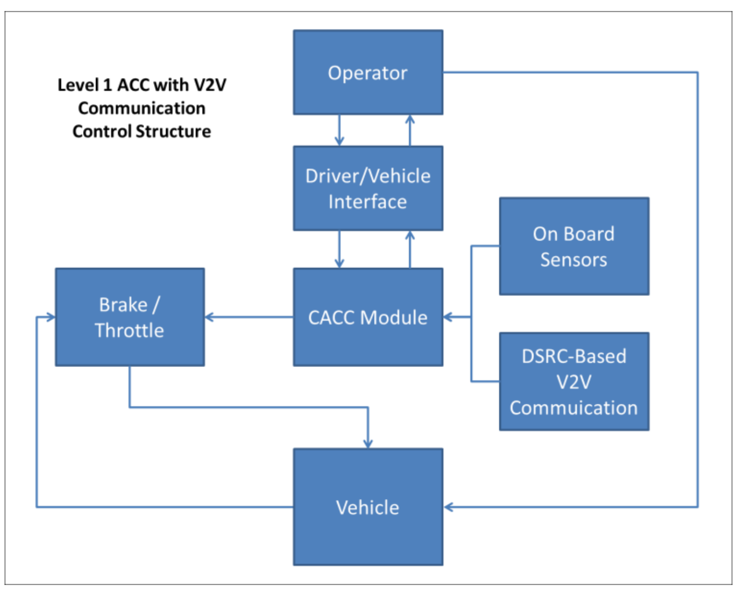
The ISO 26262 [12] focuses primarily on the functional safety in risks arising from random hardware/software faults as well as systematic faults in system design. It assesses driver behavior only indirectly through controllability studies, which are questionable for automated applications where the driver may not be paying attention by design. An FMEA can be beneficial in identifying component issues but does not grasp the role of the human driver in the behavior of the vehicle and the role other traffic will have on the outcome. The STPA is advantageous because it can include driver behavior directly in the analysis.

STPA comprises multiple steps, starting with establishing the system engineering foundation for the analysis by defining the system structure with its components and interactions. Furthermore, it requires a definition of the undesired events (collisions) that could be introduced through the system. The next step is to identify Undesired Control Actions (UCAs) performed by the system and to continue with the identification of accident causal scenarios (hazards). This information can be used to specify additional requirements and constraints for the system and its operation.

4.3.2 Undesired Events

In the context of STPA, an accident is defined as “an undesired or unplanned event that results in a loss, including loss of human life or human injury, property damage, environmental pollution, loss of mission, etc.” [11] For CACC systems, we consider only accident scenarios in which there is a rear-end collision with a preceding vehicle. Collision with another vehicle in an adjacent lane is outside the scope of the CACC control structure.

Viewing CACC as an extension of ACC, the envisioned control structure is depicted in Figure 6. The required longitudinal control actions the CACC module can issue are: i) decelerate and ii) accelerate. These control actions are issued through the corresponding engine and brake control systems.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium

Figure 4-5: CACC Control Structure

The two UCAs by the longitudinal controller are improper i) deceleration and ii) acceleration. These actions in general can be hazardous for longitudinal control system when either:

- the control actions are not given
- the control actions are given prior to the system activation or engagement
- the control actions are given with incorrect timing or in incorrect order
- the control actions are stopped too soon or applied for too long
- the control actions fall outside defined performance limits

4.3.3 Collision Causal Scenarios (Hazards)

STPA defines hazards as “a system state or set of conditions that, together with a particular set of worst-case environment conditions, will lead to a collision (loss).”[11] For example, CACC potentially places the driver in a following situation at shorter time headways than typical under ACC operation. Should a CACC fault occur requiring the system to disengage, an orderly transition of control must take place to enable the ACC system or the driver to safely resume control of the vehicle. A CACC-initiated transition from shorter to typical headway may be needed.

The next steps in the STPA involve developing accident causal scenarios for each UCA by identifying what might cause it to happen and how control actions may not be followed or executed properly. A detailed STPA will be conducted as a part of a recommended follow-on research project. The following list provides limited set of examples of possible CACC failure scenarios that should be considered. In the following conditions, a hazard may occur as a result of the system applying incorrect acceleration/deceleration levels and/or timing.

- Due to vehicle position error, the system incorrectly identifies the position of the preceding vehicle to be in the adjacent lane
- The system miscalculates the following distance between the HV and the preceding vehicle
- A vehicle from an adjacent lane cuts in very closely and the HV is unable to detect the cut-ins in time for the appropriate controller action
- The object detection system fails to identify the preceding vehicle and the CACC system transitions to CC mode
- The controller braking reaches the limit and is unable to decelerate the vehicle any further
- Sensor and/or V2V communication latency or failure/fault at a given time
- System processing latency

Additional investigation is needed to identify the possibility of transferring control to the driver in case of major CACC system failure when driving at a shorter headway. Such investigation is discussed further in Subsection 4.5.

The implementation of shorter time gaps between vehicles will likely require faster system responses to avoid hazards as well as the addition of infrastructure information such as weather (visibility) and road conditions (e.g., road surface coefficient of friction) in order to properly establish a minimum gap.

Additionally it may be necessary to enable the system to apply greater braking force than employed in some current ACC systems. Current production collision mitigation braking systems are typically capable of applying higher levels of automated deceleration to avoid or mitigate imminent rear-end collisions.

4.4 Broader Research Areas for CACC

In this section, broader research questions and the implications of implementing CACC systems are outlined. We envision addressing these research questions in a follow-on work.

4.4.1 Effects of Reduced Headway in CACC

CACC proposes to leverage V2V communication to reduce headway in a string of vehicles. Consider the scenario where a CACC system is operating with reduced headway and the vehicular communication link is disrupted. CACC will be disengaged and the system will transition into ACC using the driver's previously set configuration. How much time will this require? Could there be a synchronized maneuver for all the vehicles in the string?

In considering these and other questions, it is proposed to develop algorithms and evaluate their performance for a variety of use cases and establish baseline performance metrics.

4.4.2 Provisioning Additional Features in V2V-Based Messages

Another relevant question is whether the current V2V-based BSM content and frequency are sufficient to support CACC functionality/string stability. How should the HV consider messages from preceding vehicles? Messages from how many preceding vehicles should be considered for decision-making by the HV? Such logic requires a mechanism to determine whether the Remote Vehicles (RVs) are in the same lane as the HV. This problem may be addressed by incorporating lane-level localization accuracy.

Another possible way to approach this problem is to leverage the RV's sensor information. While not part of the current message set, theoretically one RV may use its sensor to validate its preceding vehicle lane and communicate this information to the HV following behind. Further research is needed to develop this concept for a variety of typical use case scenarios such as string formation, vehicle cut-in, etc. It is proposed to investigate this in a recommended follow-on project.

4.4.3 Impact of Vehicle Positioning and Localization Performance

Given that the first step is to look at a string of vehicles in a single lane, information regarding the vehicles' lane becomes necessary. The data obtained using the on-board sensor system and V2V communications can be compared to remove the uncertainties in localization.

Radars in CACC systems must have comparable or better performance than those in ACC systems. This is because ACC mode may be a fallback in case of communication disruptions during travel at shorter headway.

Additional position and sensor requirements are highly dependent on the actual implementation details. A reduction in headway will likely impose more stringent requirements such as very low sensor processing and communication latencies and higher accuracy. Further research is needed to understand the effects of positional and localization performance.

4.4.4 Use of Multiple Sensor Data

While operating in CACC mode, the vehicle receives both ranging sensor and V2V data, and the challenging problem is to weigh and process them correctly. There are many possible approaches to utilize multiple data streams. One approach is to combine multiple sets of data (e.g., using a Kalman filter). Another solution is to use the distance of the preceding vehicle as detected by the ranging sensor and the acceleration as transmitted over the V2V link. This approach leverages the two systems and combines information that is likely to be more precise from each of them. It is recommended that future research develop a CACC reference implementation to explore utilization of multiple sensor data.

4.4.5 Assessment of Communication Performance

Incorporating V2V communication capabilities in a production ACC system will entail additional considerations for a secure, reliable communication link. As stated earlier, CACC operation might be feasible only when certain performance criteria are met. As an example, would a rate at the receiver side of five messages per second be sufficient for CACC operation? Should the vehicle monitor the communication channel for a certain amount of time before disengaging the CACC mode based on further investigation? Furthermore, channel congestion may have a negative effect on the communication performance causing CACC operation to be unavailable (or very limited) in these conditions.

4.4.6 Considerations for Commercial Vehicles

Incorporating CACC functionality safely in traffic scenarios involving a mix of both passenger and commercial vehicles entails consideration of a variety of challenges, a subset of which is listed below. It is proposed to address these open questions in the follow-on work.

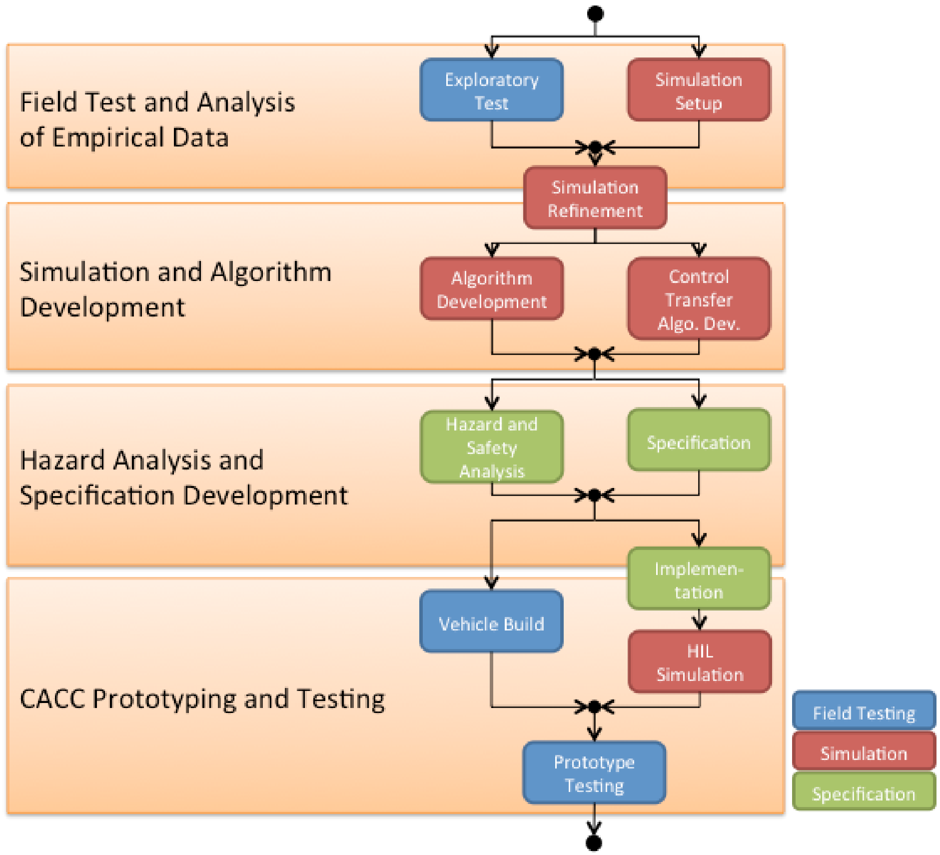
- Identify what is the standard origin point of the GPS location of the vehicle (especially for large and/or articulated vehicles)
- Determine how to handle total length with more than one trailer
- Consider establishing time gap partially based on vehicle response bandwidth (i.e., commercial vehicle payload may vary)
- Determine how DSRC communication range impacts maximum platoon length, and whether the parameter is static or dynamic

4.4.7 Infrastructure Considerations

Infrastructure considerations may include, for example, message content providing lane information where CACC operation is permitted, speed limit, etc. This may be investigated in the longer-term CACC research.

4.5 Proposed Follow-on Work

Considering the breadth and complexity of the issues discussed, we propose the following roadmap for prototyping and evaluating CACC functionality as an evolutionary extension of production ACC systems in order to approach the wide range of topics in a structured manner. The suggested follow-on work is comprised of four major activities illustrated in Figure 7.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium

Figure 4-6: Proposed Follow-on Work

4.5.1 Field Test and Analysis of Empirical Data

The purpose of this activity is to provide a real time comparison between received vehicle data from V2V communication and ACC system input. Predefined scenarios with maneuvers such as acceleration, braking and lane change using small numbers of vehicles equipped with ACC and DSRC communication will be conducted for real-time comparison between V2V-based and ACC systems data. The experimental data will also be utilized to further develop algorithms. Example scenarios are:

- In-path Range Detection: Investigate the differences between ACC range detection sensor and the distance computed using V2V-based data
- Cut-in and Cut-out Detection: Investigate parameters such as latencies, positional accuracy and range accuracies in detecting the cutting-in vehicle as well as data reliability using both ACC range sensor and V2V communication

Data collected will be used in simulation and HIL testing. This will include sensor latencies, noise and localization performance.

4.5.2 Simulation and Algorithm Development

Some research gaps related to the communication and networking specifications for CACC functionality are listed below. As this may not be a complete list, further research is needed to explore the impact of these parameters. Examination of communication channel congestion percentage level (Channel Busy Ratio/Percentage) on the reliability of V2V / V2I communication for CACC control is needed. For example, an analysis of the impact of the following communication parameters between HVs and RVs will be useful to understand the reliability of CACC information from any RV:

- Age of data
- Time between messages (Inter-Packet Gap) as imposed by safety requirements
- Message latency
- Message received rate
- Data packet loss (Packet Error Rate)
- Received communication power levels (Received Signal Strength) with respect to distance

A microscopic test bed/simulator platform will be established to develop and evaluate a reference CACC implementation considering the performance impacts of realistic variations in these parameters. It is also appropriate to evaluate CACC disengagement scenarios under which additional control or safety measures may be needed for headway shorter than typical under ACC operation considering human reaction times. The output of this activity will provide a reference CACC implementation for use in prototype vehicle evaluations.

This activity will generate multiple algorithms and the selected algorithm will be used in a reference CACC implementation that will be evaluated in a prototype vehicle as outlined in Subsection 4.5.4

The simulator platform will facilitate:

- Development of a CACC control algorithm to use multiple sensor data
- Development and testing of enhanced algorithms (e.g., one vehicle look-ahead, multiple vehicle look-ahead, etc.) to evaluate performance at shorter headway and string stability at various vehicle speeds
- Assessment of the need to adjust headway before disengaging CACC and switching to Manual mode

4.5.3 Hazard Analysis and Specification Development

As indicated in Section 4, STPA Step 2 will be conducted to identify causes of UCAs and control flows. The analysis will be coupled closely with the system specification, looking for the generation of UCAs between the components. This will help establish system specifications and additional requirements for safety. It will include detailed descriptions of the algorithms and the system architecture design. Furthermore, both the functional and the system requirements will be defined in this activity.

4.5.4 CACC Prototyping and Testing

After establishing a system architectural design and functional and system requirements, a reference implementation will be developed in both hardware and software.

- HIL simulation and testing before installing them on the vehicles: The focus will be on specific use cases where a mitigating behavior is necessary
  - HIL simulation to ensure system behaves as intended and in a reliable manner. Simulations will connect the real hardware platform, running the real implemented software with simulated environmental data (e.g., vehicle dynamics, sensor readings, and DSRC data).
  - HIL simulation can examine potential CACC benefits as well as system performance under scenarios of interest across a wide variety of operating conditions
  - It may be feasible to extend the HIL simulation by integrating a roadway and environmental model if available from an external source
- Prototype development for integration and testing: The integration of CACC into vehicles is likely to be more complex than for warning applications, and requires connection to the vehicle data including brake and acceleration control systems
- Controlled vehicle level testing: After completing integration, tests will be conducted to evaluate the overall system performance of the reference implementation. A performance analysis will help evaluate the anticipated advantages of CACC.

4.6 Summary of Recommendations for Assessing the Potential for Production Implementation of CACC

The CAMP V2I Consortium accomplished the following during this task:

- Conducted a preliminary look at possible enhancements of production ACC systems by combining V2V communication systems
- Developed a working definition for CACC systems
- Established guidelines for prototyping CACC as a short-term research project in the near future
- Developed example hazard analysis for an envisioned CACC system

As a first step in exploring the utility of implementing CACC functionality in future vehicles, it will be useful to delineate the potential benefits and associated issues of utilizing V2V communication systems in conjunction with current production ACC systems. A follow-on research project is anticipated to facilitate such an analysis by: gathering data for production ACC systems in operational scenarios with and without V2V communication to establish the baseline performance differences for the two ACC configurations; to explore system safety and establish reference scenarios using STPA; and to design and test CACC controller algorithms using simulation and HIL testing to provide a reference CACC implementation for use in controlled prototype vehicle testing.

5 Task 4 – Prototyping and Small-Scale Test Plan

In this task, a plan has been developed for investigating, designing and prototyping CACC systems to explore traffic flow, throughput and potential safety issues resulting from operating a coordinated string of vehicles.

5.1 Rationale for Prototyping and Small-Scale Testing

Prior FHWA-sponsored research [1] suggests a key benefit of implementing CACC could be improved fuel economy resulting from platooning at shorter headways. Prototyping CACC will explore multiple mechanizations, facilitate feasibility assessments and hazard analysis, and establish a foundation for quantitative research. The experimental data obtained will be utilized to design and test CACC controller algorithms under various simulation-based use cases and enable a data-based evaluation of the potential benefits and dis-benefits of CACC systems. Analysis of the experimental data is expected to support the development of technical standards such as the SAE J2945.6 for supporting CACC and platooning services.

5.2 Prototyping and Small-Scale Test Plan

It is proposed that the follow-on research project on CACC will consist of two phases – Phase 1 and Phase 2 – as described below.

5.2.1 Follow-on Research Project Phase 1

The first phase of the follow-on project contains two broad steps: 1) field testing and subsequent analysis of empirical data, followed by 2) the development of a simulator to design and test CACC algorithms. These steps are described below.

5.2.1.1 Field Test and Analysis of Empirical Data

This subtask will establish baseline performance of ACC systems and to compare the results with V2V communication data to identify the benefits of adding communications (referred to as exploratory tests). During Phase 1, scenarios and test conditions will be defined for the exploratory and HIL tests. Scenarios include, but are not limited to:

- Passing vehicles on both adjacent lanes of the host vehicle simultaneously
- Driving in a string of vehicles with oscillations introduced from the first vehicle and repeated with different time-gaps to assess string-stability
- Communication interruptions while following in CACC mode
- Position inaccuracies introduced into the preceding vehicle and/or a vehicle on an adjacent lane

Furthermore, a microscopic traffic simulation platform will be set up to design, evaluate and optimize the performance of the CACC algorithms under a variety of traffic scenarios against a mutually agreed upon set of performance measures. The simulation platform will incorporate DSRC message sets, vehicle dynamics and road scenarios as well as radar and GPS sensor models based on the data collected from the exploratory tests.

5.2.1.2 Algorithm Development, Simulation and Specification

CACC algorithm development entails the following steps:

- Use the aforementioned simulation environment to iteratively develop and test algorithms to optimize algorithm performance. It is proposed to consider the following aspects:
    - Single versus multiple vehicle look-ahead
    - Multiple sensory inputs
    - Time gap requirements while maintaining string stability
    - System response with respect to different scenarios (e.g., cut-ins, cut-outs, sudden deceleration of preceding vehicle)
    - Infrastructure advisory data (e.g., road and traffic conditions)
    - Traffic flow and throughput
    - Prior research work conducted and simulation tools developed by Turner- Fairbank Highway Research Center (TFHRC) and academic institutions will be considered in this subtask to the extent that the information is publicly available
- Develop basic control transfer algorithm(s) for enabling the vehicle operator to assume control and investigate the implications of this control sequence under a selection of scenarios (e.g., subsystem failures, reduced headways, disruption in communication)
- Prior research work conducted by academic institutions for control algorithms will be considered in this subtask to the extent that the information is publicly available
- Results from the earlier tasks will be used to develop CACC system specifications for hardware and software subsystems, control algorithms and overall system behavior
- Conduct a representative hazard analysis on the project specific implementation. This will be an iterative process during the course of CACC algorithm and system specification development process

5.2.2 Follow-on Research Project Phase 2

The plan for Phase 2 will be closely aligned with the outcomes of the first phase and could possibly be revised upon reaching the Phase 1 decision gates as shown in Figure 8. Very broadly, Phase 2 comprises the following steps:

- Implementation of hardware and software for HIL simulation and testing prior to installing CACC on the vehicles

- Controlled testing and evaluating the performance of CACC using two or more different prototype vehicles

5.2.3 Schedule for the Follow-on Research Project

The V2I Consortium estimates that Phase 1 will span 21 months, while Phase 2 is expected to run 14 months, totaling 35 months for the technical tasks in the project. Six additional months for project administrative close-out yields a 41-month period of performance. The details of this plan will be provided in a separate technical proposal.

5.3 Summary of Prototyping and Small-Scale Test Plan

In summary, a two-phase follow-on research plan is presented for designing, testing, and evaluating a CACC implementation on prototype vehicles. During the follow-on work, baseline performance will be established using data from reference ACC and DSRC-based V2V communication systems operating concurrently. This includes, for example, an evaluation of response times during brake maneuvers in vehicle-following scenarios. Furthermore, a simulation environment including a microscopic traffic simulator, communication models, and sensor models is proposed to develop and optimize CACC algorithms prior to implementation on test vehicles. Finally, a hazard analysis will be performed on the proposed CACC concept system and a model based estimate of potential benefits and dis-benefits from deploying such systems will be generated.

This work would be carried out using engineering prototypes and trained drivers to explore the utility and feasibility of various system design concepts. Human factors evaluations to understand naïve subject behavior and driver acceptance will be necessary as well, but are not part of the next phase of proposed research.

6 References

1. Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO); Assessment of Relevant Prior and Ongoing Research; Final Report – March 15, 2012; FHWA-JPO-13-011
2. ISO 15622:2010 Intelligent Transport Systems -- Adaptive Cruise Control systems -- Performance Requirements and Test Procedures
3. BOSCH: Chassis Systems Control LRR3: 3rd generation Long-Range Radar Sensor
4. Hermann Winner, Stephan Hakuli, Gabriele Wolf; Handbuch Fahrerassistenzsysteme, ISBN 978-3-8348-1457-9
5. Jeroen Ploeg; Analysis and Design of Controllers for Cooperative and Automated Driving; http://www.dct.tue.nl/New/Wouw/phdthesisploeg2014.pdf
6. Dedicated Short Range Communications (DSRC) Message Set Dictionary; http://standards.sae.org/j2735_200911/
7. R.P.A. Vugts; String-stable CACC design experimental validation; http://www.mate.tue.nl/mate/pdfs/11998.pdf
8. D.V.A.H.G. Swaroop; String Stability of Interconnected Systems: An Application to Platooning in Automated Highway Systems; California PATH Research Report; UCB-ITS-PRR-97-14
9. SAE-J3016: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems; http://www.sae.org/misc/pdfs/automated_driving.pdf
10. Christopher Nowakowski, Jessica O'Connell, Steven E. Shladover, and Delphine Cody; Cooperative Adaptive Cruise Control: Driver Acceptance of Following Gap Settings Less Than One Second; University of California PATH Program; Berkeley, CA
11. An STPA Primer, Version 1, August 2013; http://sunnyday.mit.edu/STPA-Primer-v0.pdf
12. ISO 26262: Road Vehicles-Functional Safety

APPENDIX A. List of Acronyms

ACC	Adaptive Cruise Control
BSM	Basic Safety Messages
CACC	Cooperative Adaptive Cruise Control
CAMP LLC	Crash Avoidance Metrics Partners LLC
ConOps	Concept of Operations
DSRC	Dedicated Short Range Communication
DVI	Driver-Vehicle Interface
FHWA	Federal Highway Administration
FMEA	Failure Modes and Effects Analysis
GPS	Global Positioning System
GTM	Government Task Manager
HMI	Human-Machine Interface
HV	Host Vehicle
I2V	Infrastructure-to-Vehicle
INFLO	Intelligent Network Flow Optimization
LIDAR	Light Detection and Ranging
OEM	Original Equipment Manufacturer
RF	Radio Frequency
RSE	Road-side Equipment
RV	Remote Vehicle
SARTRE	SAfe Road TRains for the Environment
SOW	Statement of Work
STPA	System-Theoretic Process Analysis
TMC	Traffic/Transportation Management Center

UCA	Undesired Control Action
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

APPENDIX B. List of Reviewed Publications

	Publication	Remark
1	Shladover, S.E., "AHS research at the California PATH program and future AHS research needs," *Vehicular Electronics and Safety, 2008. ICVES 2008. IEEE International Conference on*, vol., no., pp.4,5, 22-24 Sept. 2008, doi: 10.1109/ICVES.2008.4640915 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4640915&isnumber=4640848,	Automated Highway System (AHS) research report describes platoon scenarios
2	Shladover, S.E., "Truck automation operational concept alternatives," Intelligent Vehicles Symposium (IV), 2010 IEEE , vol., no., pp.1072,1077, 21-24 June 2010 doi: 10.1109/IVS.2010.5548061, URL:http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5548061&isnumber=5547951	HMI and responsibility transfer from the driver to the vehicle
3	Lu, X. -Y; Shladover, S.; Hedrick, J.K., "Heavy-duty truck control: short inter-vehicle distance following," *American Control Conference, 2004. Proceedings of the 2004* , vol.5, no., pp.4722,4727 vol.5, June 30 2004-July 2 2004 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1384058&isnumber=30144	String stability of actual vehicles (2 trucks) testing
4	Randolph Hall, Chinan Chin, "Vehicle Sorting for Platoon Formation: Impacts on Highway Entry and Throughput", 2002, California PATH Research Report, UCB-ITS-PRR-2002-7 URL:http://www.path.berkeley.edu/sites/default/files/publications/PRR-2002-07.pdf	AHS publication on platoon formation
5	Morbidi, F.; Colaneri, P.; Stanger, T., "Decentralized optimal control of a car platoon with guaranteed string stability," *Control Conference (ECC), 2013 European* , vol., no., pp.3494,3499, 17-19 July 2013 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6669336&isnumber=6669080	String stability for CACC
6	Thanh-Son Dao, Jan Paul Huissoon, A strategy for optimization of cooperative platoon formation 1 Int. J. Vehicle Information and Communication Systems, Vol. x, No. x, xxxx URL:http://www.hmc.edu/lair/publications/2013/dao_IJVICS_2013.pdf	Platoon formation
7	Yi Jiang, Shuo Li, and Daniel E. Shamo, "Development of Vehicle Platoon Distribution Models and Simulation of Platoon Movements on Indian Rural	FHWA-sponsored

	Corridors", FHWA/IN/JTRP-2002/23, URL:http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1543&context=jtrp	publication on platoon size
8	Fang, TaeHyun;Cho, DeukJae; Choi, JaeWeon; International Journal of Control, Automation and Systems," Optimal scheduling of a communication channel for the centralized control of a platoon of vehicles", 2013-08-01, p. 752-760, URL: http://ijcas.com/original/topic_abstract.asp?idx=1330	Communication channel
9	SARTRE EU project URL: http://www.sartre-project.eu/en/Sidor/default.aspx	SARTRE Website
10	Carl Bergenhem, Qihui Huang, Ahmed Benmimoun, Tom Robinson "Challenges of Platooning on Public Motorways", 2010, URL: http://www.sartre-project.eu/en/publications/Documents/ITS%20WC%20challenges%20of%20platooning%20concept%20and%20modelling%2010%20b.pdf	SARTRE publication on platooning challenges on public roadways
11	PROJECT FINAL REPORT: SAfe Road TRains for the Environment, 2013, URL: http://www.sartre-project.eu/en/publications/Documents/SARTRE_Final-Report.pdf	SARTRE final report on platooning general concepts, scenarios and results of the Eurpoean Union project

12	L.H.X. Hobert, Master's Thesis "A study on platoon formations and reliable communication in vehicle platoons", 2012 URL:http://essay.utwente.nl/61943/1/master_thesis_Laurens_Hobert.pdf	Master's Thesis on platooning and communication
13	Fernandes, P.; Nunes, U., "Platooning of autonomous vehicles with inter vehicle communications in SUMO traffic simulator," Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on , vol., no., pp.1313,1318, 19-22 Sept. 2010, URL:http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5625277&isnumber=5624963	Constant spacing versus constant time headway simulation of platooning and communication
14	Jonsson, Magnus; Kunert, Kristina; Böhm, Annette; Book Section, "Increased Communication Reliability for Delay-Sensitive Platooning Applications on Top of IEEE 802.11p", 2013, URL: http://dx.doi.org/10.1007/978-3-642-37974-1_10	Platooning and communication
15	Chi-Ying LIANG and Huei PENG, "String Stability Analysis of Adaptive Cruise Controlled Vehicles", 2000 URL:http://wwwpersonal.umich.edu/~hpeng/JSME2000.pdf ,	String stability introduction
16	S. Shladover, C. Nowakowski, D. Cody, F. Bu, J. O'Connell, J. Spring, S. Dickey, D. Nelson, "Effect of Cooperative Adaptive Cruise Control on Traffic Flow: Testing Drivers' Choices of Following Distances", Technical Report for State of California Department of Transportation, 2009. URL:http://www.dot.ca.gov/newtech/researchreports/reports/2009/final_report_task_0818.pdf	Nissan-sponsored CACC at UC Berkeley PATH
17	Steven E. Shladover, Christopher Nowakowski, Xiao-Yun Lu, Raymond Hoogendoorn "Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams - Definitions, Literature Review and Operational Concept Alternatives" California PATH Program, Technical University of Delft, File: EAR CACC Task 1 Concept of Operations Report Revised 063014.docx; URL: https://team-server.campllc.org/	Sponsored by FHWA Exploratory Advanced Research Program – Cooperative Agreement No. DTFH61-13-H-00013 – June 2014
18	Christopher Nowakowski, Steven E. Shladover, Delphine Cody, et al., "Cooperative Adaptive Cruise Control: Testing Drivers' Choices of Following Distances" File: PRR-2011-01.pdf URL: https://team-server.campllc.org/	Report on FHWA Exploratory Advanced Research Program
19	Sinan O¨ ncu¨, Nathan van de Wouw, W. P. Maurice H. Heemels and Henk Nijmeijer, "String Stability of Interconnected Vehicles Under Communication	String stability

	Constraints" URL: http://www.dct.tue.nl/New/Wouw/CDC2012_Oncu.pdf	
20	Ioannis Lestas and Glenn Vinnicombe, "Scalability in heterogeneous vehicle platoons" URL:http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4283022	Platooning scalability
21	Bart van Arem, Member, IEEE, Cornelie J. G. van Driel, and Ruben Visser, "The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics" URL:http://www.utwente.nl/ctw/aida/research/publications/AremDrielVisser2006.PDF	CACC impact on traffic flow
22	Fei Liu1, Rattaphol Pueboobpaphan1, and Bart van Arem2, "Assessment of Traffic Impact on Future Cooperative Driving Systems: Challenges and Considerations" URL: http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB0QFjAA&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D5345339&ei=smH3U-_7E9GqyASspoGwAg&usg=AFQjCNHRa1qMvWFF07TDKPNUAjSPuMLrjg&sig2=IRtrzzsziNO7wSjdfMWpJg&bvm=bv.73612305,bs.1,d.cGU&cad=rja	Cooperative driving system impact on traffic flow
23	Vicente Milanés, Steven E. Shladover, John Spring, Christopher Nowakowski, Hiroshi Kawazoe, and Masahide Nakamura, "Cooperative Adaptive Cruise Control in Real Traffic Situations", IEEE TRANSACTIONS ON ITS	CACC in real traffic situations
24	Steven E. Shladover, Dongyan Su, and Xiao-Yun Lu, "Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow"	CACC impacts on traffic
25	Fanping Bu, Han-Shue Tan and Jihua Huang, "Design and Field Testing of A Cooperative Adaptive Cruise Control System", 2010 American Control Conference Marriott Waterfront, Baltimore, MD, USA, June 30-July 02, 2010	CACC controller design and field testing
26	Christopher Nowakowski, Jessica O'Connell, Steven E. Shladover, and Delphine Cody, "Cooperative Adaptive Cruise Control: Driver Acceptance of Following Gap Settings Less Than One Second", PROCEEDINGS of the HUMAN FACTORS and ERGONOMICS SOCIETY 54th ANNUAL MEETING – 2010; File: HFES 2010 (CACC Driver Acceptance of Subsecond Gap Settings)	CACC Driver Acceptance of Subsecond Gap Settings

APPENDIX C. Research Timelines

Note: The numbering of research questions corresponds to material presented in Sections 3.4 through 3.7 of the report.

Overall Timeline – Task 2 Research Plan

	ACTIVITY	PLAN START	PLAN DURATION
3.4	Assess ACC Functionality Enhancement Using V2V Communication	1	18
3.5	V2V Communication for Cooperative ACC	1	31
3.6	Safety for CACC	7	34
3.7	CACC for Vehicle Platooning	1	24

Timeline – Assess ACC Enhancement Using V2V Communication

ACTIVITY	PLAN START	PLAN DURATION
3.4 Adaptive Cruise Control		
3.4.1, 3.4.1.1, 3.4.1.2		
Assess ACC Performnace and Headway Gap Reduction Using V2V Communication		
Adopt (standards/prior work)	1	2
Sys Design, Analysis and ConOps	3	4
Modeling & Simulation	7	4
Experimental Setup	11	2
Proto Built	13	3
Small-scale Test	16	3

PERIODS in MO. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Timeline – V2V Communication for Cooperative ACC

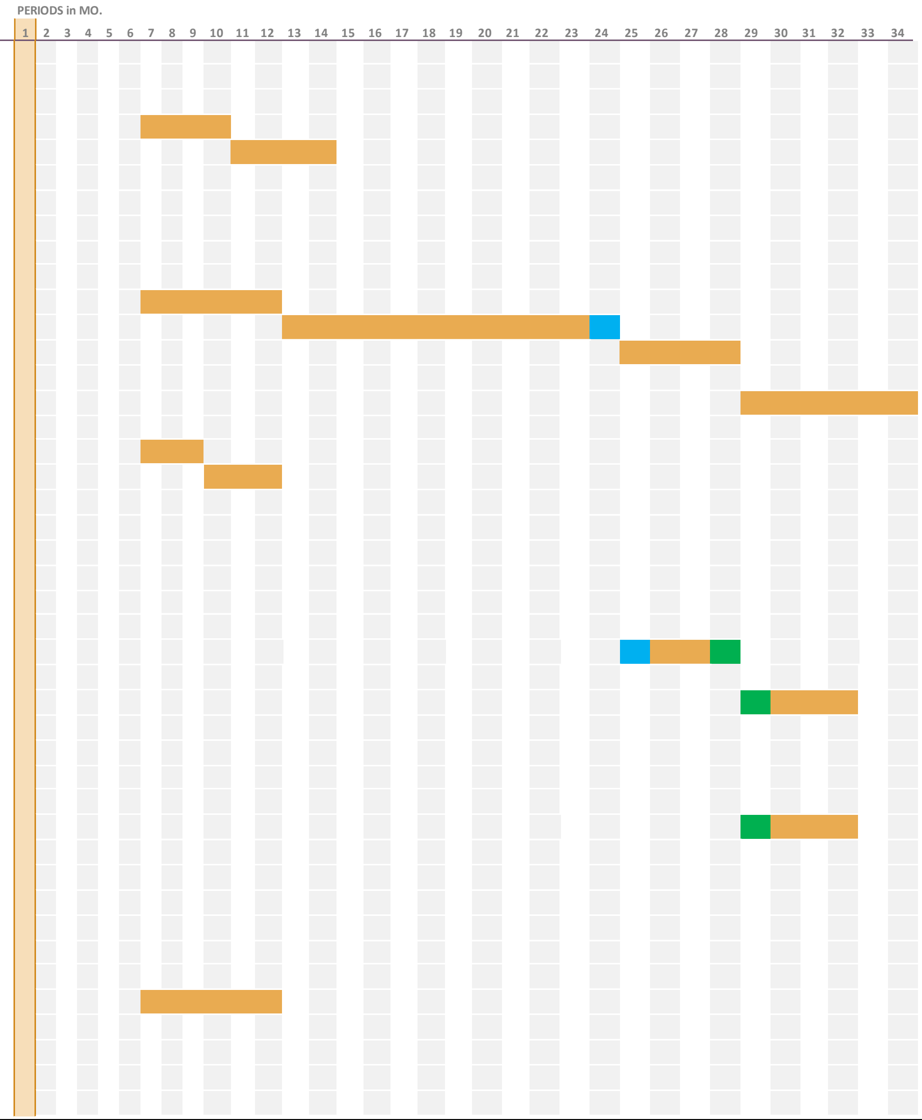
	ACTIVITY	PLAN START	PLAN DURATION
3.5	**V2V Communication for Cooperative ACC**		
3.5.1	**"Communication Only" Method for CACC**		
	Adopt (standards/prior work)	N/A	N/A
	Sys Design, Analysis and ConOps	1	2
	Modeling & Simulation	N/A	N/A
	Experimental Setup	N/A	N/A
	Proto Built	N/A	N/A
	Small-scale Test	N/A	N/A
3.5.2	**V2V Comm Msg & Transmission Rate**		
	Adopt (standards/prior work)	1	3
	Sys Design, Analysis and ConOps	4	2
	Modeling & Simulation	6	6
	Experimental Setup	12	1
	Proto Built	13	3
	Small-scale Test	16	3
3.5.2.1	**Assess sufficiency & effectiveness of V2V BSM**		
	Adopt (standards/prior work)	1	3
	Sys Design, Analysis and ConOps	4	2
	Modeling & Simulation	6	6
	Experimental Setup	12	1
	Proto Built	13	3
	Small-scale Test	16	3
3.5.2.2	**Assess comm latency/message loss**		
	Adopt (standards/prior work)	1	3
	Sys Design, Analysis and ConOps	4	2
	Modeling & Simulation	6	4
	Experimental Setup	10	1
	Proto Built	11	3
	Small-scale Test	14	3
3.5.2.3	**Determine Required Minimum Message Transmission Rate**		
	Adopt (standards/prior work)	1	3
	Sys Design, Analysis and ConOps	4	2
	Modeling & Simulation	6	6
	Experimental Setup	12	1
	Proto Built	13	3
	Small-scale Test	16	3

	ACTIVITY	PLAN START	PLAN DURATION
3.5.3	**Communication Protocol for CACC Platoon Discovery and Management**		
3.5.3.1	**Assess Need for "CACC Platoon Discovery Protocol"**		
	Adopt (standards/prior work)	12	3
	Sys Design, Analysis and ConOps	15	3
	Modeling & Simulation	18	6
	Experimental Setup	24	2
	Proto Built	26	3
	Small-scale Test	29	3
3.5.4	**Assess Impact of Communication Channel Management and Behavior**		
3.5.4.1	**Assess Need for Increased Message Transmission Rate and Impact on Processing Requirements and Channel Behavior**		
	Adopt (standards/prior work)	1	3
	Sys Design, Analysis and ConOps	4	3
	Modeling & Simulation	7	4
	Experimental Setup	11	2
	Proto Built	13	3
	Small-scale Test	16	3
3.5.5	**Assess Communication Security**		
3.5.5.1	**V2V Security Methodology**		
	Adopt (standards/prior work)	1	6
	Sys Design, Analysis and ConOps	7	3
	Modeling & Simulation	10	8
	Experimental Setup	18	2
	Proto Built	20	3
	Small-scale Test	23	3
3.5.6	**Assess Needs for Additional Comm Methods**		
	Adopt (standards/prior work)	1	2
	Sys Design, Analysis and ConOps	3	3
	Modeling & Simulation	6	4
	Experimental Setup	10	2
	Proto Built	12	3
	Small-scale Test	15	3

PERIODS in MO. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32

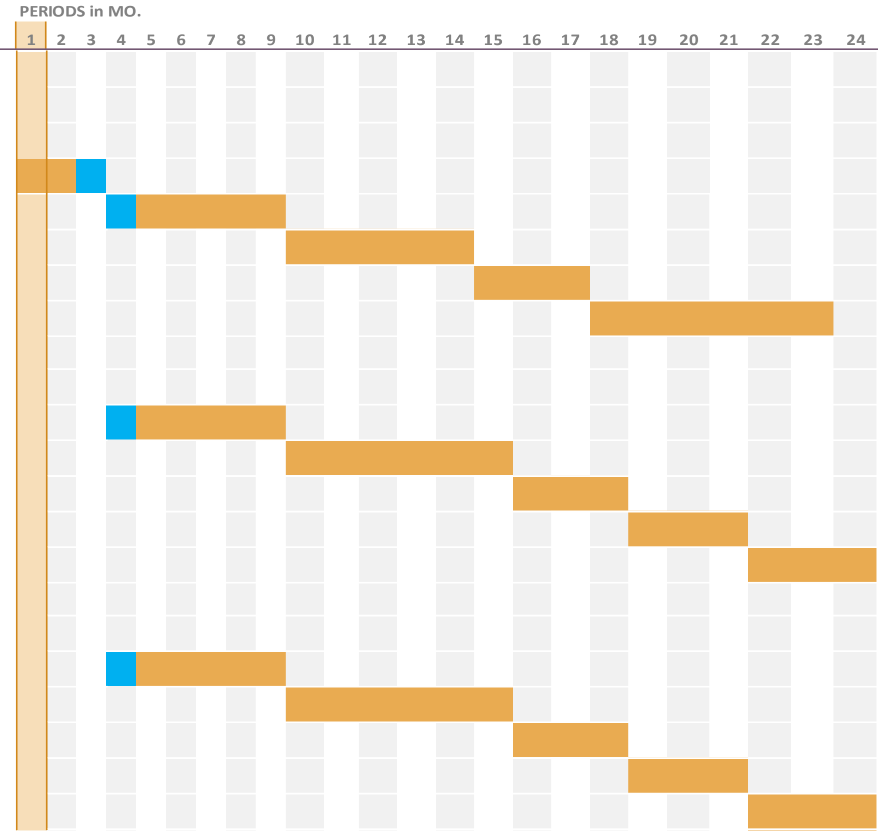
Timeline – Safety for CACC

	ACTIVITY	PLAN START	PLAN DURATION
3.6	**Safety for CACC**		
3.6.1	**Operational Safety**		
	Adopt (standards/prior work)	N/A	N/A
	Sys Design, Analysis and ConOps	7	4
	Modeling & Simulation	11	4
	Experimental Setup	N/A	N/A
	Proto Built	N/A	N/A
	Small-scale Test	N/A	N/A
3.6.1.1	**Assess Comm/Sensor Failure Impact**		
	Adopt (standards/prior work)	N/A	N/A
	Sys Design, Analysis and ConOps	7	6
	Modeling & Simulation	13	12
	Experimental Setup	25	4
	Proto Built	N/A	N/A
	Small-scale Test	29	6
3.6.1.2	**Impact of Road and Weather Condition for Safe Platooning**		
	Adopt (standards/prior work)	7	3
	Sys Design, Analysis and ConOps	10	3
	Modeling & Simulation	N/A	N/A
	Experimental Setup	N/A	N/A
	Proto Built	N/A	N/A
	Small-scale Test	N/A	N/A
3.6.2	**Minimum System Requirements**		
	Adopt (standards/prior work)	N/A	N/A
	Sys Design, Analysis and ConOps	25	4
	Modeling & Simulation	N/A	N/A
	Experimental Setup	29	4
	Proto Built	N/A	N/A
	Small-scale Test	N/A	N/A
3.6.3	**System Architecture for Safety**		
	Adopt (standards/prior work)	N/A	N/A
	Sys Design, Analysis and ConOps	29	4
	Modeling & Simulation	N/A	N/A
	Experimental Setup	N/A	N/A
	Proto Built	N/A	N/A
	Small-scale Test	N/A	N/A
3.6.4	**Functional Safety Requirements**		
	Adopt (standards/prior work)	N/A	N/A
	Sys Design, Analysis and ConOps	7	6
	Modeling & Simulation	N/A	N/A
	Experimental Setup	N/A	N/A
	Proto Built	N/A	N/A
	Small-scale Test	N/A	N/A



Timeline – CACC for Vehicle Platooning

	ACTIVITY	PLAN START	PLAN DURATION
3.7	**CACC for Vehicle Platooning**		
3.7.1	**Vehicle Platoon Sizing**		
	Adopt (standards/prior work)	N/A	N/A
Includes Truck, limited by communication range	Sys Design, Analysis and ConOps	1	3
	Modeling & Simulation	4	6
	Experimental Setup	10	5
	Proto Built	15	3
	Small-scale Test	18	6
3.7.2	**Platoon Formation & Management**		
	Adopt (standards/prior work)	N/A	N/A
	Sys Design, Analysis and ConOps	4	6
	Modeling & Simulation	10	6
	Experimental Setup	16	3
	Proto Built	19	3
	Small-scale Test	22	3
3.7.3	**Process of Joining and Leaving a Platoon**		
	Adopt (standards/prior work)	N/A	N/A
	Sys Design, Analysis and ConOps	4	6
	Modeling & Simulation	10	6
	Experimental Setup	16	3
	Proto Built	19	3
	Small-scale Test	22	3



U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free “Help Line” 866-367-7487
www.its.dot.gov

FHWA-JPO-16-257

U.S. Department of Transportation