Cooperative Adaptive Cruise Control Small-Scale Test – Phase 1

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16. Abstract

The focus of the Cooperative Adaptive Cruise Control – Small-Scale Test Project is to develop and implement CACC functionality as an extension of conventional ACC technology leveraging DSRC communications between vehicles and with the infrastructure. This report covers activities performed during Phase 1 of the research plan in which a reference ACC system was implemented in four prototype vehicles of different makes and models and baseline performance established through structured vehicle testing in a controlled environment. A simulation environment was established to model the behavior of vehicle strings under automated longitudinal control in freeway traffic. CACC algorithms were developed and evaluated in simulation, a preliminary hazard analysis was performed, and a safety concept was established for DSRC-enabled CACC.

Specific technical goals for the project were to assess the ability of DSRC-enabled CACC to improve situational awareness, reduce system latency and optimize time gap. The proposed CACC system was implemented in simulation using BSMs with a small message extension containing additional necessary data elements. Acceleration forecasts played an important role in improving CACC performance. Overall it was shown that, through use of data exchanged via DSRC, improvements in string-stability may be realized. Reduced time gaps within a string of equipped vehicles may also be feasible, if close attention is paid to the additional functional safety requirements. These results were obtained in simulation and will need to be verified through vehicle implementation in Phase 2 of the research plan.

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Executive Summary

Background

This report documents the work completed during the Cooperative Adaptive Cruise Control – Small-Scale Test Project (CACC-SST). The project was conducted by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium. The companies that participated in the project are Ford, General Motors, Hyundai-Kia, Honda, Mazda, Subaru, Volvo Technology of America, and Volkswagen Group of America. The project is sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH6114H00002, Work Order 6. The project began in July 2015 and was concluded in July 2017.

Previous research conducted by the CAMP V2I Consortium [1] considered the feasibility of implementing Cooperative Adaptive Cruise Control (CACC) utilizing Dedicated Short Range Communication (DSRC) to expand the functionality of Adaptive Cruise Control (ACC). The resulting research plan follows a two-phase approach. This report covers Phase 1 in which a reference ACC system was implemented in four prototype vehicles of different makes and models and baseline performance was established through structured vehicle testing in a controlled environment. These test results were used to parameterize the simulation environment which was established to model the behavior of vehicle strings under automated longitudinal control in freeway traffic. CACC algorithms were developed and evaluated in simulation. A preliminary hazard analysis was performed and a safety concept established for DSRC-enabled CACC. Phase 2, if conducted, would implement the proposed CACC system design in the prototype ACC vehicles and perform controlled testing and evaluation.

Objectives

Prior research suggests that CACC may provide benefits such as improved throughput on a given road segment resulting in improvements in fuel efficiency. Gains in throughput may result from more efficient vehicle distribution and consistent flow of traffic [2]. Improvements in fuel efficiency may result from the increased aerodynamic efficiency, provided by decreasing gaps between string members [3], and from reducing instances of unnecessary acceleration / deceleration [4]. Considering these suggested benefits, specific technical goals were defined for the project.

<u>Technical Goal 1 - Improve Situational Awareness</u>

Objective: Improve longitudinal control performance within the string by providing ACC with additional context information through communication.

<u>Technical Goal 2 - Reduce System Latency</u>

Objective: Reduce the latency of the string response to perturbations to provide smoother, more consistent traffic flow leading to increased throughput.

<u>Technical Goal 3 - Optimize Time Gap</u>

Objective: Reduce time gap within a string to improve traffic throughput under stable conditions by allowing an increase in vehicles per hour per lane.

Technical Approach

Prototype Vehicles

Four prototype ACC vehicles were built to provide longitudinal control characterization data for the simulation environment and to provide a platform for implementing DSRC-enabled CACC functionality in Phase 2. Vehicles were chosen which span the typical range of light vehicle size, mass and dynamic response characteristics. Different makes and models were chosen to span differences in longitudinal control system design. All vehicles contained production ACC systems capable of stop-and-go operation, which provided the base longitudinal control actuators needed to implement the prototype ACC / CACC system. A third-party ACC controller was also implemented to provide a common control architecture across vehicles.

Test scenarios were developed and executed to characterize prototype vehicle ACC performance and provide model parameterization data to the simulation environment. Model parameterization tests collected information on each of the four prototype vehicles individually including DSRC, vehicle dynamics, and radar characterization data. ACC performance testing characterized multi-vehicle string behavior in a variety of driving scenarios.

Simulation Environment

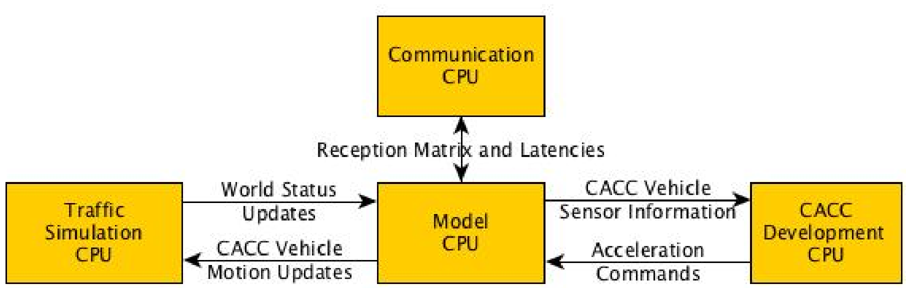
The simulation architecture includes four separate processing environments implemented using four different central processing units (CPUs) as shown in Figure 1.

Traffic Simulation CPU operating a Verkehr In Städten – SIMulationsmodell (A Traffic Flow Simulation) (VISSIM) traffic simulation model

Communication CPU operating a ns-3 Network Simulator to implement vehicle-to-vehicle (V2V) communications

Model CPU operating MATLAB/Simulink to implement vehicle sensors and dynamics

CACC Development CPU operating Automotive Data and Time-Triggered Framework (ADTF) to implement CACC algorithms in multiple vehicles



Source: CAMP V2I Consortium

Figure 1 - Simulation Environment Block Diagram

The output of the traffic simulation is location, speed, and lane position for each vehicle in the environment. This information is fed into a set of MATLAB/Simulink models to emulate the sensing aspects of the CACC, which includes a radar model, a GPS model (for all vehicles), and onboard vehicle sensor signals used by ACC or CACC. The Communication CPU applies a simplified model of the DSRC communication protocol to assign delay times or dropouts of BSM packets between each pair of vehicles. The results of simulated V2V communications are also fed into the MATLAB/Simulink model. The output of the MATLAB/Simulink model are the composite simulated sensor inputs to CACC which are fed to the CACC algorithm(s) for each vehicle that is currently being simulated. These algorithm instances produce acceleration and deceleration commands, which are fed back into the MATLAB/Simulink vehicle-dynamics model to simulate throttle, brake system, and vehicle-dynamics effects. The resulting CACC vehicle motion updates are then fed back into the traffic simulation to complete process.

CACC Software Development

A system architecture was established that implements CACC as an extension of ACC, leveraging the lessons learned from prototype ACC vehicle testing as well as ideas from prior research. The CACC algorithm development was initiated by creating a preliminary software architecture, assigning functionalities to the different software modules and establishing development priorities. The algorithm architecture was divided into essential and optional components and three software versions were defined.

Software Version 1 provides the core CACC functionality with all necessary basic software modules such as the object fusion, target selection and the longitudinal controller.

Software Version 2 builds upon software version 1 adding a multi-vehicle look-ahead (MVLA) function, which utilizes information from vehicles beyond the immediate preceding vehicle, and an assessment of the communication quality which, depending on the outcome of that assessment, dynamically adapts the time gap to the current situation.

Software Version 3 is the final software version that adds infrastructure support in the form of a merging assistant that would reside in a roadside unit at a highway on-ramp as well as performance improvements in other software modules.

Software modules were developed and implemented addressing key aspects of CACC operation for the proposed architecture including:

Adaptive Time Gap and Speed Support adapts the current time gap and speed setting of the CACC system based on an assessment of current communication quality and a hazard flag from preceding vehicles.

Communication Quality Determination observes Basic Safety Message (BSM) data received over time and calculates communication statistics to estimate the quality of DRSC communications including: Information Age and Communication-Induced Tracking Error.

In-lane Assessment receives a list of vehicles ahead, filters them for vehicles that are in the host vehicle's lane and outputs a subset of the original list of vehicles.

State Machine defines the logical behavior of the entire system transitioning to and from Manual, CC, ACC, CACC, Manual Recovery, and ACC Recovery states.

Virtual Target Creation synthesizes a virtual target based on various inputs and sends it to the vehicle's ACC longitudinal controller to implement CACC operation.

Hazard Analysis

Functional safety of the prototype CACC system was evaluated using a formal hazard analysis. Safety requirements were established and means to realize those requirements established in a Safety Concept developed for the experimental system. Three core operating scenarios were defined.

This analysis does not reflect any specific OEM implementation of ACC or CACC, which may differ from these findings.

Scenario 1 - Designated CACC Lane on a Freeway

Vehicles only operate in CACC mode on a designated freeway lane. A physical separation between this lane and the other driving lanes is possible and lane changes are either impossible or very unlikely. When entering and leaving the CACC lane, either the driver manually or the system automatically performs the activation / deactivation task.

Scenario 2 - CACC Operated on a Multi-Lane Freeway

CACC could be operated anywhere on a freeway and it would be the driver's responsibility to activate and deactivate the system whenever appropriate. This would include operation in a multi-lane environment. The CACC system would need to handle cut-ins by other vehicles as well as lane changes initiated by the host vehicle's driver.

Scenario 3 - CACC Operated on Non-Freeway Roads

CACC operation would be possible on non-freeway roads such as secondary or country roads but not on city streets. Operational speeds and traffic densities are assumed to be lower than the first two scenarios.

Outcomes and Implications

The results obtained in simulation suggest that improvements in CACC string-stability may be possible through use of data exchanged via DSRC. Reduced time gaps within a string of equipped vehicles may be feasible if close attention is paid to the additional functional safety requirements identified. These results will need to be verified through vehicle implementation in Phase 2 of the research plan. Significant progress was attained on the technical goals established for the project.

Technical Goal 1 - Increase Situational Awareness

Result: The CACC algorithm developed demonstrated enhanced awareness of and reaction to downstream traffic perturbations beyond the immediately preceding vehicle. Software modules that identify which vehicles are part of the same string were implemented and a concept for the anticipation of cut-in and cut-out maneuvers was evaluated.

Technical Goal 2 - Reduce System Latency

Result: In comparison to baseline performance of the prototype ACC system, the CACC algorithms implemented showed slightly improved response times using knowledge of the current state of preceding vehicle(s) and significantly improved response using future state forecast(s) exchanged using DSRC.

Technical Goal 3 - Optimize Time Gap

Result: CACC algorithms were characterized using reduced time gaps and were shown to perform appropriately under most conditions. Dynamic adjustment of time gap based on current performance conditions was implemented and evaluated.

ACC Baseline Performance

Response Lag: For prototype ACC vehicles driving in a string, a reaction time from one vehicle to another of ~1.5s was identified for the reference system implemented. The first half of this lag appears to be the result of sensing and processing delays. The second half is the result of implementing the desired system reaction. DSRC-enabled CACC may improve system performance by reducing the first half of the observed response delay.

Performance Harmonization: Characterization testing of the prototype ACC vehicles revealed that even with a uniform ACC algorithm implemented in each vehicle, following performance differs significantly. ACC strings were observed breaking up during acceleration maneuvers. These effects were amplified by road grade. This behavior was the result of differences in the way each OEM manages their production ACC interface with the vehicles' brake and engine control systems and restrictions intentionally placed on system response.

Road Grade Effect: The longitudinal control performance of prototype ACC vehicle strings was significantly impacted by road grade. Individual vehicle systems were not designed to compensate for acceleration / deceleration due to grade and prototype ACC string performance became unstable as a result.

CACC Algorithm Development

Extending ACC: CACC was implemented using an existing ACC longitudinal controller without modification. Benefits were realized by optimizing the input variables sent to the ACC controller based on the additional knowledge in the CACC platform. This approach may enable adaptation of longitudinal control systems found in ACC or automated driving vehicles to CACC.

Vehicles as Individual Agents: The prototype CACC system developed understands vehicles as individual agents that form their own decision. The situation is always analyzed from the perspective of the host vehicle considering driver inputs and downstream vehicle behavior(s). At a minimum, the behavior of the immediately preceding vehicle is addressed. Additional vehicles further down the string may be considered as well. Autonomous operation using information received from equipped vehicles nearby is less affected by potential communication issues and eliminates the risk of responding to third party commands.

Look-Ahead Concepts: Simulation results suggest that CACC implementation based on looking one vehicle ahead in the string can provide string-stable performance. Using acceleration status and forecasts from the preceding vehicle, it appears feasible to realize the benefits of CACC at a 1s time gap. When considering information received from multiple vehicles ahead, accurate determination of lane position is necessary to reduce false positives and false negative responses. The prototype CACC system proposed utilizes a simple method to make accurate lane assessment using the Basic Safety Message (BSM) temporary ID of the preceding vehicle's target vehicle to build a linked list of the vehicles in the string. This establishes a verified list of string members, where each member is validated through sensor fusion. This concept relies on adding target vehicle ID to the BSM data transmitted rather than sensor data, minimizing the impact on message size.

Lane-Change Detection: Analysis of data collected during prototype ACC vehicle testing found that assessment of individual parameters is insufficient for reliable lane-change detection. An algorithm that estimates lead vehicle lane-change probability based on multiple weighted parameters was implemented in simulation. The resulting performance suggests that a multi-parameter lane-change detection may be feasible but that additional testing and improvements beyond this project are required as the current implementation is not robust.

Reduced Time Gaps: Simulations of the proposed CACC algorithm show string-stable behavior at a time gap of 1s or more. However, for shorter time-gap operation, additional restrictions need to be considered:

- Time gaps below 1s should only be used if an acceleration forecast is received from the preceding vehicle which is also under CACC control.
- Concepts such as considering information from multiple preceding vehicles and adapting time gap based on a brake activation can significantly improve string stability and adherence to set time gap.
- Vehicles with slower responses to deceleration commands should restrict selectable time gaps accordingly. Driver assumption of control may be necessary for harsh braking events in both ACC and CACC modes. Restricting allowable minimum time gap based on vehicle response characteristics may mitigate this need, particularly for vehicles with slower response characteristics.

Set Speed: Simulation of CACC system performance suggests that gaps between CACC vehicles in a string increase during dynamic driving events when their target speeds are set to the same value. If tighter cohesion in a string is desired, the traditional concept of limiting vehicle response to the driver selected maximum set speed during recovery may need to be revisited.

Vehicle Jerk: Analysis of vehicle jerk levels indicates that jerk increases from vehicle to vehicle in the case of ACC and decreases from vehicle to vehicle in the case of CACC. The maximum (increased) jerk level in ACC was observed at the end of the string while the (reduced) maximum jerk level in the CACC string was observed at the second vehicle.

Road Grade Effect: The need to report true acceleration over ground is an important consideration for proper CACC operation, particularly if the lead vehicle only transmits current vehicle-dynamics data such as when a manually driven DSRC-equipped vehicle is at the head of a string. Based on the effects of road grade on prototype ACC vehicle performance and CACC algorithm simulations, the following actions are proposed:

- SAE J2945/1 should be modified to require grade compensation for longitudinal acceleration transmitted in the BSM.
- CACC vehicles should transmit acceleration forecasts based on target acceleration without compensation for grade so that the forecast describes the true desired motion of the vehicle.
- CACC-equipped vehicles' brake and engine control systems should adjust requested accelerations for grade to avoid unintentionally speeding up or slowing down.

DSRC Messaging

BSM Extension and Channel Selection: The proposed CACC system was implemented in simulation using BSMs with a small message extension containing necessary data elements transmitted at 10Hz. Use of the extension would effectively increase the message size of BSMs from CACC-enabled vehicles by 5%. This lightweight extension would allow the application to "piggyback" on the anticipated deployment of BSMs on channel 172. However, the congestion control algorithm specified in SAE J2945/1 might be inappropriate for CACC. Additional research is required in communication channel selection and congestion control implementation. The outcome of this study should lead to a recommendation to standards bodies on how to proceed for the CACC message definition.

Acceleration Forecast: Acceleration forecasts play an important role in improving CACC performance. While CACC implemented using current BSM content improved the reaction time of the control system in simulation, the improvement did not lead to a string-stable prototype algorithm at time gaps less than 1s. However, when the preceding vehicle is CACC enabled and transmits the proposed BSM message extension including its acceleration forecast, significant improvements were realized. Transmitting acceleration forecast data via DSRC appears essential to implementing CACC.

Functional Safety

The results of the Hazard Analysis indicated that the use of dedicated lanes to shield CACC vehicles from surrounding traffic does not lead to relaxed system safety requirements, while 0.6s time gaps drove higher system safety requirements than ACC, requiring a different safety concept.

Previous research by Schaeffner et.al. [5] provides insight into the development of a safety concept for ACC. There, it is shown that limitations in sensing performance (and thus potential false reactions) can be accommodated in the safety concept by designing the system in a way that the driver can identify malfunctions and is provided with sufficient time to react and override the system. However, this is only feasible when the system is operating at time gaps that provide the driver with enough time to perform the monitoring and mitigation tasks. If CACC was to be designed with reduced time gaps, its safety concept must provide for automated transition from short time gap following to a state controllable by the driver.

The safety concept developed for the prototype CACC system includes:

- A three-level monitoring concept to handle higher Automotive Safety Integrity Level (ASIL) levels and unavoidable sensor malfunctions
- Recovery transitions to mitigate risks after component failures
- A maximum allowable system deceleration rate of $-6m/s^2$ to provide sufficient time during the recovery transitions for the driver to assume control

Next Steps

To further develop the CACC concept and to better understand its potential benefits and lay the path for potential production vehicle implementation, the following additional initiatives are recommended:

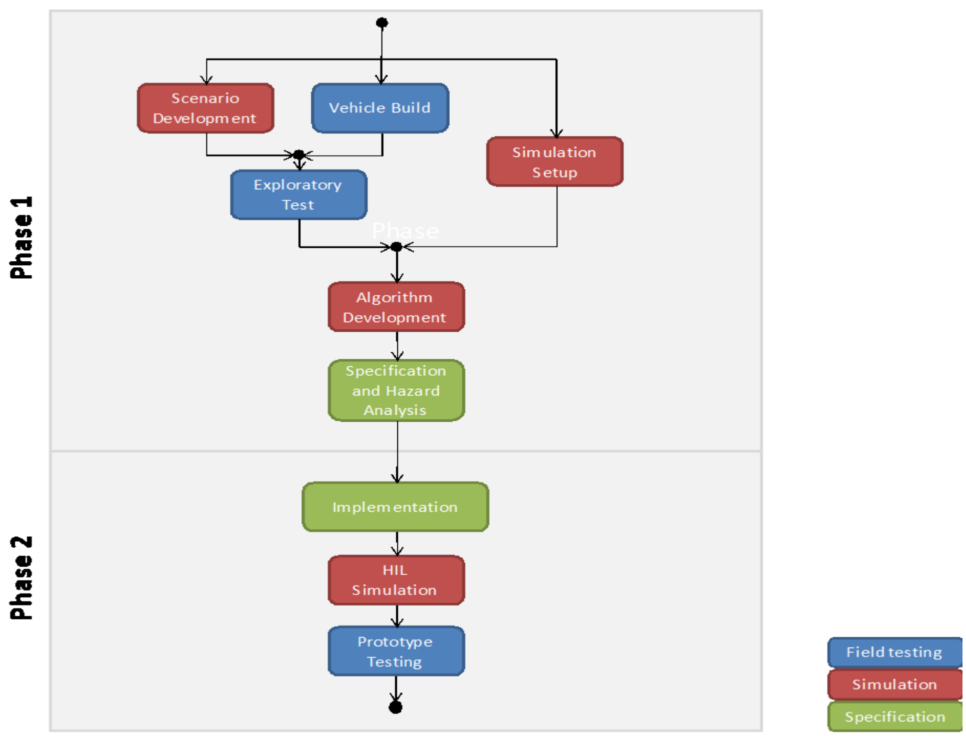
1. The performance of the CACC algorithm developed in simulation should be verified and refined through vehicle testing.
2. Discussion(s) should be initiated with relevant standards development organizations (SDO) to implement a BSM message extension containing data elements needed to support CACC operation.
3. The implications of communication congestion control on CACC operation and the implications for DSRC channel utilization should be evaluated.
4. Performance requirements for classes of CACC-equipped vehicles should be established to ensure interoperability and stable string performance.
5. Future research should explore the applicability of the CACC string stability improvement concepts developed in this project to other longitudinal control systems.

1 Project Scope & Objectives

1.1 Project Structure

Previous research conducted by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium [1] considered the feasibility of implementing Cooperative Adaptive Cruise Control (CACC) utilizing Dedicated Short Range Communication (DSRC) to expand the functionality of Adaptive Cruise Control (ACC). The analysis recommended a focused research effort to explore the viability and efficacy of DSRC-enabled CACC through prototyping and small-scale testing of a representative system.

The resulting research plan follows a two-phase approach shown in Figure 2. This report covers Phase 1, which implemented a prototype ACC system in test vehicles, characterized baseline performance, developed and evaluated CACC control algorithms in a simulation environment, performed a preliminary hazard analysis and established a safety concept for DSRC-enabled CACC. Phase 2, if conducted, would implement the proposed CACC system design in the prototype ACC vehicles and perform controlled test and evaluation.



Source: CAMP V2I Consortium

Figure 2 - CACC Phased Research Plan

1.2 Project Goals

Research suggests that CACC may provide benefits such as improved throughput on a given road segment due to more efficient vehicle distribution and consistent flow of traffic [2]; higher fuel efficiency resulting from the increased aerodynamic efficiency provided by decreasing gaps between string members [3]; and from reducing instances of unnecessary acceleration / deceleration [4]. Considering these suggested benefits, specific technical goals were defined for the project.

1.2.1 Technical Goal 1: Improve Situational Awareness

Objective: Improve longitudinal control performance within the string by providing ACC with additional context information through communication.

Reduction in unnecessary acceleration / deceleration and perturbations in surrounding traffic may be accomplished by improving the world view of the system. For example:

1. If the CACC string is approaching a group of slower vehicles, deceleration may begin earlier and more smoothly
2. If a vehicle ahead in the string is braking, deceleration may begin in anticipation prior to / in coordination with the response of the immediate preceding vehicle
3. If a vehicle in an adjacent lane activates its turn signal, the impending lane change can be anticipated and string behavior adapted more rapidly

1.2.2 Technical Goal 2: Reduce System Latency

Objective: Reduce the latency of the string response to perturbations to provide smoother, more consistent traffic flow leading to increased throughput.

Phantom traffic jams are created when perturbations are introduced in strings of vehicles which are not 'string-stable.' Research shows that strings of ACC vehicles are typically not string-stable. One study summarizes the findings from ACC and CACC vehicle testing: “The responses provide a clear indication that the CACC system is strictly L2 string stable, whereas the ACC system is not. Noteworthy is the fast increase in overshoot for increasing vehicle index in case of ACC” [6]. When a reduction in speed occurs within the string, the deceleration required by following vehicles grows from vehicle to vehicle, eventually bringing the vehicles to a full stop. Communicating the behavior of preceding vehicles, actual or planned, within the string might reduce response time and improve the string stability.

1.2.3 Technical Goal 3: Optimize Time Gap

Objective: Reduce time gap within a string to improve traffic throughput under stable conditions by allowing an increase in vehicles per hour per lane.

However, when the impact on string stability in response to perturbations and the implications for surrounding traffic are considered, the optimum time gap for throughput and system safety across a broad range of conditions may not be the minimum achievable under stable conditions. Therefore, means to identify the appropriate time gap strategy for the current situation and mode of operation need to be developed.

1.3 Assumptions

In order to manage project scope, design assumptions were made that limit the functionality of the CACC system specified in this project.

1. CACC is a level 1 automation system with longitudinal control only.
2. CACC is not a safety system and has limitations in available acceleration and deceleration.
3. If system limitations are reached, either the driver or a safety system will take over.
4. CACC system limitations (e.g., supported time gap, maximum deceleration) may be different than those of an ACC system.
5. From a driver interaction perspective, CACC will behave in a similar manner to current production ACC systems (i.e., engagement, disengagement).
6. As with ACC, the driver is expected to constantly monitor CACC operation and to take countermeasures in case of system failures.
7. CACC is intended for operation in a freeway-like driving environment. The system does not consider non-motorized road users, traffic lights or obstacles. If encountered, it is the driver's responsibility to mitigate any potential issues and maintain safe operation of the vehicle.
8. CACC can be operated in single-lane (e.g., single high-occupancy vehicle (HOV) lanes) or multi-lane environments where lane changes are to be anticipated.
9. CACC is implemented using a single, front-facing Radar sensor, a DSRC radio and a GPS receiver.
10. CACC will consider infrastructure input for the selection of both time gap settings and the set speed.
11. CACC operation is based on maintaining a constant time gap and only uses a constant distance-gap control for low-speed operation.
12. CACC string operation is possible when following a DSRC-equipped lead vehicle that does not have CACC.
13. CACC strings will form through "ad-hoc clustering."
14. Vehicles under CACC control form their own decisions based on information received from the environment.
15. Platooning can be defined as an extension of CACC that adds coordination and management aspects to the ad-hoc operation of CACC.
16. Vehicles in a platoon cede a portion of their decision-making authority to the platoon leader.

1.4 Definition of Terms

The following is a list of terms that are frequently used in this report (Table 1). While slightly different definitions may exist in other literature, these are the definitions applied in this project.

Table 1 - Definition of Common Terms

Term	Definition
Target Vehicle	The vehicle that is currently considered for control input. Typically, this is the immediate preceding vehicle that is in the same lane as the host vehicle.
Virtual Target Vehicle	The virtual target vehicle is created by the "Virtual Target Creation" software module to allow target vehicle distance and speed to be modified in order to trigger an optimized control action in the longitudinal controller.
String	A group of vehicles following each other on the same traffic lane. A string is formed by at least three or more vehicles.
Manual-String	A string that is under human driver control.
ACC-String	A string that is under ACC control.
Platoon	A string that is under management by a leader (coordinated).
Headway	Distance from the tip of the host vehicle to the tip of the preceding vehicle
Time-Headway	The time that the host vehicle would need at its current speed to travel the headway distance
Clearance	Distance from the rear bumper of the preceding vehicle to the front bumper of the host vehicle
Time Gap	The time that the host vehicle would need at its current speed to travel the clearance distance
CC	Cruise Control – A system state of an ACC or CACC system when no target vehicle is detected, and the system operates solely based on maintaining a set speed.
ACC	Adaptive Cruise Control – A Level 1 automation system that longitudinally controls a vehicle based on a set speed and distance to the preceding vehicle using sensor systems such as Radar for the detection of preceding vehicle(s). Strings of ACC vehicles form "ad-hoc" and car following is based on a constant time gap strategy.
CACC	Cooperative Adaptive Cruise Control – A system that extends ACC through the use of communication between the vehicles in addition to the other sensing techniques.
Platooning	Platooning is a more structured vehicle automation system than (C)ACC which uses a constant, distance-based-car-following strategy. Typically, formal joining and leaving maneuvers are involved and vehicles are more tightly coupled than in case of (C)ACC.

Source: CAMP V2I Consortium

1.5 Organization of the Report

The report is structured by major work activities undertaken in Phase 1. Section 2 addresses prototype ACC vehicle build and test. The vehicle level performance characterization obtained from vehicle testing feeds into Section 3 which discusses creating and operating the CACC simulation environment. Section 4 discusses CACC algorithm development and evaluation. The hazard analysis performed and system safety concept established for CACC are covered in Section 5. Section 6 concludes with a summary of key observations for Phase 1 of the project and recommendations for the further research.

2 Vehicle Build & Test

Four prototype ACC vehicles were built in Phase 1 of the project to provide longitudinal control characterization data for the simulation environment and a platform for implementing DSRC-enabled CACC functionality in Phase 2. A third-party ACC controller was implemented in all the vehicles to provide a common control architecture which can be adapted to the CACC system design being developed in simulation.

2.1 Implementation

Vehicles were chosen which span the typical range of light vehicle size, mass and dynamic response characteristics (Table 2). Different makes and models were chosen to span differences in longitudinal control system design. All vehicles contained production ACC systems capable of stop-and-go operation, which provided the base longitudinal control actuators needed to implement the experimental ACC / CACC system.

Table 2 - Vehicle Selection

Type	Length	Width	Height	Weight
Hatchback	4.2m	1.76m	1.45m	1350kg
Mid-size sedan	4.8m	1.87m	1.47m	1600kg
Full-size sedan	5.0m	1.89m	1.46m	1800kg
Large SUV	5.7m	2.05m	1.88m	3300kg

Source: CAMP V2I Consortium

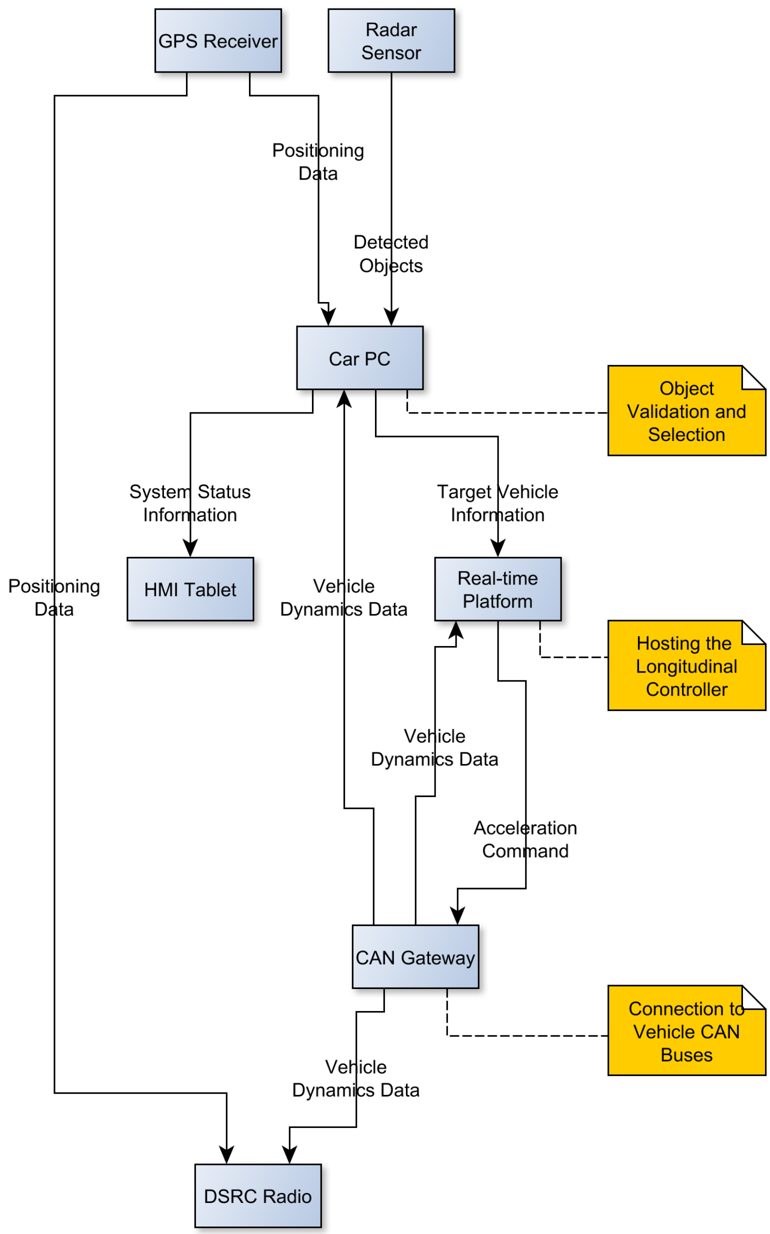
2.1.1 Vehicle Architecture

The reference ACC / CACC architecture implemented is shown at a high level in Figure 3. The detailed hardware architecture and component list are contained in APPENDIX B.

The reference architecture contains a GPS receiver and a Radar sensor, both of which are connected to an x86 Car PC. This unit hosts the object validation and target selection algorithms. Current system status information can be displayed on the driver Human-Machine Interface (HMI) using a connected tablet.

Target vehicle information is forwarded to the real-time platform where a two-staged longitudinal controller implements distance control and speed control. The resulting acceleration command is sent to the Controller Area Network (CAN) gateway, which converts the command into OEM-specific longitudinal control messages. The gateway also receives vehicle-dynamics information in OEM specific CAN messages and converts them into a uniform message format. This design makes it possible to implement an identical prototype platform into all prototype vehicles.

The architecture also includes a DSRC radio that receives current vehicle-dynamics data and transmits Basic Safety Messages (BSMs). The radio could also be used to interact with the infrastructure to implement coordinated control functions. However, this was not utilized during Phase 1 vehicle testing.



Source: CAMP V2I Consortium

Figure 3 - ACC / CACC Vehicle Hardware Architecture

2.1.2 ACC Algorithm

The prototype ACC algorithm allows the driver to set a target speed and to select one of five different time gaps.

Using distance and relative speed to the remote vehicle measured by the radar as input, the host vehicle desired acceleration is determined such that the desired distance is achieved and maintained. The desired acceleration is sent to the longitudinal controller which controls throttle, brake and gear shift accordingly. Because each vehicle's brake and engine control systems are an OEM specific design, some vehicles do not take the desired acceleration as a direct input. In this case, a converter was implemented just behind the longitudinal controller, to transform the desired acceleration into acceptable input such as torque request and brake pressure.

The ACC algorithm has stop and go capabilities, which allow the host vehicle to come to a full stop and continue after the radar has detected movement in the remote vehicle ahead without driver input. This is also dependent on the OEM specific implementation of their ACC systems.

The radar does not detect static objects, so it will acquire the target once the remote vehicle begins to move at a low speed. The ACC algorithm maximum acceleration and deceleration values are +2 m/s^2 and -3m/s^2, respectively.

2.2 Scenarios

Test scenarios were developed to characterize prototype vehicle ACC performance and provide model parameterization data to the simulation environment. The ACC characterization tests can be executed again in subsequent phases of the project when the CACC systems are available to directly compare the performance of both systems. The model parameterization tests DSRC, vehicle dynamics and radar parameterizations. Both sets of tests were performed on the Smart Road test facility at the Virginia Tech Transportation Institute (VTTI). Table 3 provides an overview of the test scenarios defined. Detailed descriptions of each scenario are provided in Appendix D.

Table 3 - Vehicle Test Scenarios

Scenario Name	Category	# of Lanes
T-1 Lane-Change Detection	Characterization	2
T-2 Lane-Change Detection 2	Characterization	2
T-3 Vehicle Cut-In Maneuver	Characterization	2
T-4 Vehicle in the Middle Leaves string	Characterization	2
T-5 Overtaking	Characterization	2
T-6 Lane Change Following	Characterization	2
T-7 Lane Assignment in Curve	Characterization	3
T-14 Vertical Curvature Effects	Characterization	1
T-10 Stop & Go	Characterization	1
T-11 String Stability	Characterization	1

Scenario Name	Category	# of Lanes
T-13 Weather	Characterization	1
T-8 DSRC Performance	Parameterization DSRC	1
T-17 Brake Pedal Step Inputs	Parameterization Vehicle Dynamics	1
T-18 Brake Pedal Step Input while already Lightly Braking	Parameterization Vehicle Dynamics	1
T-19 Maximum Acceleration	Parameterization Vehicle Dynamics	1
T-20 Transmission Gear	Parameterization Vehicle Dynamics	1
T-21 Step Inputs in Set Speed and Coast Downs	Parameterization Vehicle Dynamics	1
T-22 Lane Changes	Parameterization Vehicle Dynamics	2
T-23 Following a Lead Vehicle that is Changing Speed	Parameterization Vehicle Dynamics	1
T-24 Radar - Approach and Follow	Parameterization Radar	1
T-25 Radar - Vehicle in Adjacent Lane and Ahead	Parameterization Radar	2

Source: CAMP V2I Consortium

Most parameterization tests were single-vehicle tests aimed at collecting dynamic vehicle data for each of the four test vehicles (tests 23, 24, and 25 involved more than one vehicle). Table 4 lists the parameterization tests executed, their priority level, how many trials were required per vehicle, and the total number of runs completed as part of the final data set.

Table 4 - Model Parameterization Testing

Scenario	Description	Priority	Trials	# of Runs
17	Brake Pedal Step Inputs	1	4	16
18	Brake Pedal Step Input while Already Lightly Braking	2	2	8
19	Max Acceleration	1	2	8
20	Transmission Gear	2	2	8
21	Step Inputs in Set Speed and Coast Downs	1	2	8
22	Lane Changes	2	2	8
23	Following a Lead Vehicle that Is Changing Speed	1	2	8
24	Radar – Approach and Follow (Event 1 and 2)	1	4	8
24	Radar – Approach and Follow (Event 3)	1	4	8
25	Radar – Vehicle in Adjacent Lane and Ahead (Event 1)	1	4	4
25	Radar – Vehicle in Adjacent Lane and Ahead (Event 2)	1	4	8
			Total	92

Source: CAMP V2I Consortium

ACC characterization testing was conducted in order of scenario priority, which is detailed in Table 5. Test 13 utilized the weather towers on the Smart Road to generate 1.2 inches of rain per hour with the goal of challenging the vehicle radar sensor. This was the maximum amount of rain the weather towers could generate.

Table 5 - ACC Characterization Testing

Scenario	Description	Priority	Spacing	Set Speed	Trials	# of Runs
1	Lane Change – Out	2	1	2	10	20
2	Lane Change – In	2	1	1	10	10
3	Cut-In	1	1	1	10	10
4	Mid String – Out	1	2	1	10	20
5	Stopped Vehicle – Lead Lane Change	1	2	2	10	40
6	Lane Closure	4	3	1	4	12
7	Curve	2	1	1	10	10
8	DSRC Performance	1	2	1	10	20
10	Stop and Go	3	1	1	10	10
11	String Stability	1	2	1	10	20
13	Weather	3	1	1	12	12
						184

Source: CAMP V2I Consortium

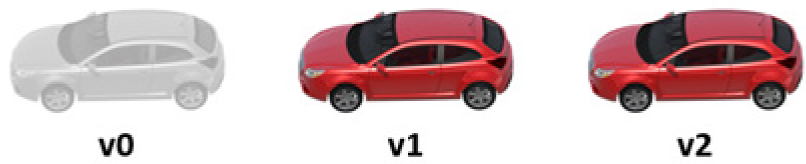
2.3 Outcomes

A wide range of CACC scenarios were examined. The results from characterization testing were used to calibrate various vehicle parameters in the simulation environment as discussed in Chapter 3. The following section summarizes key analyses conducted to examine String Stability (Response Lag Analysis), DSRC Performance, Lane-Change Detection and the Impacts of Grade on CACC performance.

2.3.1 Response Lag Analysis

During the testing, the four test vehicles were operated in a string with all ACC systems engaged. This allowed the study of string stability and how reactions to perturbations propagate from one vehicle to another. Since the reduction of these latencies are one of the key goals for CACC, the baseline performance of a typical ACC system needed to be established.

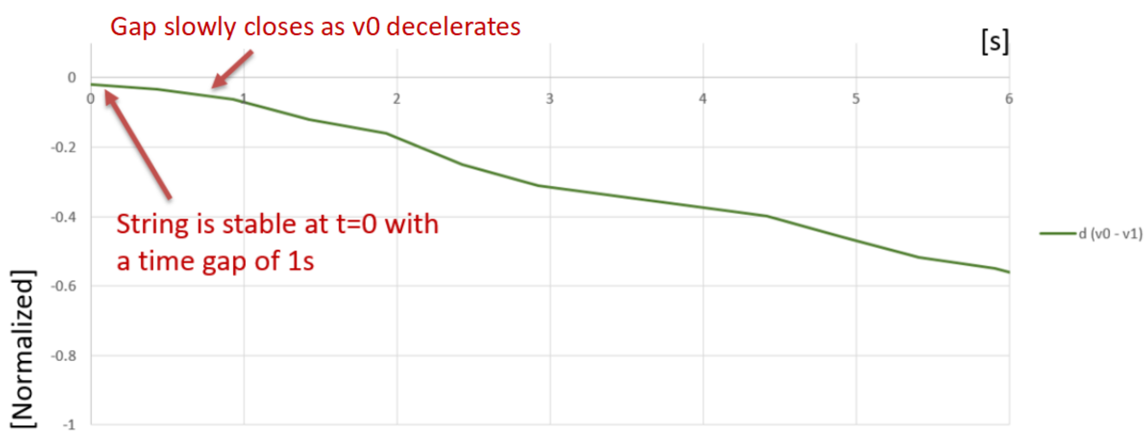
The following analysis is based on a scenario depicted in Figure 4 where a string of three vehicles (v0, v1, v2) traveling at constant speed under ACC control are following each other at a steady state with a time gap of 1s. Distance, velocity and acceleration traces are all normalized relative to their respective maximum values observed during the scenario for ease of comparison, resulting in values between -1 and +1



Source: CAMP V2I Consortium

Figure 4 - Relationship of ACC Vehicles in the String

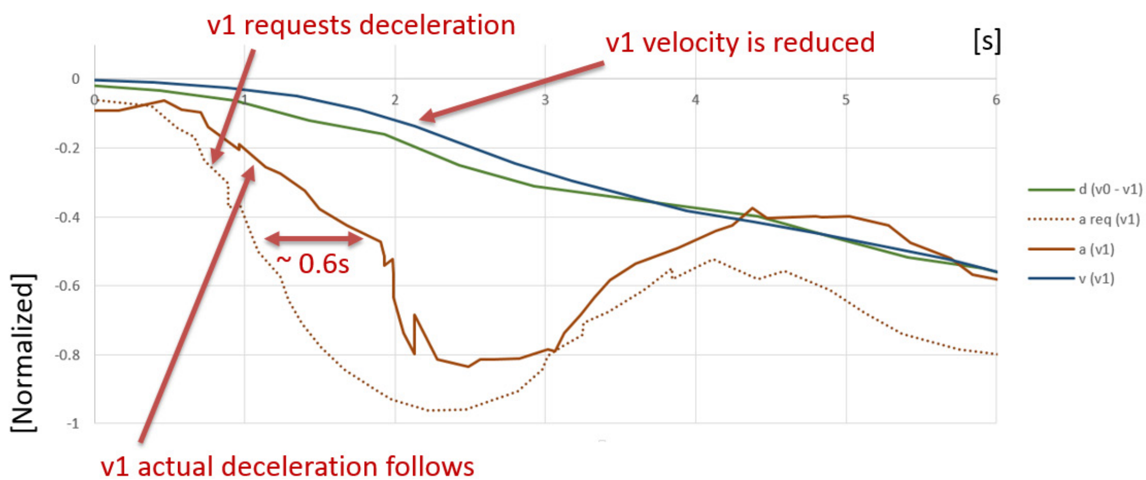
At time t=0, v0 initiates a brake maneuver. Figure 5 shows this brake maneuver as observed by v1 through the distance readings from its radar sensor.



Source: CAMP V2I Consortium

Figure 5 - Distance between v0 and v1

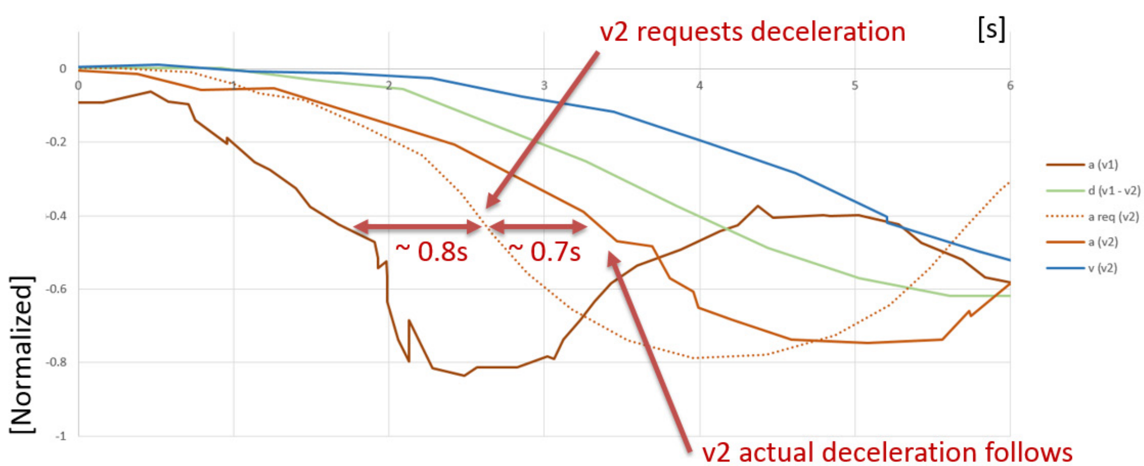
The response by vehicle 1 is shown in Figure 6. The dashed brown line represents the requested deceleration that the prototype ACC system calculates. The solid brown line shows the actual deceleration the vehicle is performing based on the request. A delay of around 0.6s between those two values can be seen.



Source: CAMP V2I Consortium

Figure 6 - Response by Vehicle 1

Figure 7 shows the reaction of vehicle 2 to the deceleration of vehicle 1. Vehicle 1's actual deceleration is represented by the solid brown line in the graph. Vehicle 2's deceleration command is shown in the dashed orange line in the graph. The actual deceleration of vehicle 2 is shown in a solid orange line.



Source: CAMP V2I Consortium

Figure 7 - Response by Vehicle 2

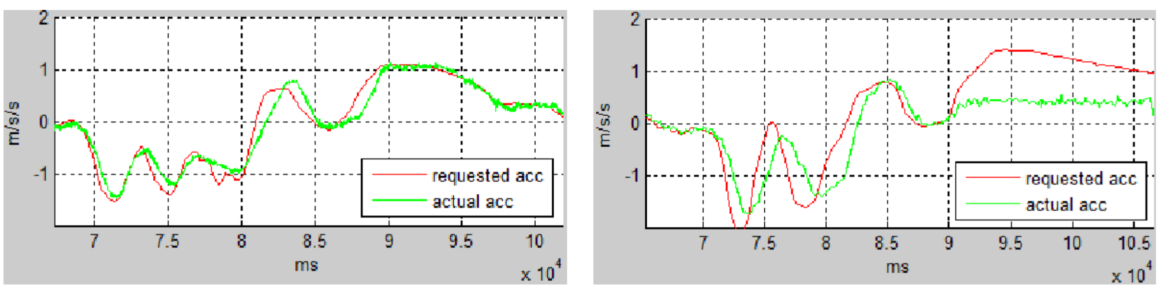
Between the actual accelerations of the two vehicles, a latency of around 1.5s can be observed. This latency is initially small but grows over time. This latency can be divided into two components:

1. The first component can be attributed to the sensing and decision making of vehicle 2's ACC system. In this example, this is around 0.8s long. This latency can potentially be reduced using CACC through faster communication of lead vehicle deceleration status or by predicting future actions.

2. The second component is the delay from issuing an acceleration command to the vehicle response. This is a property of the individual vehicle which will be the same for ACC and CACC responses. This delay includes potential filtering algorithms in the brake and engine control systems, communication latencies, as well as response latencies in the brakes and the engine. It is assumed that these components will not be modified for CACC and, therefore, these delays will remain unchanged.

In both the ACC and CACC modes, the host vehicles are controlled by acceleration commands generated by the Longitudinal Controller. The controller issues acceleration commands within the operational limits outlined in ISO22179. The acceleration commands are then forwarded to OEM brake and engine control systems. In some cases, the vehicle integrator had to implement conversion modules from acceleration commands to engine torque, brake pressure or speed commands.

During the vehicle testing, significant differences in vehicle response were observed. On multiple occasions, it was observed that the string of vehicles would break up because some vehicles did not accelerate as fast as others. This occurred in typical driving scenarios that one would experience frequently while driving on a freeway. Through a data analysis, it was found that this is not due to calculation errors in the prototype ACC system but due to limitations in the interface that was being used to control the vehicles. This is illustrated in Figure 8 comparing the requested acceleration generated by the prototype ACC system with the actual acceleration for two of the prototype ACC vehicles. The left plot shows an example where the requested acceleration is well followed by the actual acceleration with a reasonable time lag. In the right plot, the requested acceleration is not followed after 9.1 x 10^4 ms.



Source: CAMP V2I Consortium

Figure 8 - Vehicle Response to Acceleration Command

The following differences between these vehicles were identified:

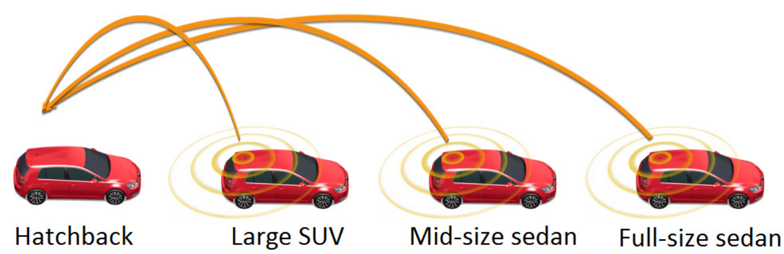
1. For one of the vehicles, the cause for the difference between the acceleration command and the actual acceleration is the result of not compensating for grade. This effect is only visible on significant grades and was observed here because testing was conducted on the VTTI Smart Road which has a grade of up to 6 percent. This is discussed further in Section 2.4.4 Impact of Grade.

2. For another vehicle, the differences between acceleration command and response originate in the interface between the production engine control module and the prototype ACC system. Here, the engine control module itself selects appropriate accelerations based on requested speed changes. Specific accelerations to reach a certain speed cannot be requested. The acceleration selection by the OEM module is more conservative than in the other vehicles.

Even with the observed limitations, CACC is expected to improve overall string performance of the string through faster communication of the lead vehicle deceleration status or by predicting future actions, limiting necessary accelerations and decelerations. However, if tighter vehicle following and minimizing strings break-ups are desired for CACC, a more harmonized vehicle performance will be necessary. ISO22179 currently only specifies maximum acceleration and maximum deceleration values. For CACC, it might be necessary to further specify minimum acceleration capabilities to ensure a more harmonized behavior. At this point, no technological restrictions have been identified that prohibit a more harmonized approach. It can be achieved through different OEM design choices and parameterization.

2.3.2 DSRC Performance Analysis

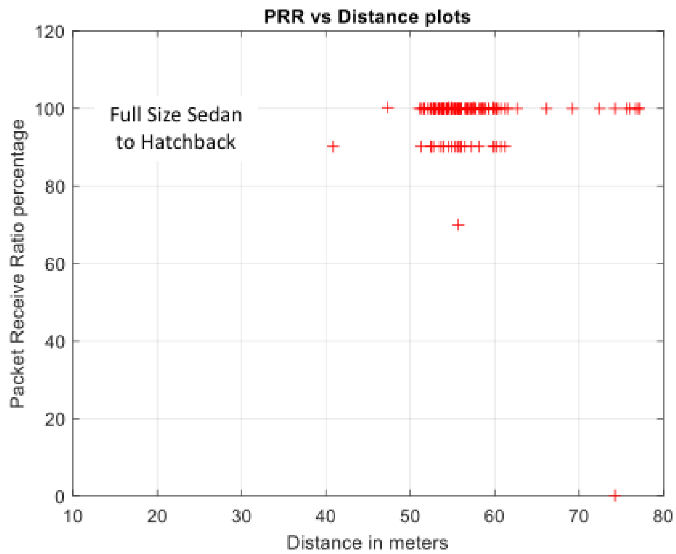
Based on the test scenario T-8 "DSRC Performance," an analysis was conducted to identify performance measures for intra-string communication and identify any potential issues with the prototype vehicle DSRC integration. Figure 9 shows the vehicle string setup to study the intra-string communication. The four prototype vehicles were driving in a string with constant headway and transmitting and receiving messages between each other. The distance between the vehicles was set to 10-20m which represents a 0.5s time gap at highway speeds.



Source: CAMP V2I Consortium

Figure 9 - Intra-String Communication Scenario

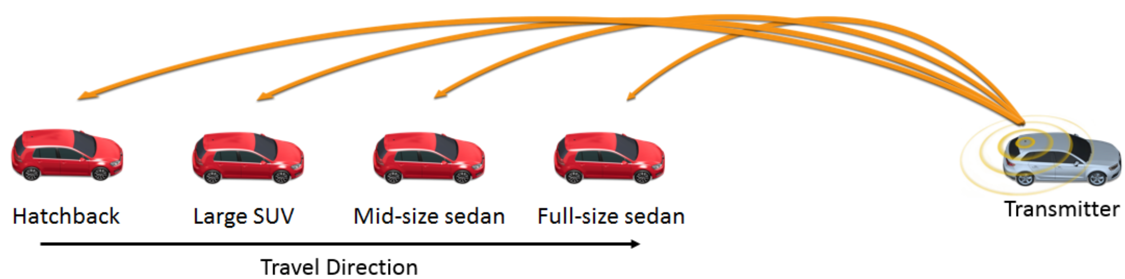
The observed communication performance can generally be described as very reliable. The communication between the first and the last vehicle achieved packet receive ratios > 90% as shown in Figure 10 demonstrating that reliable communication with vehicles ahead in the string can be extended beyond the immediate preceding vehicle



Source: CAMP V2I Consortium

Figure 10 - Intra-String Communication Hatchback - Full-size Sedan

Communication with a vehicle ahead of the string was also evaluated as shown in Figure 11. This vehicle acted as a transmitter sending messages to the four vehicles in the string as they slowly approached to evaluate communication performance at different distances.



Source: CAMP V2I Consortium

Figure 11 - Communication Range Scenario

The test was evaluated from the perspective of all four string vehicles and repeated in both downhill and uphill scenarios. Table 6 illustrates the differences in communication performance observed based on road grade and installed antenna height.

Table 6 - Communication Range with a Vehicle ahead of the String

Host Vehicle	Grade Up	Grade Down	Antenna Height
Full-size sedan (1)	400 m	900 m	142 cm
Mid-size sedan (2)	100 m	100 m	109 cm
Large SUV (3)	500 m	900 m	185 cm
Hatchback (4)	200 m	500 m	141 cm

Source: CAMP V2I Consortium

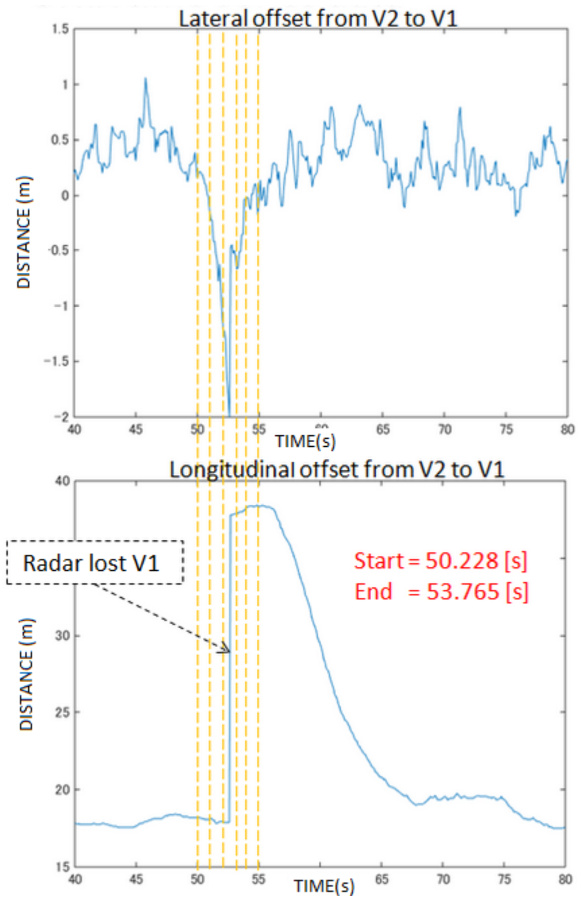
The following observations can be made based on this evaluation:

1. In general, the communication performance is better traveling downhill than when going uphill.
2. The higher the antenna is positioned on the vehicle, the better the range. In case of the mid-size sedan, the vehicle's body obstructed the communication with preceding vehicles since the antenna was mounted on the trunk.
3. The position in the string impacts the range, with obstructing vehicles negatively impacting the communication range of trailing vehicles.
4. Communication with next few preceding vehicles in a string can be very reliable. The string is also able to receive messages from vehicles further down the road to e.g., react to the upcoming end of a traffic jam.

2.3.3 Lane-Change Detection Analysis

Cut-in and cut-out maneuvers are driving situations where DSRC data might help improve the performance of ACC. The following analysis studies key parameters during lane changes that were observed during testing.

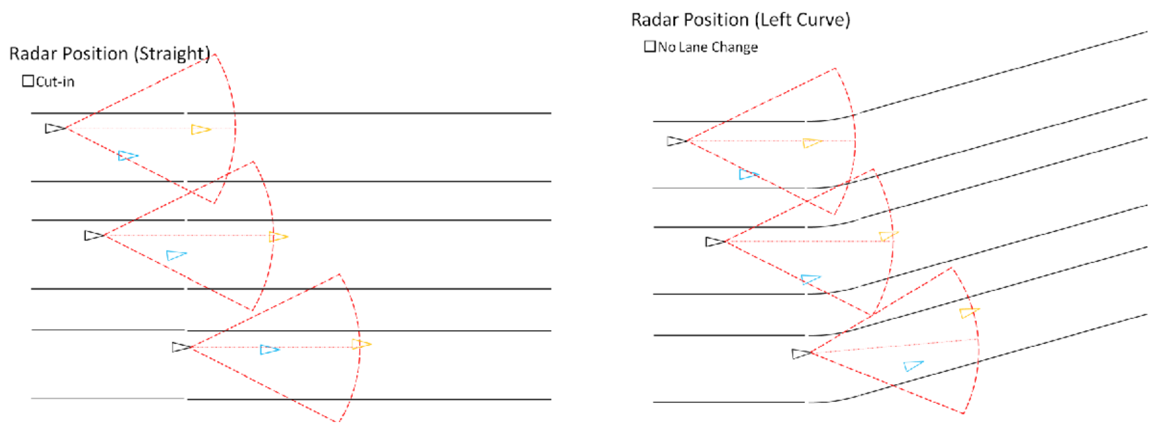
The prototype ACC system implemented selects its primary target by considering radar object information. In a cut-in situation, the target selection might switch to the new target when it has entered the host vehicle's lane to a certain percentage and/or when the radar is indicating relative lateral movement. Figure 12 shows a cut-out scenario observed by a radar sensor. The start of the cut-out maneuver was validated using the recorded video footage. The maneuver starts at the first vertical yellow line and takes about 2.5s. At that point, the longitudinal offset is discontinuous and changes to a significantly higher value. This is the point where the radar switches over to the next vehicle in the string.



Source: CAMP V2I Consortium

Figure 12 – Cut-out Maneuver Observed by Radar Sensor

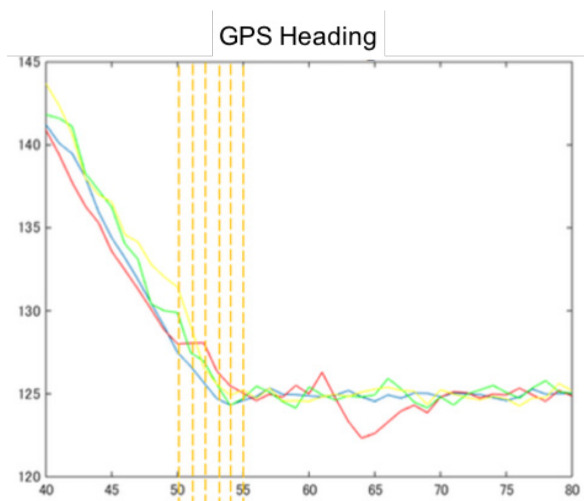
Curve situations present a challenge for proper target determination. This is where a vehicle driving in an adjacent lane (not performing a lane change) appears to the radar to be moving towards the host vehicle's lane. This issue is illustrated in Figure 13. In the first graphic, the host vehicle (black) observes a cut-in by the blue vehicle on a straight road. In the second graphic, the host vehicle observes the blue vehicle in the right adjacent lane but going through a left turn curve. Depending on the parameterization, this could seem like a lane change into the host vehicle's lane.



Source: CAMP V2I Consortium

Figure 13 - Radar Observation of a Cut-in Maneuver vs. a Curve Situation

Additional data may be available to assist CACC in these situations by considering BSMs from the remote vehicle[1]. Figure 14 shows the GPS heading of the vehicles in the string where one vehicle performs a cut-out maneuver. During the maneuver, heading differences are minimal and cannot be separated from the noise.



Source: CAMP V2I Consortium

Figure 14 - GPS Heading of Vehicles in a String during a Cut-out Maneuver

Figure 15 shows the relative yaw rate between vehicles in the string for the same situation. A distinct S-shaped pattern can be observed during the lane change. While the shape is very clear, its

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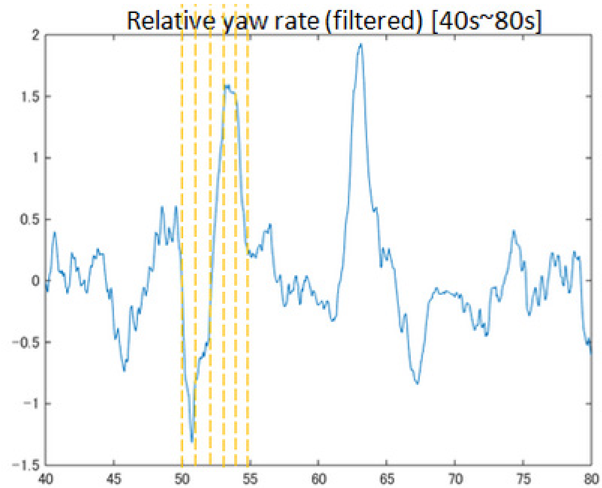
[1] *Note: The data shown in the examples was taken directly from the host and remote vehicles' CAN bus for illustrative purposes. If this data was obtained via received BSMs, the sample rate would be reduced to 10Hz and a slight delay would be introduced. The visualized data was processed using a low-pass filter to reduce sensor noise.*

magnitude is not significantly different from the general fluctuations that occur before and after the lane change. While yaw rate might be a useful variable to support the detection of lane changes the, information by itself is not sufficient.



Source: CAMP V2I Consortium

Figure 15 - Relative Yaw Rate of Vehicles in a String during a Cut-out Maneuver

Even though turn signal status was not recorded in this study, it is anticipated that it will be helpful to predict lane changes. In contrast to the GPS and yaw rate data sources, the turn signal (if operated) can be used to predict lane changes *before* the physical lane change takes place. However, the signal itself is no guarantee that a lane change will certainly take place. A driver might cancel a planned lane change in the last moment or they simply may have inadvertently turned on the turn signal. Therefore, this can only be used as an additional indicator.

Table 7 provides an overview of the potential use of DSRC data sources in detecting a lane-change. While none of the data elements by themselves can be used to reliably detect lane changes, the sum of the sources may be useful to detect lane changes with more certainty and potentially faster than radar alone.

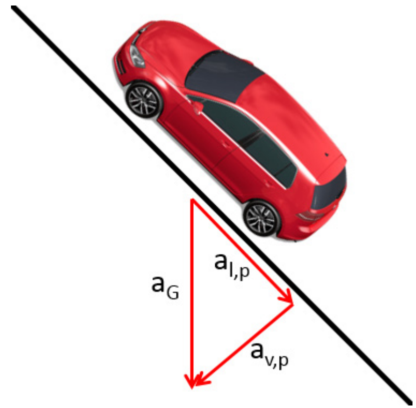
Table 7 - Utility of Data Elements to Detect a Lane Change

Data Element	Usefulness for Lane-Change Detection
Relative GPS Heading	Low
Relative Yaw Rate	Medium
Turn Signal Status	High

Source: CAMP V2I Consortium

2.3.4 Impact of Grade

A vehicle traversing a grade experiences gravitational acceleration as two components observed by the longitudinal acceleration sensor and, if present, the vertical acceleration sensor. As a result, a vehicle that is traveling at a constant speed will measure (and potentially report) a positive longitudinal acceleration as illustrated in Figure 16.



Source: CAMP V2I Consortium

Figure 16 - Gravitational Acceleration Components on a Grade

a_G - Gravitational acceleration that the vehicle is experiencing
$a_{l,p}$ - Longitudinal acceleration, perceived by the vehicle
$a_{v,p}$ - Vertical acceleration, perceived by the vehicle
s - Slope of the road [%]
θ - Angle of the road [°]
g - Gravitational constant
θ = atan(s)

The magnitude of this error can be calculated as:

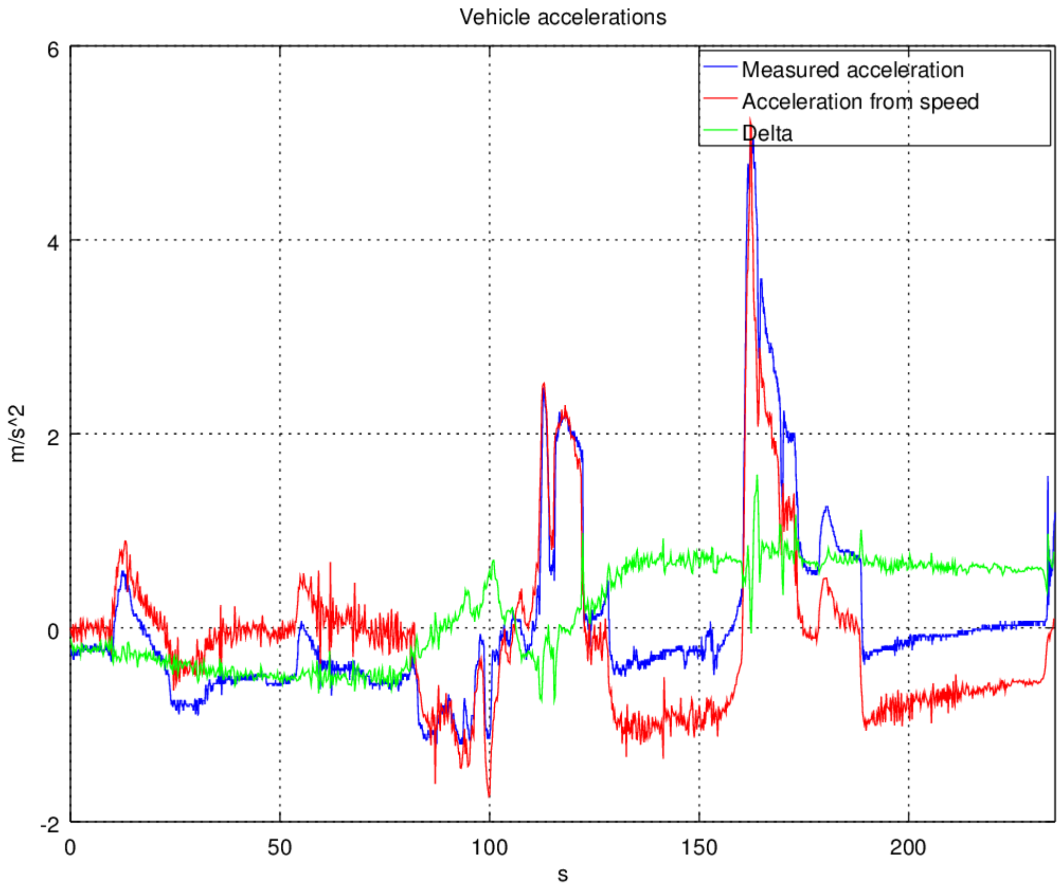
$$a_{l,p} = \sin\theta \times g$$

According to the guidelines published by the American Association of State Highway Transportation Officials (AASHTO) [7], the maximum allowable grade for a freeway in mountainous environments is 6%. This leads to the following expected worst-case error:

$$a_{l,p} = \sin(\tan^{-1}(0.06)) \times g \approx 0.59\frac{m}{s^2}$$

Since the goal for CACC is a stabilization of traffic flow and vehicles in a string should commonly travel with very low accelerations, an error of $0.59\ \frac{m}{s^2}$ is significant and could disturb the stability of the string.

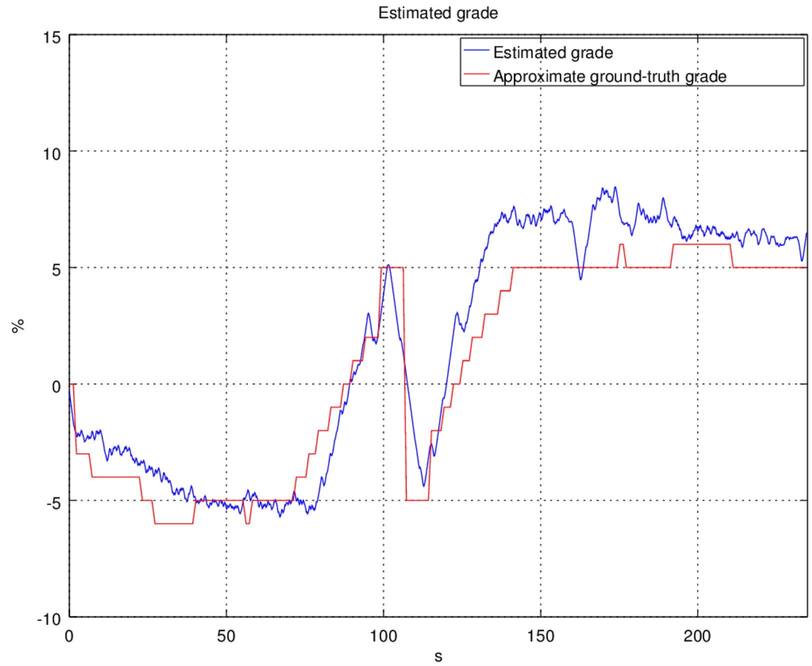
This effect can be observed in the test data shown in Figure 17. In this example, a test vehicle is traveling down the Smart Road, making a turn and then traveling up the Smart Road again. The measured acceleration from the vehicle CAN bus is shown in blue. The vehicle speed is differentiated to calculate a second acceleration value shown in red as the 'acceleration from speed.' This value represents the true acceleration over ground. During the first half of the test run, the measured acceleration has a negative offset relative to the acceleration from speed. In the second half, it has a positive offset. This difference is also shown in the 'delta' acceleration signal provided in green.



Source: CAMP V2I Consortium

Figure 17 - Measured Acceleration and Derived Acceleration

Actual grade at any point in time can be estimated by comparing these acceleration values as shown in Figure 18. Throughout the first half of the test run, a negative grade of up to ~6% is estimated and in the second half, a positive grade of ~7% is estimated. These results are very close to the expected values for the Smart Road.



Source: CAMP V2I Consortium

Figure 18 - Estimated Grade Based on Measured vs Derived Acceleration

The prototype ACC algorithm used in these tests operates on relative distance and relative speed. Therefore, this issue does not impact the longitudinal controller when calculating appropriate accelerations. In contrast, the CACC longitudinal control algorithm will consider both measured acceleration and acceleration forecasts from preceding vehicles, both of which could be affected by the grade induced error observed. The potential consequences of this are discussed in the following sections.

2.3.4.1 Longitudinal Acceleration from Remote Vehicles

Based on the definition of the longitudinal acceleration data element taken from SAE J2735 and J2945 (Table 8), it is assumed that the value being transmitted as part of the BSM is affected by gravitational effects on grades. However, it must be noted that there might be a class of BSM transmitters using Aftermarket Safety Devices (ASDs) that operate without vehicle CAN bus access and don't necessarily include an accelerometer. In this case, vehicles would transmit acceleration derived from the GPS speed reported by the GPS receiver, which would not be affected by grade induced acceleration errors.

Table 8 - Longitudinal Acceleration Data Element Definitions

J2735	J2945
Longitudinal acceleration is the acceleration along the X axis or the vehicle's direction of travel which is generally in parallel with a front to rear centerline. Negative values indicate deceleration and possible braking action.	*The DE_Acceleration (Longitudinal) and DE_Acceleration (Lateral) data elements in this data frame shall be accurate to within vAccelAccuracy of the actual vehicle longitudinal and lateral accelerations, respectively, over 68% of test measurements under Open Sky Test Conditions and flat road test conditions (grade < 0.2% and cross-slope < 2%). [6.3.6-V2V-BSMTX-DATAACC-025*

Source: CAMP V2I Consortium

2.3.4.2 Acceleration Forecasts Received from other CACC Vehicles

The acceleration forecast received from a remote CACC vehicle is an output of that vehicle's longitudinal controller and is not affected by the grade. The longitudinal controller would request zero acceleration when traveling on a hill at a constant speed. It is the responsibility of the brake and engine control system to perform any necessary compensations due to grade such as braking to maintain constant speed when going downhill.

2.3.4.3 Host Vehicle Measured Longitudinal Acceleration

The host vehicle's (HV) longitudinal acceleration is taken directly from the HV's sensor and is affected by the grade. This value is also transmitted in the HV's BSM. As shown in this analysis, it is possible to estimate the current grade and to compensate this value to reflect true acceleration over ground.

2.3.4.4 Relative Acceleration

The HV can calculate relative acceleration by subtracting HV and remote vehicle (RV) measured acceleration. By doing so, the grade effects cancel each other out. This is the case for situations where both vehicles experience the same grade. In situations where the HV is still driving on a leveled surface but the RV is experiencing a change in grade, the effect will be visible. These events are rare and short in time (because of the close following) and, therefore, it should be possible to ignore them.

3 Simulation Environment

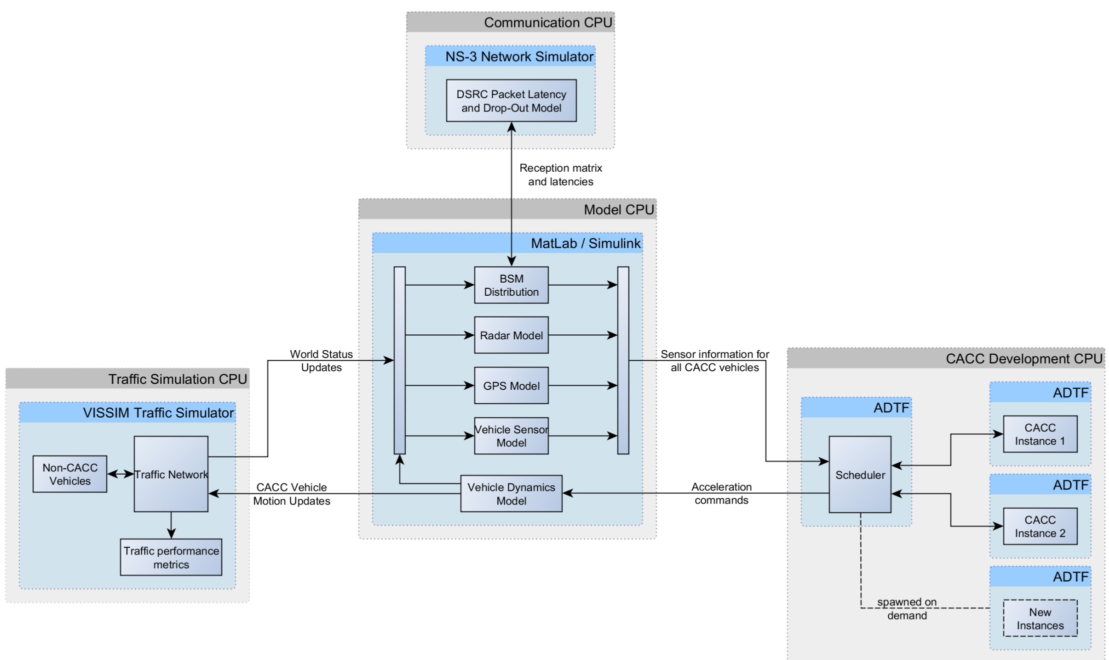
The CACC simulation environment was implemented to design and evaluate the proposed CACC algorithm considering its ability to manage time headway in response to traffic disturbances and to evaluate the effects of CACC on measures of string stability.

3.1 Implementation

Different simulation models were developed to build the simulation environment. The simulation architecture was made up of three subsystems: Traffic simulation, Model CPU, and Communication modeling. A detailed description for each model is provided in the following sections.

3.1.1 Simulation Architecture

The simulation architecture includes four CPUs, which are depicted in Figure 19. The Traffic Simulation CPU hosts the VISSIM traffic simulator version 9. The output of the traffic simulator is position, speed, and lane position for each vehicle in the traffic simulation. The output of the VISSIM vehicle is fed into a set of MATLAB/Simulink models housed in the "Model CPU" platform to emulate the sensing aspects of the CACC, which includes a radar model, a GPS model (for all vehicles), and the onboard vehicle sensor signals used by ACC or CACC.



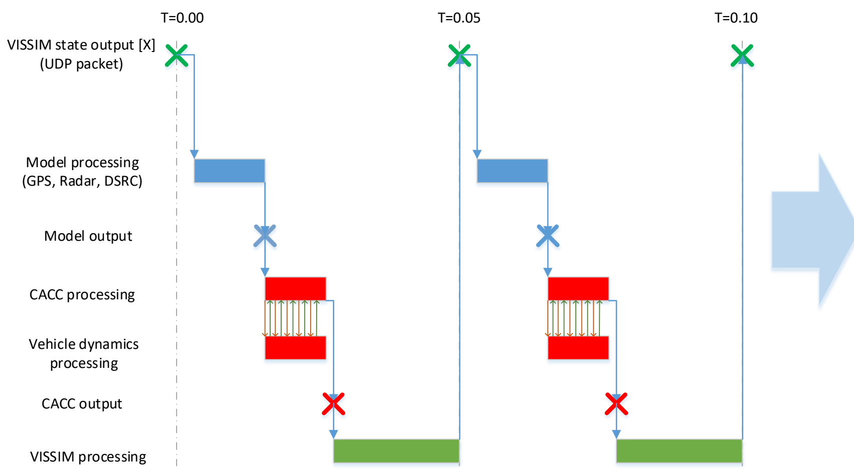
Source: CAMP V2I Consortium

Figure 19 - Architecture of the Simulation Environment

Communication of DSRC messages is simulated in two ways. First, the over-the-air propagation is modeled statistically based on a model derived by CAMP from Safety Pilot Model Deployment (SPMD) data [8] that depends on range. For simulations in this report, the ranges are modest and are rarely affected by this model. The latency and message congestion is modeled using the ns-3 open source network simulator (www.nsnam.org) which is housed in the Communications CPU. The latency is based on broadcast protocols, so that for an individual vehicle, the WAVE broadcast jitter setting affects the delay by a magnitude of approximately 10 ms. Reception latency is not modeled. For scenarios in this report, the number of vehicles is not large and message congestion effects are not seen.

The simulated inputs to CACC are then fed to the CACC Development CPU platform, which includes an instance of the CACC algorithm for each CACC vehicle that is currently being simulated. These algorithm instances produce acceleration and deceleration commands. These commands are fed into the vehicle-dynamics model in the Model CPU to simulate throttle, brake system, and vehicle-dynamics effects. The CACC algorithm and the vehicle-dynamics model exchange data at a rate of 50 Hz, similar to commercial ACC systems.

Since different simulation components operate at different frequencies, a synchronization among the simulation models is required. The structured flow of data over time is illustrated in Figure 20.



Source: CAMP V2I Consortium

Figure 20 - Synchronization between Simulation Modules

3.1.1.1 Communication CPU

A major part of the CACC-SST Project involved developing a simulation environment to evaluate CACC operation and establish baseline performance criteria. Two major independent simulation software tools, VISSIM and ns-3 are integrated to develop and analyze real-world like CACC string operation on different traffic networks. ns-3 is an open-source, discrete-event network simulator that can be used to understand the wireless communication complexities of the CACC string operation in a multitude of network topologies. With Wireless Access in Vehicular Environments (WAVE) models included, ns-3 can simulate DSRC applications. Each vehicle/OBU is modeled as a moving node in the wireless communication environment. The focus of the WAVE module is on Media Access Control (MAC) layer and the multi-channel coordination layer.

The primary components of ns-3 simulation in the CACC-SST Project are propagation model, mobility model, multi-channel coordination model, and transmission control protocol. These are defined below.

- *Propagation model*: This describes how wireless signal strength varies from the radio antenna to the desired position. A large-scale, Two-Ray, Path-Loss model and a small-scale, Nakagami Fading model are applied in the project to simulate deterministic path loss and random fading. The parameters of the models were calibrated by researchers from West Virginia University based on a multi-lane highway scenario in the Vehicle-to-Vehicle Interoperability Project that was conducted by the CAMP Vehicle Safety Communications 3 Consortium.
- *Mobility model:* This is used to describe the movement of nodes (vehicles) in the network. At the very beginning of every time step in ns-3 simulation, the position, velocity, and acceleration of each node will be updated based on the “ground truth” in VISSIM simulation. During each time step, each node is assumed to move with a constant acceleration.
- *Multi-channel coordination model:* This is about the coordination between DSRC control channel and service channels. When only BSMs are broadcast by OBUs, continuous access to the control channel is assumed. If service messages are involved, effects of channel coordination will be considered, such as guard intervals when radio channel is switched.
- *Initial Transmission control protocol:* This is designed to avoid BSM conflicts when traffic flow is dense. Each BSM has a random back-off time before being broadcast at the first time. In the following time steps, the back-off time will be the initial back-off plus or minus a jitter. Transmission control protocol can significantly reduce the probability of channel congestion, although communication latency should be sacrificed a little bit.

3.1.1.2 Traffic Simulation CPU

For the traffic simulation, VISSIM traffic simulator version 9 has been used. VISSIM is a microscopic, time-step, and traffic-behavior-based simulation model developed to model urban traffic operations. VISSIM is heavily dependent on data inputs and parameters used when coding the traffic network. With VISSIM, road networks can be built in a scaled overlay manner with any level of complexity, and changes in the road network and link properties can be easily edited. The software offers the flexibility to the users to individually parameterize and assign micro-attributes to the vehicles and drivers characteristics, thus making it a valuable and realistic testing environment. Additionally, many external interfaces to both the hardware and software modules makes integration of the traffic model with other vehicle development tools possible.

3.1.1.3 CACC Development CPU

The CACC development environment is hosted on a dedicated computer connected to the other components of the simulation environment. Vehicles can be introduced to and removed from the traffic network during a simulation run. As a result, dynamic spawning and destruction of CACC algorithm instances need to be handled. This is the responsibility of the *scheduler* which is the component in the development environment that interacts with the Model CPU to:

1. Spawn and destroy CACC algorithm instances when necessary
2. Distribute sensor data to the instances
3. Collect computed acceleration commands and send them back to the modeling CPU

The CACC algorithm instances include all the CACC software components. To host all these software components, the Automotive Data and Time-Triggered Framework (ADTF) was chosen. This framework is also used for the prototype ACC algorithm in the developed test vehicles. This should allow for a relatively easy transition from simulation into test vehicles in future phases of the project.

3.1.1.4 Model CPU

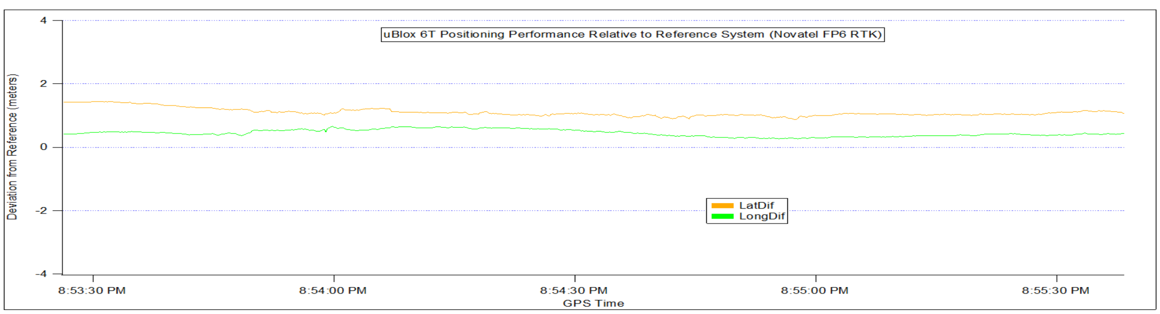
In the Model CPU, five models have been developed to bring together independent modelling components for a comprehensive simulation analysis. These models are Simulink based models and reside on the Model CPU machine as illustrated in Figure 19. The following subsections describe in detail the functionality of the five developed simulation models.

3.1.1.4.1 GPS Sensor Model

The GPS sensor model provides absolute location information to equipped vehicles (CACC and V2V). The model receives ideal positions in lat/lon world coordinates from VISSIM and then applies additional errors to the signal. Furthermore, the model ensures that GPS readings are generated with a fixed update rate of 10Hz.

To establish a GPS reference performance, a one-hour test drive on different road types around Ann Arbor was conducted. During this drive, the test receiver collected GPS data. At the same time, another receiver was used as a reference for ground-truth comparison. Both receivers were connected to the same survey grade antenna.

The datasets were joined based on their GPS timestamps to calculate the error of the test receiver. Data from multiple drives during different times of day was collected. Figure 21 represents an example of the lateral and longitudinal GPS errors that were observed in the collected dataset.

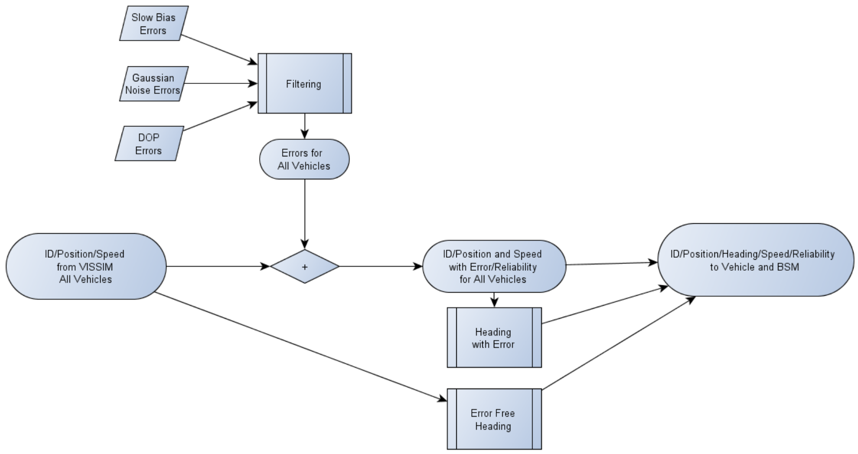


Source: CAMP V2I Consortium

Figure 21 - Noise and Bias during Regular Driving

Based on the receiver comparison from these test drives, a GPS error model was parameterized.

An overview of the data flow within the GPS error model is illustrated in Figure 22.



Source: CAMP V2I Consortium

Figure 22 - GPS Error Model

An overview of the different simulated error classes and their features is given in Table 9.

Table 9 - Simulated Error Classes

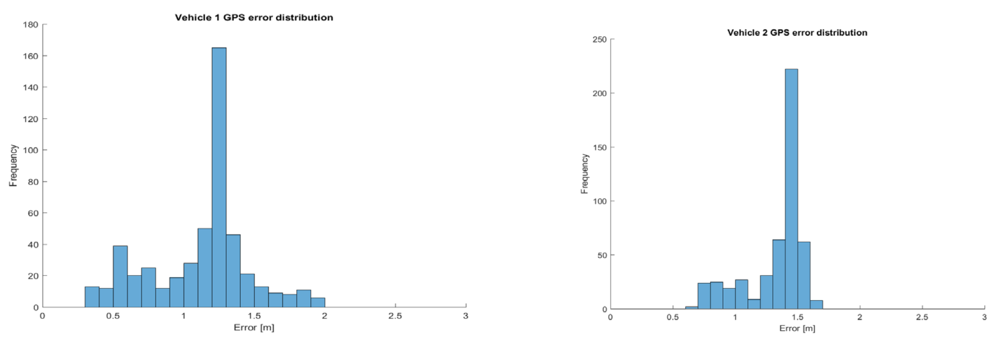
Error Class	Unique to each vehicle	Generation	Relation with other errors	User configuration
Gaussian Noise	yes	Standard deviation selected from Poisson distribution prior to runtime Mean of the noise values is 0	Affected by Dilution of Precision (DOP)	Can be modified through 'GPS error level'
Slow Bias	yes	Error vectors generated prior to runtime Bias values are normally distributed	None	Cannot be modified
Dilution of Precision (DOP)	no	Error vectors generated prior to runtime DOP values follow F distribution	None	Cannot be modified

Source: CAMP V2I Consortium

The generated localization errors are representative of a GPS receiver without the use of additional techniques to improve localization performance such as dead-reckoning or Real-Time Kinematics

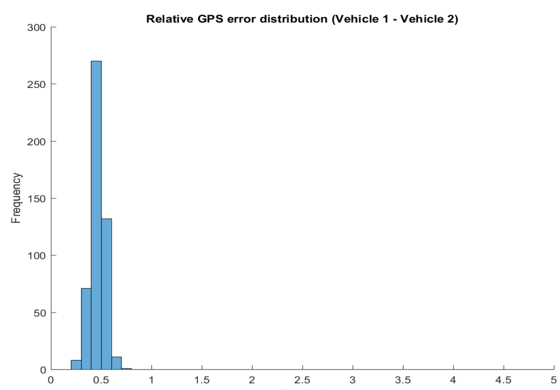
(RTK). Furthermore, the heading value is not latched in standstill which can lead to degraded performance during stop and go maneuvers.

The model simulates absolute GPS positioning errors. However, the CACC vehicles mainly rely on relative positioning between the vehicles which is expected to show smaller errors than absolute positioning. This is mainly relevant for the error class of biases. It is expected that these biases would be similar for all vehicles in the area. Therefore, this is considered for the selection of the bias values. Figure 23 shows the different error distributions for two vehicles during an example simulation run. The relative position error between those two vehicles during the same simulation run is represented in Figure 24. The resulting relative localization error is lower than the individual absolute errors as expected.



Source: CAMP V2I Consortium

Figure 23 - Error Distributions for Two Vehicles



Source: CAMP V2I Consortium

Figure 24 - Exemplary Relative Positioning Error Distribution

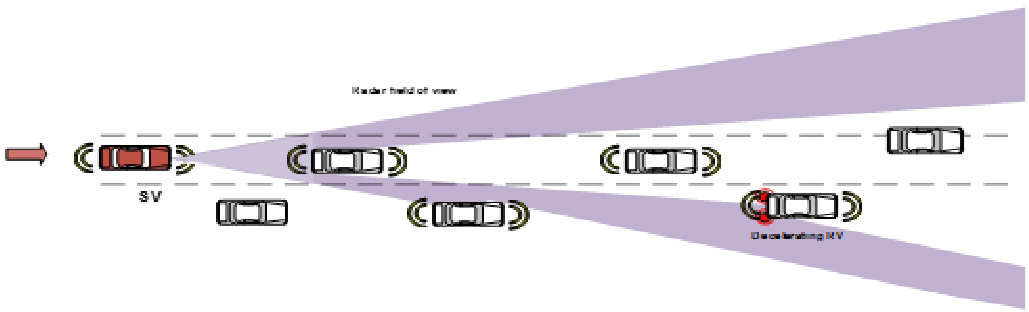
3.1.1.4.2 Radar Sensor Model

The radar sensor model is used to simulate the radar sensor input and provide it to the vehicle control algorithm. The model receives the position and speed values for every vehicle within the radar sensor range in front of the CACC vehicle. The radar model tracks other vehicles by generating range, closing speed and azimuth angle for each vehicle detected.

A Mid-range Radar Sensor (MRR) with a frequency band of 76–77 GHz has been used in this project. The MRR field of view depends on the main and elevation antennas. The main antenna defines a long range up to 160 meters with an opening angle of ± 6 degrees. The elevation antenna achieves an opening angle of ± 42 degrees at close range.

The radar sensor model was developed based on the assumption of following effects:

- Radar field of view: This is based on the maximum range and maximum azimuth. The radar field of view has a very sharp edge and range as illustrated in Figure 25. The radar field of view implemented uses both antennas.

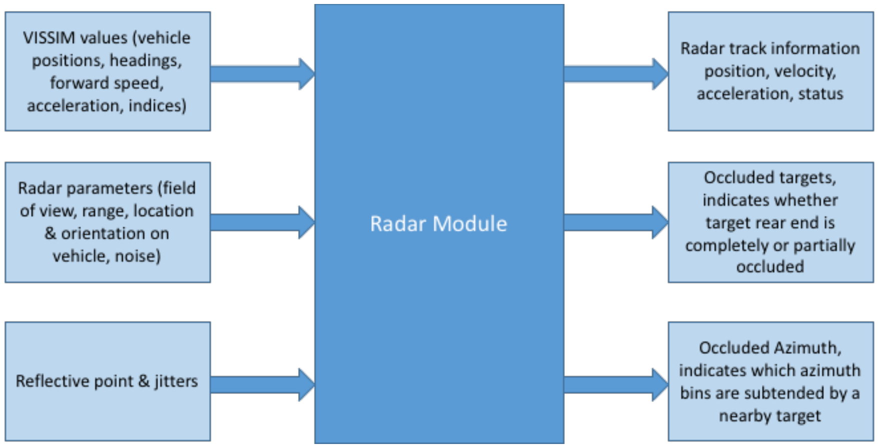


Source: CAMP V2I Consortium

Figure 25 - Radar Field of View

- Bumper and vehicle size offsets: This is where the radar always returns the middle of the rear bumper. Vehicles consist of their rear bumper only. No targets are returned for the side of vehicles. Only the rear bumper can occlude the ‘view’ of another vehicle.
- Occlusion by other vehicles: The radar requires a clear line of sight between the radar unit and the target vehicle. However, the occlusion of target vehicles is computed for each C/ACC vehicle. The center of the radar track is nominally at the center of the visible portion of the target vehicle’s rear end.
- Noise, limited resolution, and jitters on range and azimuth measurements are modeled and considered independent.
- The target vehicle might be entirely in view, or partially in view, of the radar. An adjustment for the coordinates based on the radar field of view is required.

The logic of the radar module logic is elaborated in Figure 26.



Source: CAMP V2I Consortium

Figure 26 - Radar Module Logic

3.1.1.4.3 Vehicle Sensor Models

The vehicle sensor models include five different models; vehicle speed, yaw rate, acceleration, turn signal, and brake switch model. Following is a description of each model.

- *Vehicle speed*: The vehicle speed signal that is provided to the CACC is the 'true' simulated speed and has no error components modeled.
- *Yaw rate*: The yaw rate signal that is provided to the CACC algorithm is intended to simulate the OEM onboard sensor. Yaw rate is derived by differentiating the VISSIM value of absolute heading. Note that VISSIM updates at 20 Hz and the vehicle algorithm needs 50 Hz values of yaw rate. As a result, a prediction algorithm has been added to estimate yaw rate between the 20 Hz updates. No model components are included to emulate the types of errors seen in real yaw rate gyros, such as errors that are due to a sensor bias, which often drifts slowly over time, and zero-mean noise.
- *Accelerations*: The acceleration signals (longitudinal and lateral) that are provided to the CACC algorithm simulates the data from onboard accelerometers. The model takes the simulated "true" acceleration and adds any gravity influence if the simulated roadway has vertical grade. In real-world sensors, the actual accelerometers will have a bias, a bit of crosstalk (i.e., lateral acceleration appearing as longitudinal and vice versa, due to sensing element orientation offset), gain error and noise. However, these were not included in the analysis. In addition, the pitching during hard braking will cause the longitudinal acceleration signal to have an error equal to the sine of the pitch angle picking up the gravity vector. This may be modeled later, if significant.
- *Turn signals*: Turn signals are not relevant to ACC or CACC, apart from CACC algorithms that may use turn signals to delay deceleration when approaching slower vehicles. The simulation environment creates turn signal information when the user configures the simulation such that a lane change is prescribed to occur. The turn signal is initiated two seconds before this lane change.
- *Brake switch*: If the brake switch in the high position, it tells the C/ACC algorithm that the driver is intervening, which presumably leads to C/ACC disengaging. The simulation generates a brake switch signal when a certain deceleration threshold is exceeded. The current threshold value is 0.1 m/s^2.

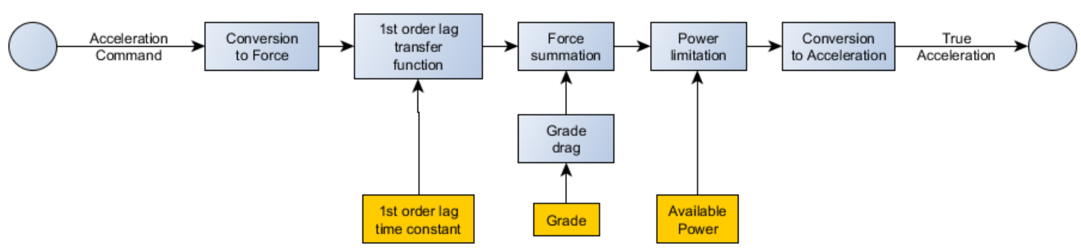
3.1.1.4.4 Vehicle-Dynamics Model

The vehicle-dynamics model is used to simulate the CACC vehicle responses to acceleration commands issued by the CACC system. This is simulated outside of the traffic simulator in order to have direct control of these vehicles and to give more accurate simulation of the dynamics internal to the vehicle. The vehicle-dynamics model receives acceleration commands and the current vehicle speed from the simulation environment. It generates the true acceleration of the vehicle as well as the true speed. The acceleration is forwarded to the traffic simulator where it is used to move the vehicle forward in the traffic network.

The following assumptions were made when the vehicle-dynamics model was developed.

1. Since longitudinal control is the focus of CACC, only the longitudinal dynamics of the vehicles are considered.
2. CACC is not expected to operate close to the road friction limits and, therefore, a linear tire/road model can be applied.
3. The vehicle model includes the ability to model aerodynamic drag and rolling resistance. Typically, aerodynamic drag force would be modeled as proportional to the square of speed while rolling resistance force would be modeled as proportional to vehicle mass. However, the parameters for aerodynamic and rolling resistance drag are set to zero in the analysis described in this report because, for the purposes of matching test data, the controller is assumed to be able to compensate rolling resistance and air resistance perfectly.
4. Effects of grade(slope) are considered in the model. The controller assumed to be able to compensate a drag by grade.
5. Available power during CACC operation assumed to be limited to a specific value which differs by vehicle.

Figure 27 provides an overview of the internal vehicle-dynamics model behavior.



Source: CAMP V2I Consortium

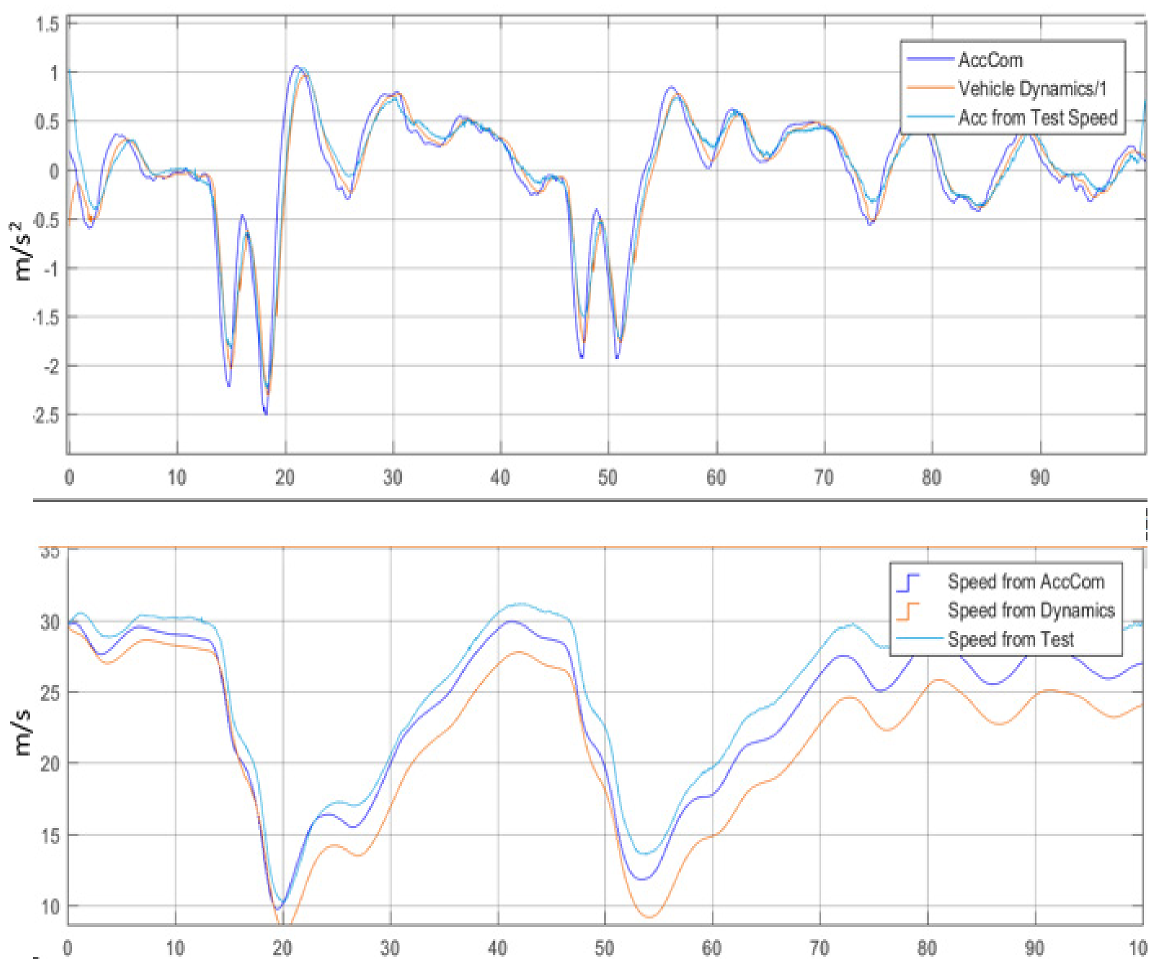
Figure 27 – Vehicle-Dynamics Model Control Diagram

When acceleration commands are received, they are converted into the equivalent force based on Newton's second law. Then, drag by grade is added to calculate a necessary force. The drag is calculated by gravity and the vehicle mass in a simple geometrical way. Furthermore, the effect of grade is implemented to be able to compare simulation results with test data measured on a road with significant grades, while air and rolling resistance are ignored.

Depending on the current mode of operation (acceleration/deceleration), the relevant transfer function is applied to the brake or the engine system. In case of positive acceleration, the acceleration is limited by the available engine power depending on the vehicle speed. The available engine power is not the maximum power of the vehicle but a predetermined power in the CACC state. The driving force is converted back into an acceleration that represents the computation result of the vehicle-dynamics model. The parameter values were identified by analyzing the results from the exploratory test. The following provides a list of the identified parameter ranges across the four test vehicles.

- vehicle mass: 1350kg - 2600kg
- 1st order lag time constant during acceleration: 0.4s - 0.9s
- 1st order lag time constant during deceleration: 0.2s - 1.2s
- Available Power: 10%-100% of the maximum power: 13kW – 127kW

Figure 28 shows the correlation between the model and test results for two vehicles.



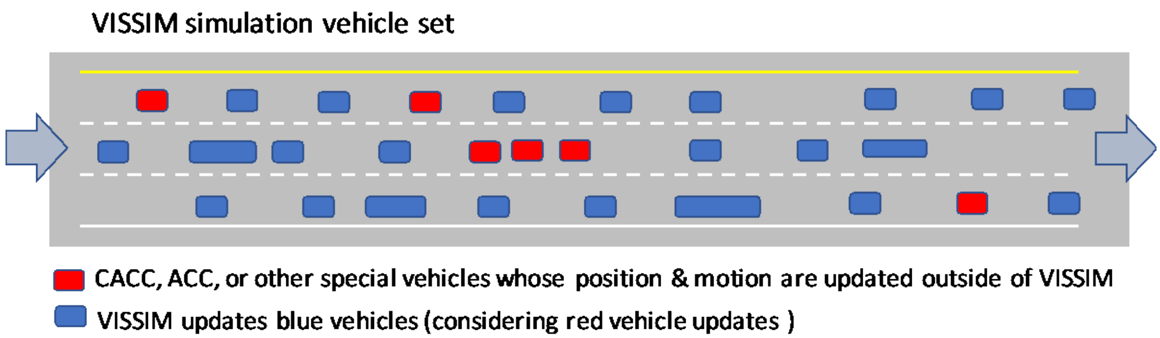
Source: CAMP V2I Consortium

Figure 28 - Vehicle 1 on 6% Upward Grade

3.1.2 Vehicle Feature Classes

The simulation environment supports the simulation of different type of vehicles: “human-driven” vehicles and “special” vehicles that are under CACC longitudinal control, which includes CACC vehicles, ACC vehicles, or other vehicles that the user wishes to control explicitly such as vehicles with scripted motion (e.g., to create a traffic disturbance).

Since a traffic simulator supports the simulation of human driving behavior, those vehicles are handled by the traffic simulator. However, the motion of “special” vehicles is propagated outside of the traffic simulator and simulated in the Model CPU, which illustrated in Figure 29 (red vehicles). The other vehicles’ motion is propagated by the traffic simulator while considering the motion of the special vehicles, as depicted in Figure 29 (blue vehicles).



Source: CAMP V2I Consortium

Figure 29 - Simulated Vehicle Types

In the scenario definition, the user can insert single vehicles or vehicle streams with randomized vehicle classes into the simulation environment. The user can select the following parameters for the vehicles.

1. A vehicle feature class which influences how the environment is treating the vehicle.
2. A vehicle parameter class which changes among other parameters the physical dimensions and the vehicle-dynamics behavior

Table 10 provides an overview of the supported vehicle classes and their features with regards to the different simulation models.

Table 10 - Vehicle Feature Classes

Vehicle Feature Class	BSM Transmission	BSM Reception	Constitute Radar Objects	Vehicle Dynamics Calculated	Controlled by Algorithms
Unequipped Vehicle	no	no	yes	no	no

Vehicle Feature Class	BSM Transmission	BSM Reception	Constitute Radar Objects	Vehicle Dynamics Calculated	Controlled by Algorithms
DSRC Vehicle	yes	no	yes	no	no
CACC Vehicle	yes	yes	yes	yes	yes

Source: CAMP V2I Consortium

3.2 Scenarios

This section describes simulation scenarios that were developed for use in the simulation environment to assess and compare the performance of CACC algorithms. A simulation scenario defines a constellation of vehicles and their actions or a constellation of traffic flows and their parameters in a traffic network.

The simulation scenarios can be classified in three different categories: microscopic, intermediate, and real-world traffic scenario.

- Microscopic Scenarios are used to study the interactions of CACC-equipped vehicles with the immediate surrounding vehicles. Scenarios range from simple following scenarios to cut-in and string stability scenarios. These scenarios were relevant during the early development of CACC algorithms to debug the implementation. Furthermore, these scenarios helped to assess the effectiveness of incorporating V2V information from surrounding vehicles for improving the performance of single CACC vehicles.
- Intermediate Scenarios consider CACC operation in surrounding traffic. The scenarios are based on a random fashion and include traffic flows with a certain percentage of CACC-equipped vehicles to study their effect on the traffic. The scenarios are executed on simpler traffic networks that are limited in size and, for instance, contain a single off-ramp and on-ramp combination.
- Real-world Traffic Scenarios are used to study the effect of CACC on the macroscopic traffic flow. Potential reductions in travel time and the effectiveness under different traffic densities can be studied. Scenarios are executed on miles long traffic networks with calibrated traffic flows and with multiple on-ramps and off-ramps.

3.2.1 Scenario Overview

Table 11 provides an overview of the developed test scenarios, their category and an assigned priority based on their value in answering the project's research questions and their applicability to the currently envisioned set of algorithm features.

Table 11 - Simulation Test Scenarios

Simulation Scenario	Category	Priority	Related Test Scenario
S2 Vehicle Time Gap	microscopic	low	

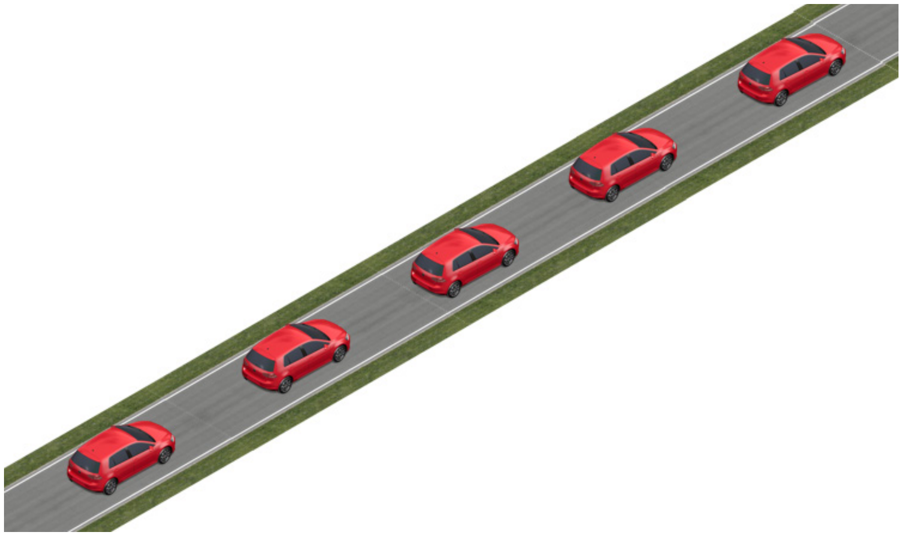
Simulation Scenario	Category	Priority	Related Test Scenario
S3 Truck in CACC-string	microscopic	medium	
S4 String stability	intermediate	high	T-11 String Stability
S5 Communication Failure	microscopic	high	
S6 GPS Inaccuracies	intermediate	high	
S7 Car Following	microscopic	medium	
S8 String Joining	microscopic	medium	
S9 Overtaking	microscopic	high	T-5 Overtaking
S10 Lead Vehicle Slows Down	microscopic	medium	T-11 String Stability
S11 Stop and Go	microscopic	medium	T-10 Stop & Go
S12 Acceleration and Deceleration Maneuvers	microscopic	high	T-11 String Stability
S13 Standing Object	microscopic	low	
S14 Lane-Change Detection	microscopic	medium	T-2 Lane-Change Detection
S15 Traffic Benefits	real-world	high	
S16 Infrastructure - Merging	intermediate	high	
S17 Infrastructure - GPS/DSRC outage	intermediate	high	

Source: CAMP V2I Consortium

The following three examples outline the definition of the scenarios and their purpose.

3.2.1.1 S4 String Stability

A single-lane traffic network is filled with CACC-strings of vehicles at varying traffic densities. The initial speeds and gaps could potentially be slightly different. Vehicles will accelerate to their set speed and time gap. If the system is string-stable, the speed of vehicles will stabilize. If not, this might lead to harder and harder acceleration and deceleration maneuvers. This scenario is used to compare the string-stability of different algorithm implementations. S4 has a high priority and is illustrated in Figure 30.

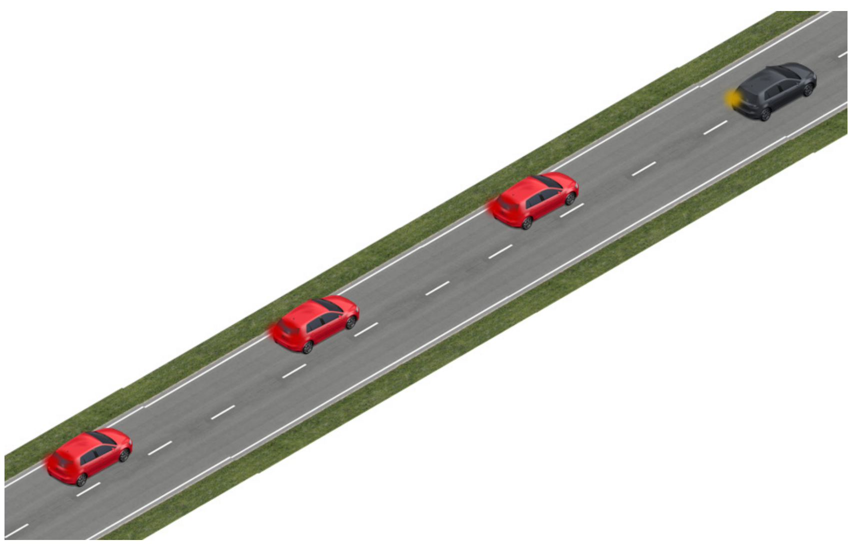


Source: CAMP V2I Consortium

Figure 30 - String Stability Scenario

3.2.1.2 S14 Lane-Change Detection

This scenario mirrors the test scenario "T-2 Lane-Change Detection" for comparison between the vehicle test results and the simulations. Three CACC vehicles form a string on the left lane. The string approaches another vehicle driving on the right lane at slower speed. Right when the string is about to pass, the vehicle on the right lane performs a lane change into the left lane. S14 is illustrated in Figure 31.



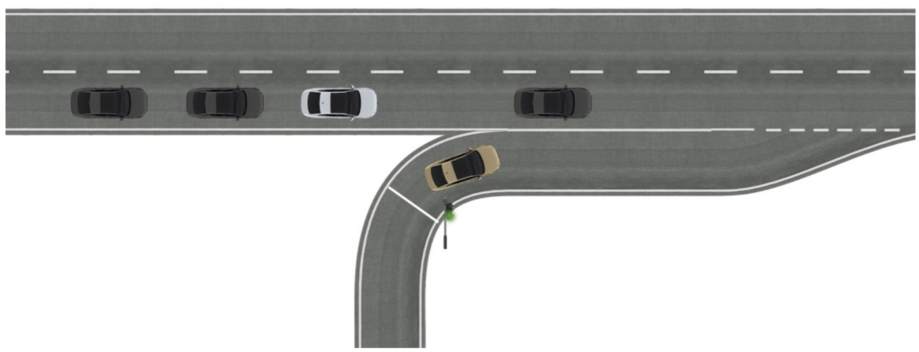
Source: CAMP V2I Consortium

Figure 31 – Lane-Change Detection Scenario

This scenario has a medium priority and assists in identifying if CACC improves the vehicle's behavior by comparing the simulation run with the test results on lane changes.

3.2.1.3 S16 Infrastructure - Merging

In this scenario, strings of CACC vehicles travel on a freeway designated CACC lane with a prescribed speed and time gap. As the CACC string approaches an entrance ramp of a freeway, it is anticipated that several vehicles will enter the freeway. These vehicles could be a mix of both CACC-enabled or non-CACC-enabled vehicles. An infrastructure message is broadcast indicating lat/lon information about the location of the freeway ramp and length indicating "vehicles merging ahead." The oncoming CACC string of vehicles receives the Infrastructure-to-Vehicle (I2V) message and relaxes the speed and time gap to accommodate smooth merging of vehicles into the CACC lane. This scenario has high priority and illustrated in Figure 32.



Source: CAMP V2I Consortium

Figure 32 - Infrastructure Merging Scenario

3.2.2 Scenario Execution

In this project, 16 simulation scenarios have been developed from different categories. During the development of the simulation environment, the following limitations were identified.

1. Scenarios were envisioned as the combination of a traffic network, vehicle constellation and vehicle and environmental parameters. The environment didn't allow combined definition of the three and, therefore, complicated a unified configuration.

2. VISSIM doesn't support the setup of a constellation of vehicles on a roadway. Vehicles can only be made to enter a road at a certain point in time. This leads to limitations in scenario setup.

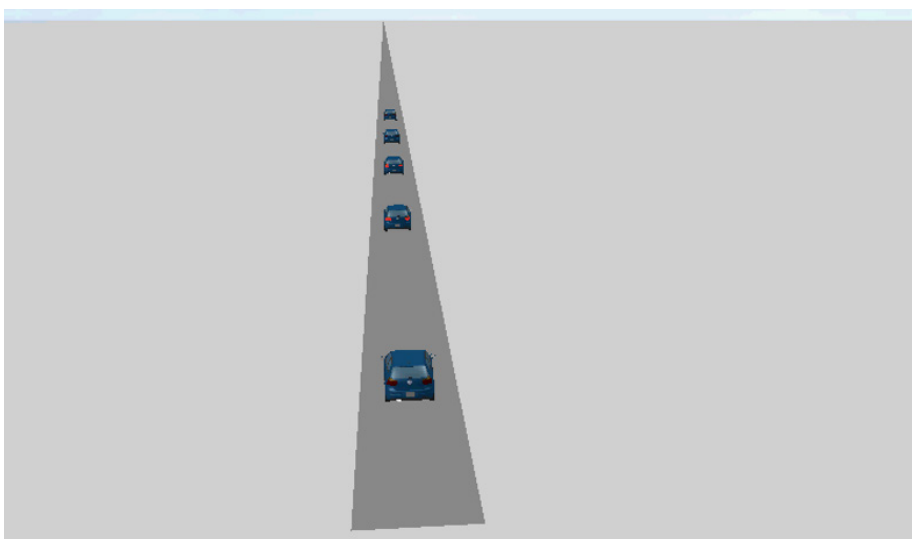
3. The environment initially only supported the simulation of five CACC vehicles. Therefore, the intermediate and real-world traffic scenarios couldn't be executed in the envisioned manner.

Therefore, the approach to scenario definitions was adjusted. Simulations were executed by combining certain traffic networks with input perturbations and environment parameters. The implemented options are outlined below.

3.2.2.1 Traffic Networks

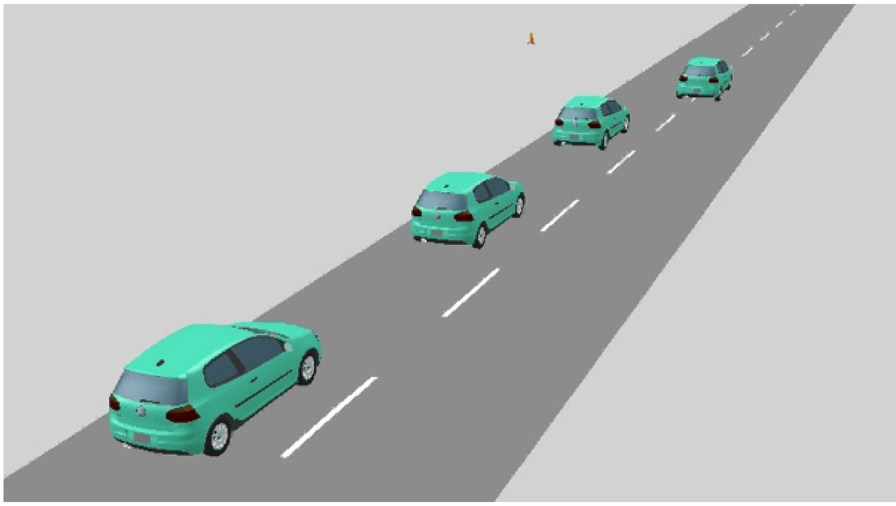
Three main traffic networks were implemented to allow for the setup of different vehicle constellations and to perform different maneuvers:

- *Single-Lane Network*: This network consists of a single straight lane as shown in Figure 33. It is mainly used to force an input perturbation upon an established string of CACC vehicles and study its response.
- *Two-Lane Network*: This network consists of two lanes and is used to have vehicles travel on both lanes and to then execute scripted lane-change maneuvers into and out of an established string as shown in Figure 34.
- *On-Ramp Network*: As shown in Figure 35, this network consists of a single lane (representing the rightmost freeway lane) which is joined by a second lane representing the on-ramp. A ramp meter is installed on that lane, injecting single vehicles into the mainline traffic.



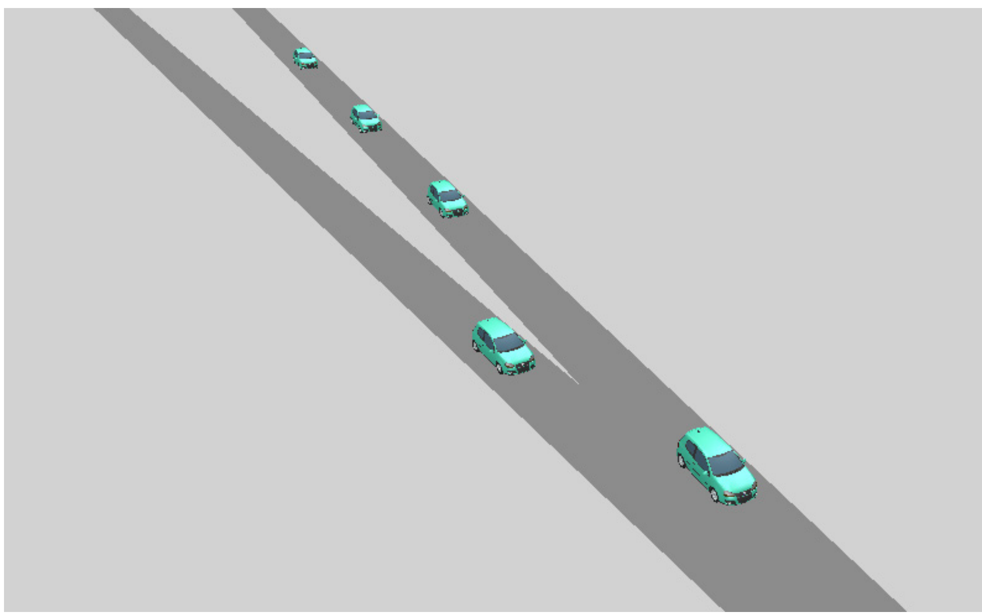
Source: CAMP V2I Consortium

Figure 33 - Single-Lane Network



Source: CAMP V2I Consortium

Figure 34 – Two-Lane Network



Source: CAMP V2I Consortium

Figure 35 – On-Ramp Network

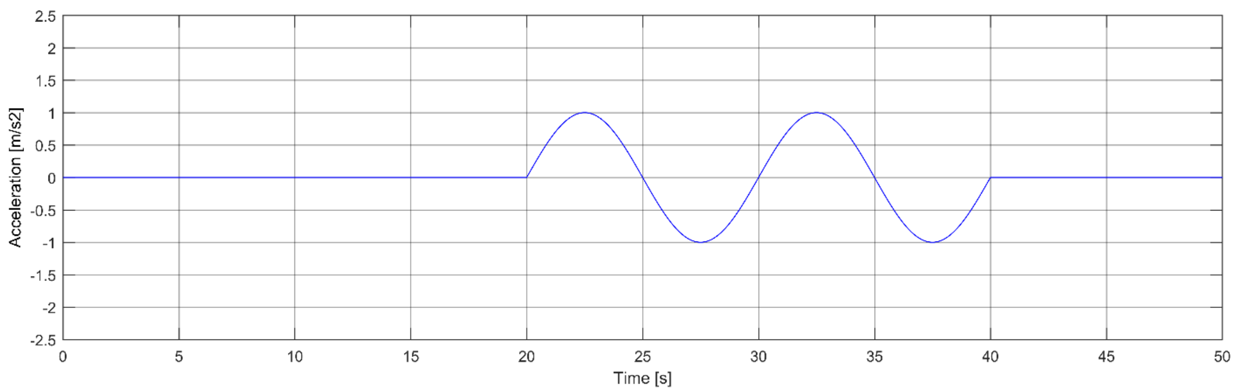
3.2.2.2 Input Perturbations

In the environment, it is possible to artificially control the longitudinal acceleration of one or more vehicles. This is used to study the response of a string of CACC vehicles to a certain input perturbation. The following types of perturbations have been implemented:

- Simple step perturbations which can represent harsh braking maneuvers

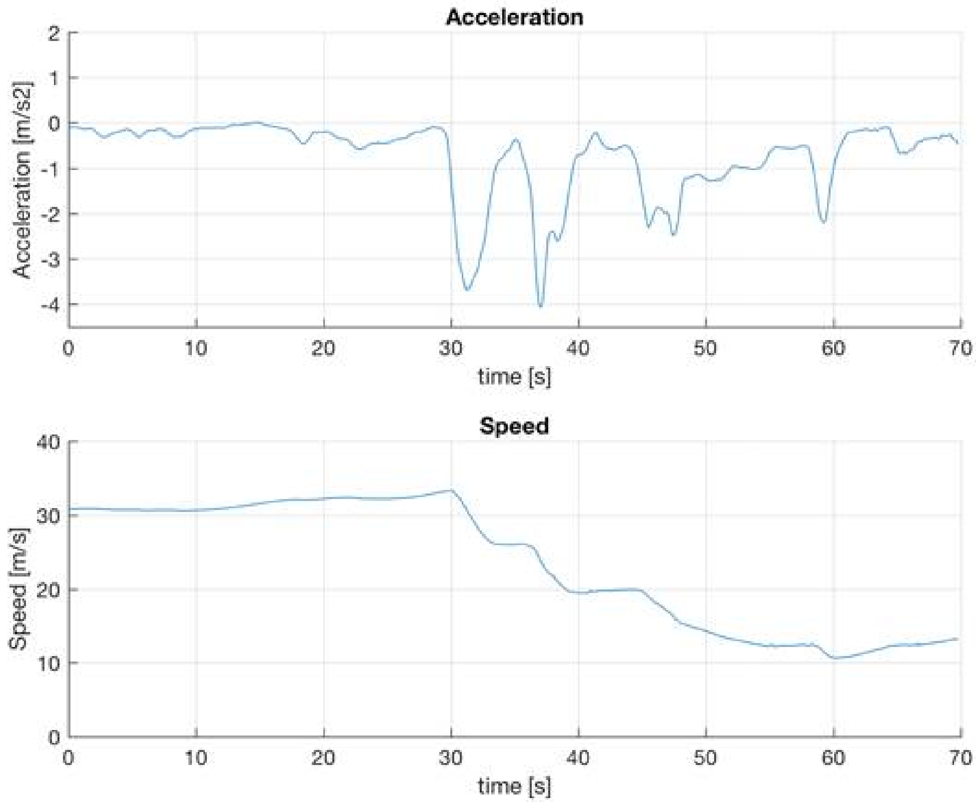
- Sine shaped perturbations that can be used to study the string stability by varying amplitude and frequency
- Replay of previously recorded acceleration profiles. Profiles were taken from the project's vehicle tests and from a naturalistic driving study representing freeway driving.

Figure 36 and Figure 37 provide an overview of exemplary perturbations that have been used in the project. The first perturbation has a simple sine form with two periods and an amplitude of $1 m/s^2$. The second perturbation was created from accelerations measured in a manually driven vehicle in freeway traffic and it shows multiple harsh decelerations with peaks of up to $-4 m/s^2$.



Source: CAMP V2I Consortium

Figure 36 - Sinusoidal Perturbation



Source: CAMP V2I Consortium

Figure 37 - Naturalistic Driving Perturbation

3.2.2.3 Environment Parameters

The simulation environment allows the modification of key parameters to simulate certain environmental conditions that can also vary over time. Specifically, the following adjustments can be made when conducting a simulation run.

- *Vehicle set speed and time gap:* The vehicle set speed and time gap can be modified in the simulation environment on a per-vehicle basis. This can be used to characterize the algorithm at different speeds and with different operational scenarios.
- *Communication quality:* Artificial communication obstructions can be introduced that lead to either random or predefined packet drops. This is utilized to study the algorithm's reliability with regards to communication issues. Furthermore, communication can be fully deactivated to force the vehicles to solely rely on the radar. This let the vehicles to become ACC vehicles which is used in baseline simulations to compare ACC and CACC systems.
- *GPS quality:* The GPS model allows the selection of different quality levels that will reduce or increase the errors applied to localization readings of the individual vehicles.

4 Algorithm Development & Evaluation

The approach taken was to establish a system architecture that implements CACC as an extension of ACC, thereby leveraging the lessons learned from prototype ACC vehicle testing as well as ideas from prior research.

4.1 Implementation

The CACC algorithm development was initiated by creating a preliminary software architecture, assigning functionalities to the different software modules, and establishing development priorities. The algorithm architecture was divided into essential and optional components and three software versions were defined. An iterative process of specification, implementation, evaluation and refinement was established with each new software version building on the prior, either by enhancing the functionality of existing modules or by adding features using new modules while refining the algorithm architecture. The different software versions can be characterized as follows.

Software Version 1 provides the core CACC functionality with all necessary basic software modules such as the object fusion, target selection and the longitudinal controller.

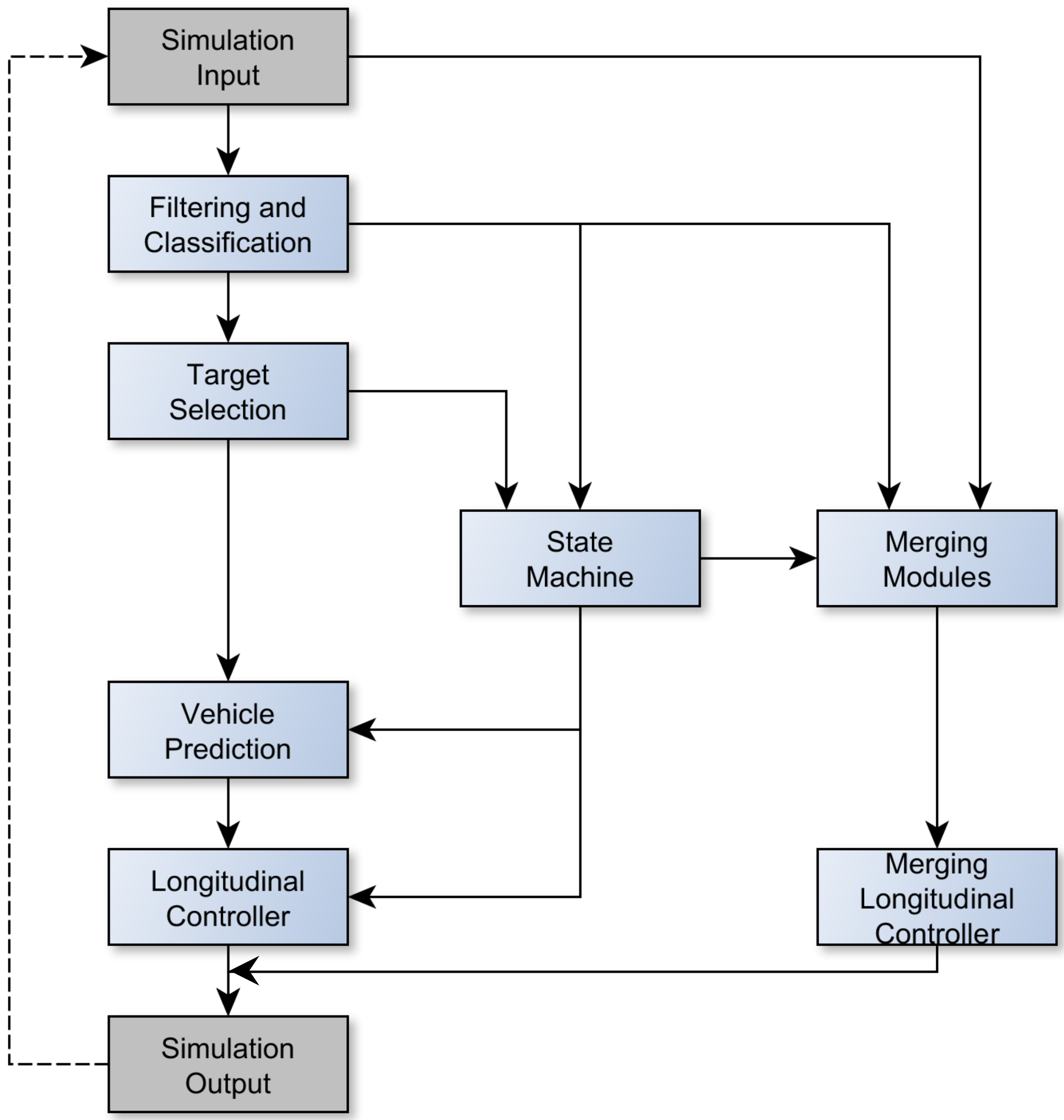
Software Version 2 builds upon software version 1 adding a "multi-vehicle look-ahead" function which utilizes information from vehicles beyond the immediate preceding vehicle and an assessment of the 'communication quality' which, depending on the outcome of that assessment, dynamically adapts the target time gap to the current situation.

Software Version 3 is the final software version that adds infrastructure support in the form of a 'merging assistant' that would reside in a roadside unit at a highway on-ramp as well as performance improvements in other software modules.

The CACC algorithms were implemented in the simulation environment using ADTF, which is the same environment used to implement the prototype ACC algorithm in the project vehicles. This approach enables a simplified transition of the CACC algorithm from the simulation environment into the prototype vehicles.

4.1.1 Algorithm Architecture

The high-level algorithm architecture diagram in Figure 38 shows the different software modules implemented and their data exchanges. Further detail underneath these modules is provided in APPENDIX C



Source: CAMP V2I Consortium

Figure 38 - CACC Algorithm Architecture

4.1.2 Software Modules

The following list of software modules implemented in the simulation environment includes both CACC algorithm elements and components required to interface with the simulation environment. A brief explanation of their responsibilities within the overall system architecture is provided. Modules highlighted in bold are unique to the evolution of ACC to CACC and are discussed in more detail in subsequent sections.

Acceleration Command Transmitter receives acceleration commands from the longitudinal controller, encapsulates them and sends them to the simulation environment through the network protocol.

Adaptive Time Gap and Speed Support adapts the current time gap and speed setting of the CACC system based on an assessment of the current communication quality and the hazard flag.

BSM Transmitter forwards additional data elements to the simulation environment through the network protocol for inclusion into the BSM.

Communication Quality Determination observes BSM data received over time and calculates communication statistics to estimate the quality of the communication between the HV and RV including: Information Age (IA), Communication Induced Tracking Error (CITE).

Coordinate Transformation receives decoded BSMs and converts relevant data elements from earth-fixed coordinates into host-vehicle-centric coordinates. As BSM information is received asynchronous to GPS readings, the module extrapolates the HV's position based on vehicle speed measured by the vehicle's sensor and the GPS heading.

Event Input Receiver receives event information from the simulation environment and forwards it to other modules in the CACC algorithm. This includes actions that in a vehicle would be triggered by the driver such as system activation/deactivation and modification of set speed and time-gap settings.

First Order Lag Look-Up receives the acceleration command from the longitudinal controller and looks up the time constant and time delay parameters based on the current vehicle-dynamics conditions.

Infrastructure Message Assessment receives and evaluates merging request messages from the infrastructure to determine relevance for the current HV, choose the correct sensor object, and provides any necessary information to other modules by setting the merging flag and forwarding object information.

In-lane Assessment receives a list of fused objects ahead, filters them for vehicles that are in the HV's lane and outputs a subset of the original list of fused objects.

Lane-Change Detection receives a list of objects that have been processed by the lane classification module and performs lane-change detection based on the current lane assignment and other remote vehicle data. The classification result is appended to the information in the fused object list.

Lane Classification assigns objects into virtual lanes around the center position of the host vehicle based on their relative position. The result of the classification is appended to the information in the fused object list.

Logging Output Transmitter receives internal logging variables that were not otherwise exposed to the simulation environment and sends that data to the simulation environment through the network logging interfaces.

Longitudinal Classification performs an initial filtering of objects identified from DSRC and the radar sensor and longitudinally categorizes them based on distance to the host vehicle.

Longitudinal Controller calculates an acceleration command based on a provided virtual target object.

Merging Flag Switches are responsible for passing through the correct variables based on the current state of the merging flag.

Merging Target Creation is a second instance of the Virtual Target Creation that creates a virtual target for the merging vehicle.

Merging Target Modifier adjusts the lateral offset of the fused sensor object so that it is projected into the HV's lane and adjusts its longitudinal offset based on the distance to the merging point

Move Data Extractor uses a simple vehicle-dynamics model to calculate the host vehicle's movement in HV-centric coordinates and calculates displacements in x-Axis, y-Axis and yaw/heading relative to the previous timestamp when vehicle-dynamics data was received.

Move Data Receiver receives vehicle sensor information from the simulation environment and provides it to the Move Data Extractor.

MRR Object Validation receives radar object information and verifies and improves object existence probability and movement state data.

Object Fusion receives radar and BSM object information and fuses them when appropriate. The output of the module includes fused and unfused objects.

Path Prediction calculates the host vehicle's predicted path based on the vehicles motion data. The data output is provided in the HV coordinate system.

Primary Target Validation receives information about objects ahead (in the HV's lane or adjacent lanes) and selects a single primary target by considering information from the modules that perform lane classification and lane-change detection.

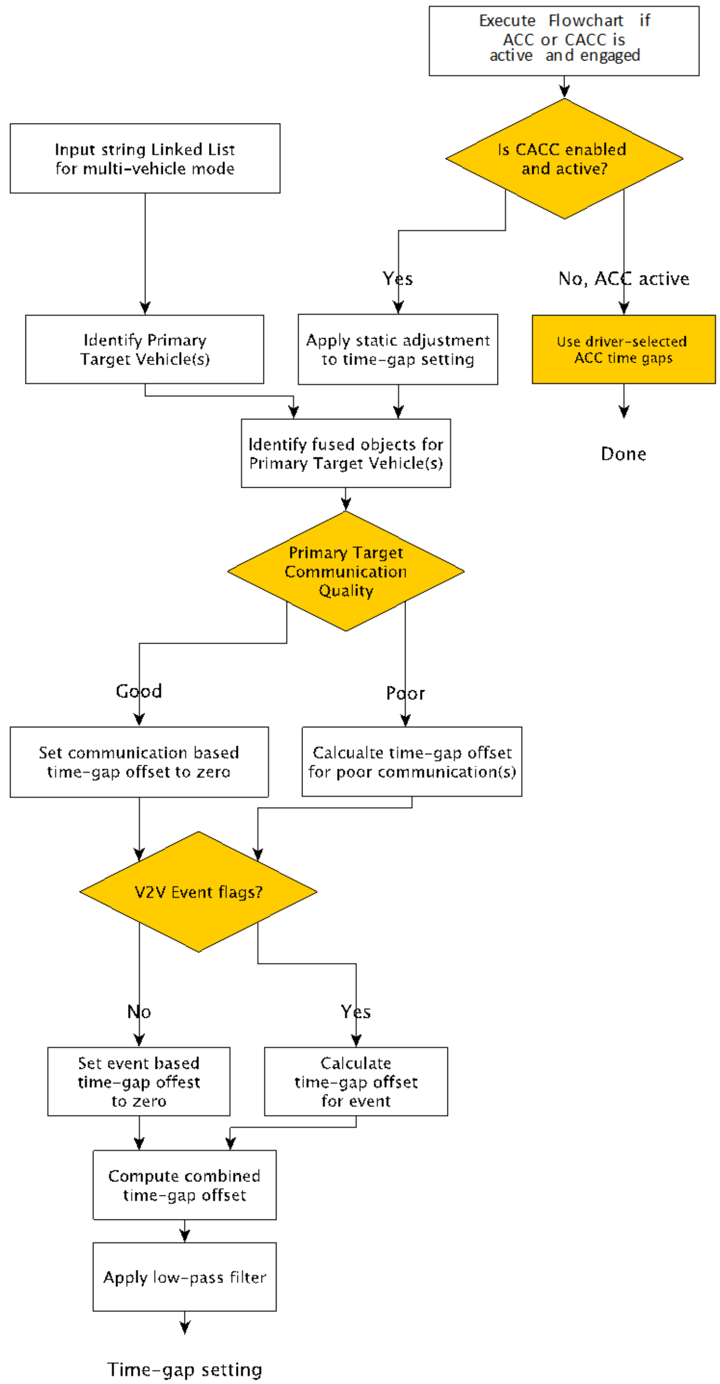
State Machine defines the logical behavior of the entire system for transitioning to and from Manual, CC, ACC, CACC, Manual recovery, and ACC recovery states. When system inputs satisfy the requirements for a transition, the system will then execute and support the behaviors required of the newly entered state.

Vehicle Behavior Estimation studies vehicles that are part of the CACC string and ahead of the target vehicle. If one of those vehicles performs potentially hazardous maneuvers, such as hard braking, the module informs other modules about the severity of the hazard by raising the hazard flag.

Virtual Target Creation synthesizes a virtual target based on various inputs interfaces and sends it to the longitudinal controller. Depending on the system state, the Virtual Target is based on onboard sensor measurements and, if applicable, V2V message information.

4.1.2.1 Adaptive Time Gap

While the system is in the CACC state, the time gap is constantly adjusted from its base setting to compensate for decreases in communication reliability and in response to event flags such as hard braking received from vehicles ahead to improve the string’s ability to respond to perturbations in traffic flow as shown in the flow chart in Figure 39.



Source: CAMP V2I Consortium

Figure 39 - Adaptive Time-Gap Flowchart

The algorithm first identifies the fused objects for preceding vehicles that will be considered for time-gap adjustment. The In-lane Assessment Module provides a “fused object list” data structure, comprised of the ID of the primary vehicle in CACC mode, as well as the ID of any vehicle ahead of the preceding vehicle including the position of the RV in the given fused object list.

The algorithm then determines the quality of the communication link between the vehicle and the primary vehicle and preceding vehicles when applicable. If the algorithm determines that communication quality is poor, it calculates a time-gap offset to accommodate the communication uncertainties. This time-gap offset is set to zero when the communication quality is determined to be good.

The algorithm then looks for any relevant V2V-based event flags. In the presence of such an event flag, a time-gap offset is calculated to accommodate the perturbations due to the event. The time-gap offset is set to zero in absence of any event.

Finally, the algorithm then combines the two computed time-gap offsets with the selected time gap and ensures that it falls within the pre-determined thresholds. This new time gap is then passed through a low-pass filter to produce the Adaptive Time-Gap setting.

4.1.2.2 Communication Quality Determination

Communication quality is determined using Information Age (IA) and CITE as the primary metrics.

IA is the time measured at a HV, expressed in milliseconds, between the timestamp corresponding to the data contained in the most recently received BSM from a given RV and the current time. This metric is essential and captures how current the information about the RV is at HV. As different vehicles might be relevant for CACC in case of a multi-vehicle look-ahead configuration, multiple IA statistics are calculated and stored. The computation is periodic and will take place at a specified interval. The module calculates IA using the most recent BSM of each DSRC-equipped RV. The lower the value of IA, the better the communication quality with that vehicle is. The module will internally keep track of the last several values of IA (configurable value). If a message from an RV wasn't received within a period determined by multiplying the computation period by the number of saved values, then the storage shall be freed, and the RV is considered out of communication. As a second step, the module calculates IA quality, which is specified as the ratio of the number of samples with an IA less than a specified threshold divided by the total number of samples in the interval of interest. IA quality is a function distance between the HV and RV and HV speed.

CITE is the 2-D distance between the RV’s current position and its estimated position based on extrapolation from the previous transmitted message. CITE is computed when the HV receives a BSM from the RV in two steps (refer to Appendix A.8.2 of J2945.1 for a detailed description of the tracking error calculation). First, the HV uses RV's last known position to estimate its current position assuming the RV has constant speed and constant heading. Then CITE is calculated using the RV's position from the received BSM and the HV’s estimate. The CITE value is computed for each target RV. The lower the value of CITE, the better the communication quality. CITE quality is defined as the number of samples within a specified period that have CITE less than a specified threshold divided by the total number of samples. The CITE threshold is a function of distance between the HV and RV.

Calculation results of this module are made available to the State Machine and the Adaptive Time-Gap Module.

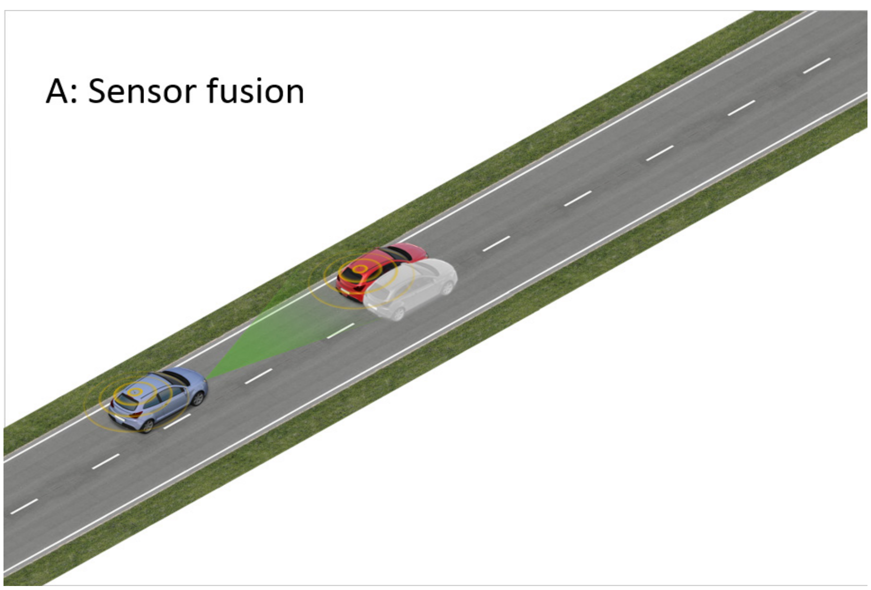
4.1.2.3 In-lane Assessment

CACC implements longitudinal vehicle control based on data received from preceding vehicle(s) in the same lane. Therefore, the host vehicle needs to verify that the remote vehicle is driving in the same lane. In-lane Assessment receives a list of fused objects ahead and filters them for vehicles that are in the host vehicle's lane. The output of the algorithm is a subset of the original list of fused objects.

Conventional ACC systems perform this assessment based on radar which has a relatively high lateral accuracy. CACC will receive part of the required information through DSRC which relies on relative GPS positioning. This solution can have an accuracy that, in certain situations, will be insufficient for a lane-level assessment. Therefore, CACC also considers radar information.

For DSRC-equipped vehicles in the line of sight of the Radar, this means that two readings (one from radar and one from DSRC) will be received. Both readings will have an offset to each other. By monitoring both readings over time and comparing relevant parameters (size, speed, and distance), the host vehicle can verify that both readings describe the same object and, therefore, "match" them. This can even work when lane affiliation is unclear for the BSM data (as visualized in the following graphic).

Whenever the vehicle is now receiving a new BSM from the vehicle with the same temporaryID as before, it can immediately consider its content for control action as it had already established "trust" through verification with the radar sensor. This situation is depicted in the Figure 40 where the blue vehicle receives a Radar reading and a BSM from the red vehicle and then “matches” both readings. This functionality can be achieved for a single-vehicle look-ahead operation by implementing a radar / BSM sensor fusion algorithm.

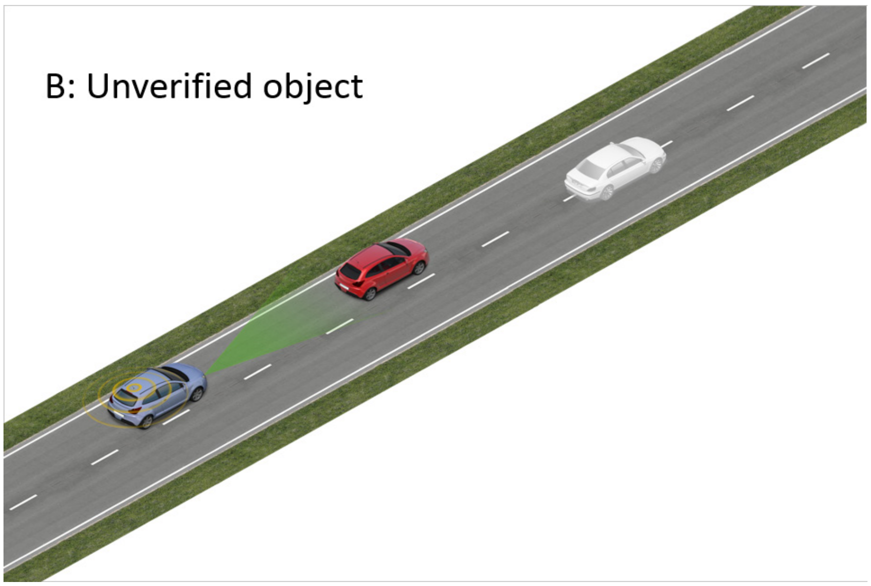


Source: CAMP V2I Consortium

Figure 40 - Sensor Fusion for In-Lane Assessment

Multi-vehicle look-ahead functionality is envisioned as a mode of CACC operation that not only considers information from the immediate preceding vehicle but also from vehicles further downstream. Frequently, a radar sensor cannot reliably detect multiple vehicles ahead in the same lane. This means that the host vehicle needs to be able to identify, based solely on DSRC information, if a vehicle more than one position ahead is either part of the same string or driving in an adjacent lane.

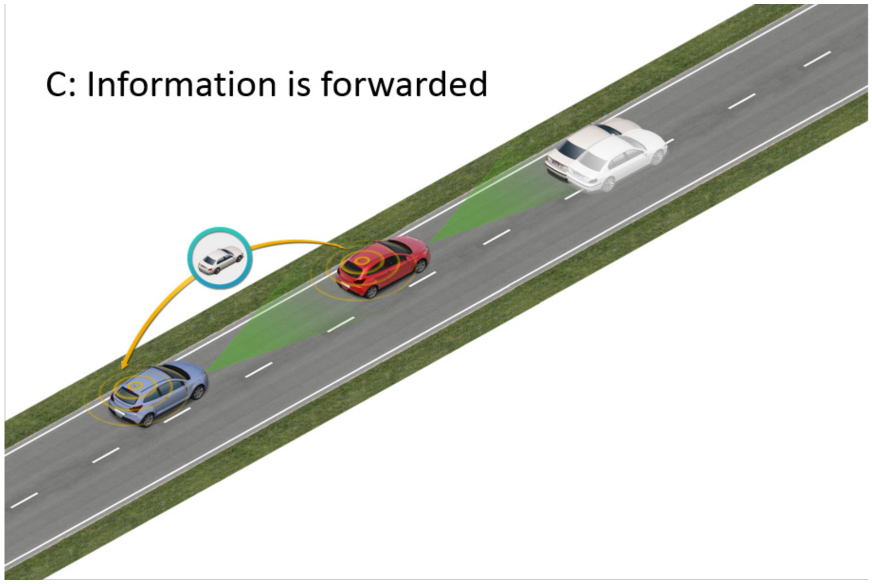
In certain conditions with insufficient GPS accuracy, this might not be possible in a reliable manner as depicted in Figure 41 where the blue vehicle receives a BSM from the white vehicle, but its radar view is obstructed and it cannot verify the lane affiliation of the white vehicle with its radar sensor



Source: CAMP V2I Consortium

Figure 41 - Unverified Object due to Field-of-View Obstruction

To solve this dilemma, the verification capability of the intermediate vehicle can be utilized. Forwarding that information to the host vehicle (blue) allows it to gain trust in the position of the vehicle reported ahead even though it was purely observed through DSRC. Figure 42 illustrates this approach, where the red vehicle validates that the white vehicle is in the same lane and passes this information to the blue vehicle. The blue vehicle has validated that the red vehicle is in its lane and now also knows that the white vehicle is in the same lane.



Source: CAMP V2I Consortium

Figure 42 - Information Forwarding for In-Lane Assessment

This approach can be extended using a 'linked-list' algorithm. Every vehicle transmits its own temporary ID (as defined in the BSM) and the temporary ID of the vehicle it currently considers its target. The identifier of the target vehicle needs to be transmitted using a BSM message extension.

By using this information, other vehicles can build a linked list of vehicles in the same string by receiving BSMs from vehicles ahead and identifying one link after each other until either communication range is exceeded or the beginning of the string is reached as illustrated in Figure 43. Whenever new information is received, the algorithm validates and potentially rebuilds the linked list. This is necessary to detect cut-in or cut-out maneuvers that require an update of the list.

However, because the algorithm requires message reception from multiple vehicles ahead, it must anticipate that the host vehicle won't receive every message that is being transmitted from vehicles further ahead. The algorithm needs to be robust against occasional DSRC packet drops, which can be achieved by implementing and tuning an age threshold up until the received BSMs will be considered valid.

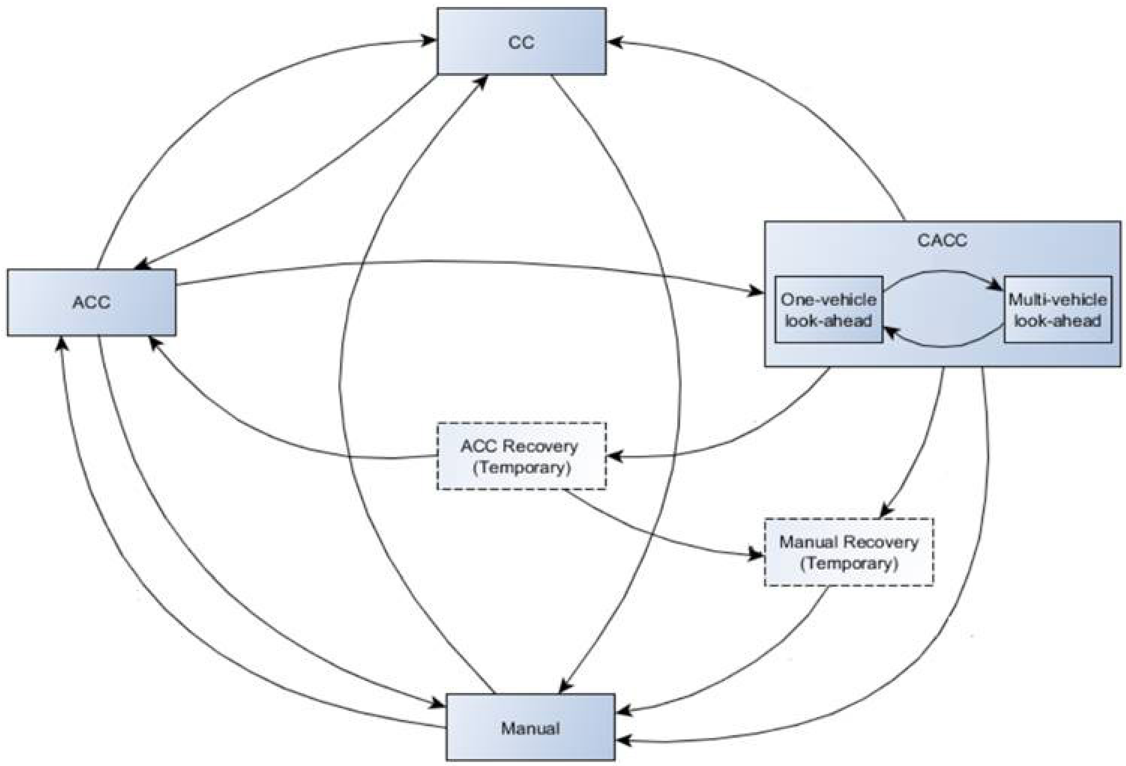
Source: CAMP V2I Consortium

Figure 43 – Linked-List Algorithm Concept.

4.1.2.4 State Machine

The state machine defines the logical behavior of the entire CACC system and includes four different states. The transition from one state to another will only occur when the system input and the state transition requirements are satisfied. The system required inputs are comprised of all stimuli that can be originated from different sources. Stimuli can come from the external environment such as radio signals, from the HV such as machine vision, and from the local processing environment, such as current state and supervisory inputs.

Figure 44 illustrates the behavior of the CACC system and its logical operating states. The state diagram includes four different operating states and two temporary states that are needed to allow for smooth transition between main modes of behavior. The main system states include CACC, ACC, CC, and Manual. The temporary states are ACC Recovery and Manual Recovery. These states define a high-level behavior and serve as a container for sub-states that exist where necessary to define the internal behavior of each state. For example, the CACC state is subject to transitions to and from other states at the same level but also supports the transitions between its sub-states to fulfill requirements on state-specific behavior. While the system is "in the CACC state," the sub-states might include multi-vehicle look-ahead and one-vehicle look-ahead.



Source: CAMP V2I Consortium

Figure 44 - State Transition Diagram

Each one of the four main states maintain unique ranges of operation. There are requirements around the conditions that should exist prior the transition between states. Once these operating parameters are in range, the transition can occur. Temporary "recovery" states accommodate these transitions by allowing time for operating conditions to settle. These temporary states are defined such that there is no direct return path to the original state. Note that while these two temporary states are necessary for proper vehicle operation, they were not implemented in the simulation environment. A brief description of each state follows.

4.1.2.4.1 Manual

In the Manual state, the vehicle is fully controlled by the driver. The system is not controlling the vehicle at all, but it is monitoring the surroundings through radar or DSRC. This is the initial state when the CACC system is initialized.

4.1.2.4.2 CC

In the Cruise Control (CC) state, the system controls the vehicle's acceleration and deceleration by maintaining the internal set speed of the system.

4.1.2.4.3 ACC

In the ACC state, the system controls the vehicle's acceleration and deceleration by maintaining a fixed time gap to the preceding vehicle based on radar data.

4.1.2.4.4 CACC

In the CACC state, the system controls the vehicle's acceleration and deceleration by maintaining a time gap to the preceding vehicle as well as other control strategies such as multi-vehicle look-ahead or single-vehicle look-ahead, which are considered sub-states of the CACC state. Whenever the system is transitioning into the CACC state, the one-vehicle look-ahead sub-state is always entered first. As soon as conditions for transition into the multi-vehicle look-ahead sub-state are met, the system performs that transition. While in the CACC state, the system transitions between the two sub-states based on the sub-state transitions requirements.

4.1.2.4.5 ACC Recovery

The ACC Recovery state is a temporary state that ensures safe transitions from the CACC state to the ACC state. In the CACC state, the system might operate with a reduced time gap and increased acceleration and deceleration limits when compared to traditional ACC operation. The ACC Recovery state ensures that the transition from the CACC to the ACC state is allowed only when the time gap, acceleration and deceleration parameters are within the ACC's designed operating limits. This is done by potentially applying appropriate braking forces until all necessary conditions are satisfied for safe transition to the ACC state. However, if the system in the CACC state is already operating within the operating capabilities of ACC before the fault occurrence, the transition via the ACC Recovery state is almost instantaneous.

4.1.2.4.6 Manual Recovery

The Manual Recovery state is a temporary state that provides safe transitions from the CACC state or the ACC Recovery state to the Manual state and ensures the driver's controllability of the vehicle. The Manual Recovery state applies appropriate braking force so that the time gap is made large enough before transitioning to the Manual state. The time the system spends in the Manual Recovery state depends on operating conditions preceding the transition to the Manual Recovery state. In the case of sensor faults leading to Manual Recovery, the time in Manual Recovery and associated deceleration values are determined with the help of the immediate last known valid sensor information.

4.1.2.4.7 Manual Override

The driver may manually override the vehicle’s longitudinal acceleration at any time by applying the accelerator pedal in any system state. If the system is in the CACC state when the driver applies the accelerator, the system will revert to ACC control when the driver releases the pedal to ensure that communication between vehicles is still active before CACC is reengaged. For all other states, the system will revert to the state it was in when the driver pressed the accelerator pedal.

If the driver applies the brake pedal, the system will disengage, regardless of state, and revert to manual control. For the sake of simplicity, manual override is not shown on the state transition diagram or list.

4.1.2.4.8 State Transitions

Table 12 illustrates the conditions for transition from one state to another. When the system is in the CACC state, the system transitions between the two sub- states. The system automatically transitions from the single-vehicle look-ahead to the multi-vehicle look-ahead sub-state when one or more relevant vehicles ahead of the preceding vehicle are identified, or when the communication with the vehicle ahead is deemed reliable. Alternately, the system will transition automatically from the multi-vehicle look-ahead to the single-vehicle look-ahead sub-state when no vehicle ahead of the preceding vehicle can be defined through received BSMs, or when the communication with the vehicles ahead is deemed unreliable.

Table 12 - State Transitions

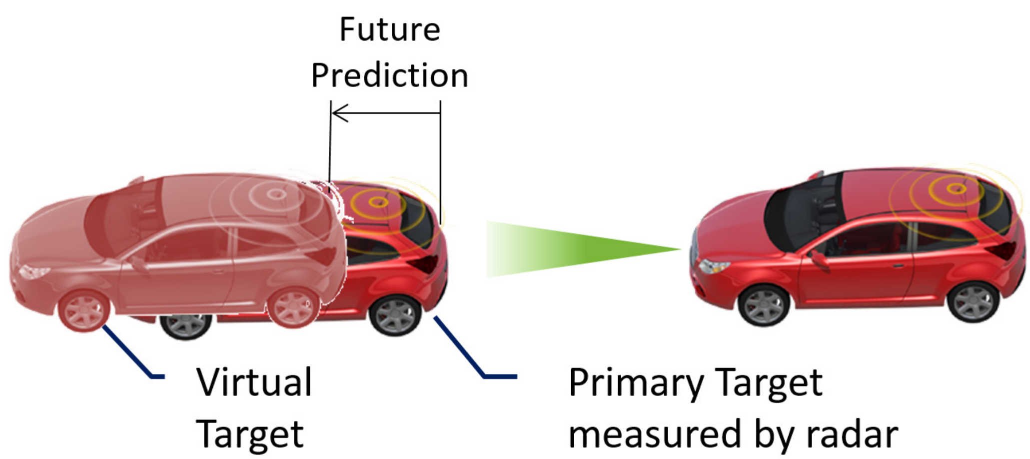
↱	Manual	CC	ACC	CACC
Manual		Driver activation without target vehicle	Driver activation with target vehicle	
CC	One of the following conditions: a) Brake activation b) Driver system deactivation		Target Acquisition	
ACC	One of the following conditions: a) Brake activation b) Driver system deactivation c) Radar malfunction	Target loss		Reliable communication and localization
CACC	One of the following conditions: a) Brake activation b) Driver deactivation c) Radar malfunction (Through the Manual Recovery state)	Target loss	One of the following conditions: a) Unreliable communication b) Unreliable sensor fusion c) Unreliable localization (Through the ACC Recovery state)	

Source: CAMP V2I Consortium

4.1.2.5 Virtual Target Creation

The Virtual Target Creation module receives the information about the actual target ahead, adjusts the data to create a future prediction of target speed and distance, and presents this the host vehicle longitudinal controller. The resulting Virtual Target can, based on the current vehicle dynamics of both the host vehicle and the target vehicle, be located closer or further away than the physical location of the target vehicle. Through this prediction, earlier reactions can be triggered in the host vehicle longitudinal controller, thereby reducing overall reaction time.

Figure 45 shows the host vehicle following a primary target vehicle and the insertion of virtual target data to modify the host vehicle's behavior. In ACC mode, the virtual target is identical with the primary target vehicle sensed by the host vehicle's radar. In CACC mode, the virtual target includes a future position adjustment based on BSM information, resulting in better longitudinal control than in ACC mode. This approach minimizes modifications on the existing ACC longitudinal controller.



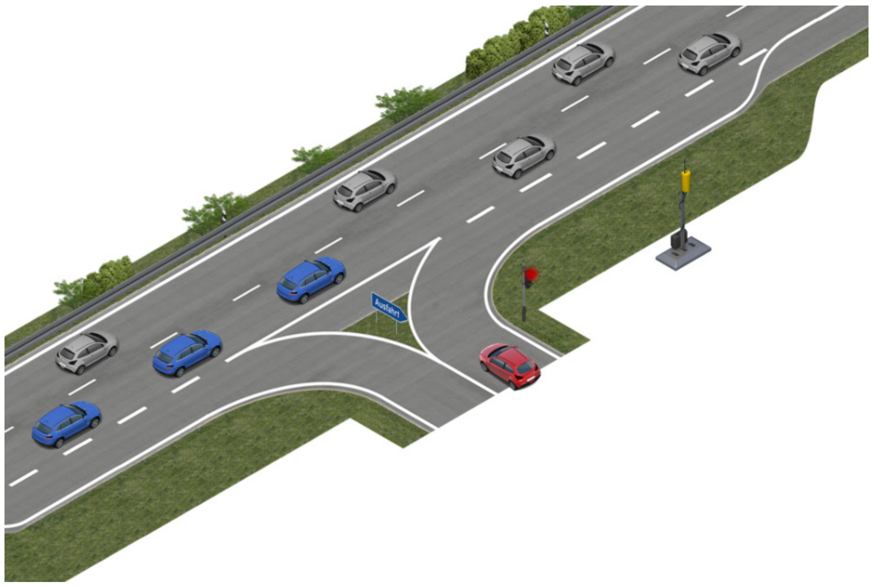
Source: CAMP V2I Consortium

Figure 45 - Virtual Target Data Creation

Virtual target trajectory estimation in CACC mode is performed by using the current acceleration and acceleration forecast information transmitted from the primary target. The prediction is made assuming current acceleration converges to the acceleration forecast using a first order lag model with a time constant for the primary target that is also transmitted in BSM. The host vehicle's trajectory can be predicted in the same manner using its acceleration, acceleration forecast, and first order lag time constant. Comparison of these two trajectories at a future point in time provides predicted changes in relative distance and speed, which are added to the values measured by the host vehicle radar to establish virtual target behavior in one-vehicle look-ahead mode.

4.1.2.6 Infrastructure Assisted Merge

CACC-equipped vehicles may encounter situations where merging traffic needs to be accommodated due to the small time gaps maintained by the vehicles. According to a CACC Human Factors Study on merging behavior [9], 18% of the merges "in which drivers were required to manually adjust speed to merge into the platoon of vehicles experienced collisions". The high percentage of collisions in this study shows the importance of incorporating a method of merging into a highway containing CACC-equipped vehicles. A merge could be handled by the driver to manually incorporate merging traffic or could be implemented as part of the CACC functionality. Merging with a CACC functionality would be desirable since it would allow the driver to remain in a higher level of automation and, depending on the implementation, it could lead to an improvement in the impact of merging maneuvers on the surrounding traffic.



Source: CAMP V2I Consortium

Figure 46 - Assisted Merge Scenario

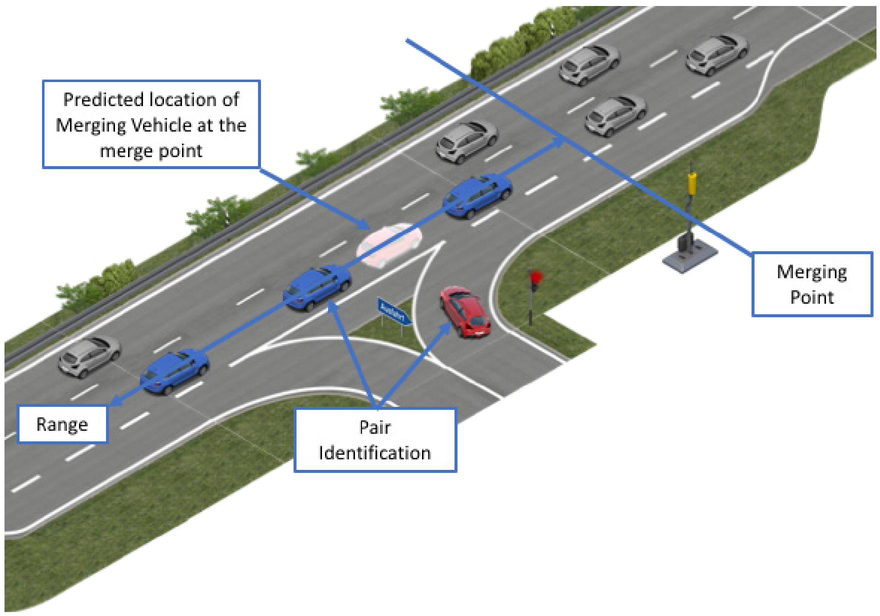
Considering the scenario illustrated in Figure 46, the red vehicle is attempting to enter the highway through the on-ramp. The blue vehicles are CACC vehicles traveling in a string. The grey vehicles represent surrounding unequipped (non-CACC) traffic. This example is expected to be one of the most common configurations. Since ramp metering is an effective method to ensure continuous traffic flow, it is assumed to be present. The vehicles of interest on the highway are CACC-equipped and have engaged the system. The vehicles on the on-ramp do not have CACC engaged and may or may not be transmitting BSMs (i.e., unequipped). The remaining sections explain the assumptions made and merging scenario further.

4.1.2.6.1 Merging Vehicle Motion

The merging vehicle motion will follow a predefined trajectory. The vehicle starts from 0 mph at the ramp meter and accelerates with a constant acceleration trajectory until the merging point. The vehicle reaches the highway speed at the merging point. As soon as the merging is completed, the merged vehicles will automatically activate CACC. The infrastructure keeps track of merging vehicles from the ramp light until they complete their merging maneuver onto the freeway. Depending on the injection frequency and the length of the on-ramp, this can mean that multiple vehicles need to be handled at the same time.

4.1.2.6.2 Pair Identification

In order for the CACC vehicles to be aware of the merging vehicles, a prediction of the merging vehicles has to be calculated and paired with a CACC vehicle on the highway. The infrastructure projects the movement of the merging vehicle onto the merging point (front bumper of the vehicle touching the merging point) based on the current time, position, speed, and acceleration to determine the time and speed of the vehicle at that point. If an auxiliary lane exists, the middle of that lane shall be assumed as the merging point. The infrastructure then identifies all CACC vehicles traveling on the rightmost highway lane that are within range of the merging point and checks whether it is necessary to pair it with a merging vehicle as illustrated in Figure 47.



Source: CAMP V2I Consortium

Figure 47 - Merging Point

4.1.2.6.3 Merging Scenarios

When vehicles are at the point of merging, several scenarios could occur. Conditions which could occur when the merging vehicle reaches the merging point and the appropriate system response(s) include the following.

- Merging vehicle aligns with a highway vehicle
- Highway vehicle accelerates to create sufficient space for merging vehicle
- Highway vehicle decelerates to create sufficient space for merging vehicle
- Merging vehicle aligns with a gap between highway vehicles
- Gap is insufficient for merge
- Highway vehicle decelerates
- Gap is sufficient for merge
- No change in speed of highway vehicles

4.1.2.6.4 Message Transmission

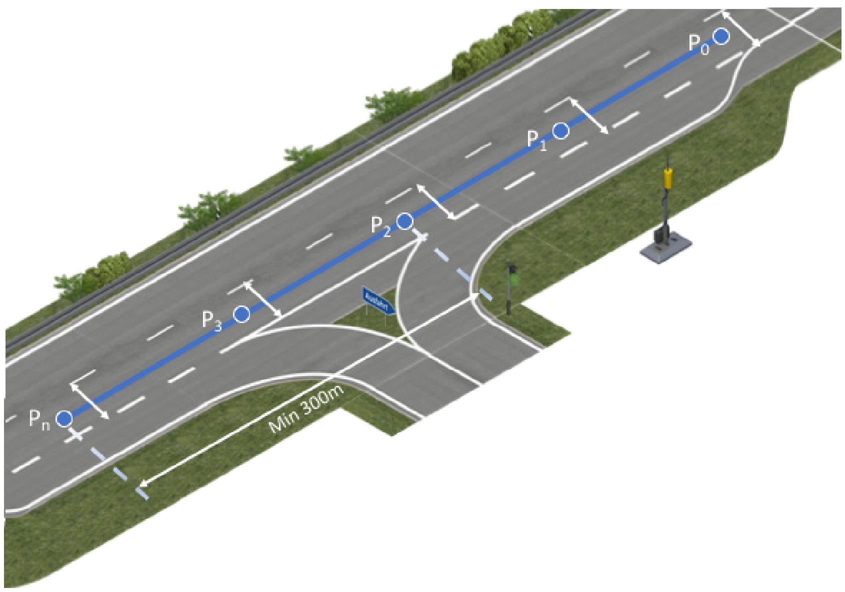
In order for the highway vehicles to be aware of the merging vehicles and to be paired to the proper merging vehicle, certain data elements need to be transmitted from the infrastructure. A BSM message should contain the proper data elements including the highway vehicle ID, merging vehicle ID, node points describing the freeway lane, and the time stamp when the message was assembled.

4.1.2.6.5 Node Point Mapping

In the message data elements, the geometry of the auxiliary lane and highway lane would need to be defined. The roadway geometry would be defined by node points placed according to the following rules.

- A minimum of 4 node points is required
- P0: End of the auxiliary lane
- P1: The merge point
- P2: Beginning of the auxiliary lane
- Pn: Ahead of the merging zone
- Additional optional points between P2 and Pn (depending on road curvature)
- The distance between P1 and Pn is to be determined based on the local characteristics ensuring enough reaction time of the vehicles
- The points shall be placed in the lateral center of the receiving lane
- Each point shall additionally include the lane width at that specific location

Figure 48 shows how the node points would be configured in the highway lane.



Source: CAMP V2I Consortium

Figure 48 - Node Point Placement

4.1.2.6.6 Merging In-vehicle Implementation

The following specification summarizes the additions to the CACC algorithm platform to ensure highway vehicles react to merging requests. The merging in-vehicle implementation has been designed with the following components.

- Interface Merging Flag
- Indicates the current mode of merging of merging vehicle, which is sent to downstream vehicles

- Infrastructure Message Assessment
- This assessment is the gateway from the infrastructure messages to the vehicle, which receives and evaluates messages and determines the correct action
- Merging Target Modifier
- Modifies the lateral offset and longitudinal offset of the Fused Object (merging vehicle) based on the information from the infrastructure message and projects the Fused Object to the HV's lane
- Merging Target Creation
- After performing the projection of the sensor object onto the HV lane, the Merging Target Creation creates a prediction of the position and speed of the sensor object and HV at the time of the merge and sets the virtual target for the HV. This is a special variant of the Virtual Target Creation with a few modifications.
- Merging Flag Switches
- Based on the current state of the Merging Flag, certain input variables from the Time Gap, System State, and Virtual Target Modules are passed through to the merging longitudinal controller
- Merging Longitudinal Controller
- The controller is a 1:1 copy of the main longitudinal controller but may operate prior to the merge and until the merge is complete

4.1.2.6.7 Integration with other Modules

During the merging maneuver, the vehicle effectively needs to consider two virtual targets at the same time. Therefore, the algorithm will utilize a variant of the virtual target creation, the 'merging target creation,' and a second longitudinal controller, the 'merging longitudinal controller,' at the same time. The minimum of the two resulting acceleration commands will be used as the final acceleration command.

4.2 Evaluations

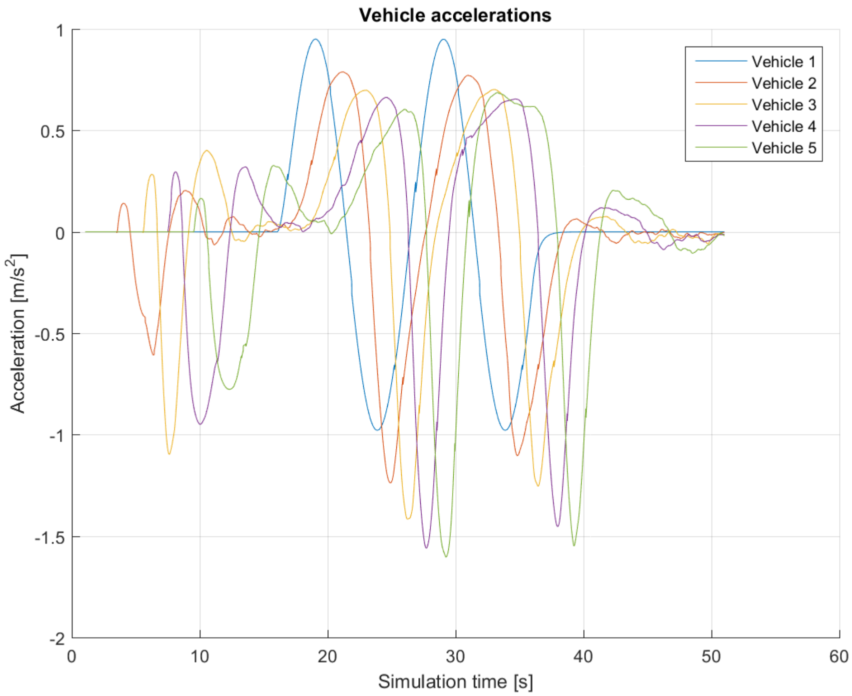
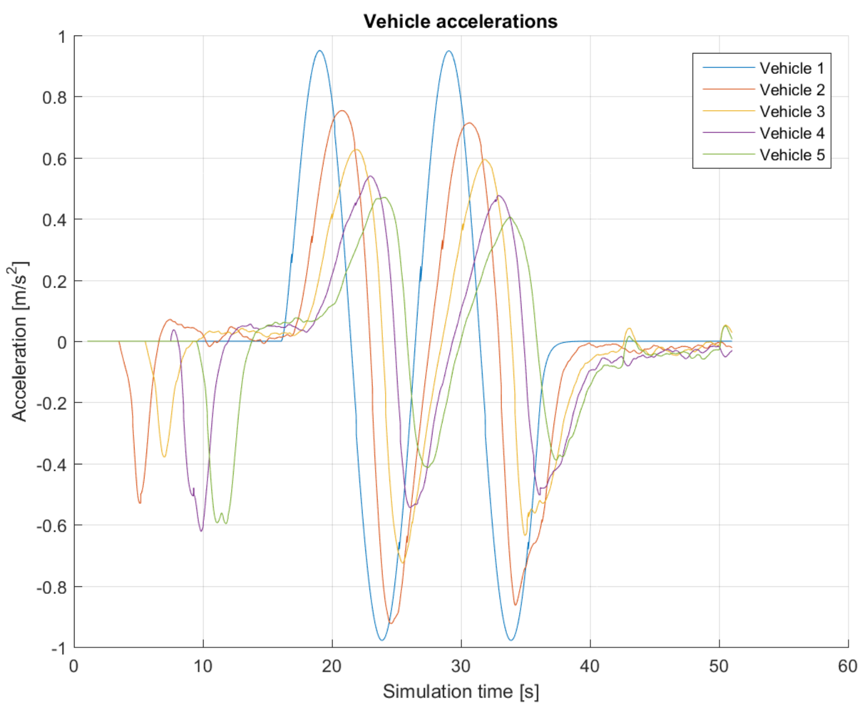
A series of CACC algorithm performance evaluations were conducted using the simulation environment to assess string behavior under a variety of operating conditions.

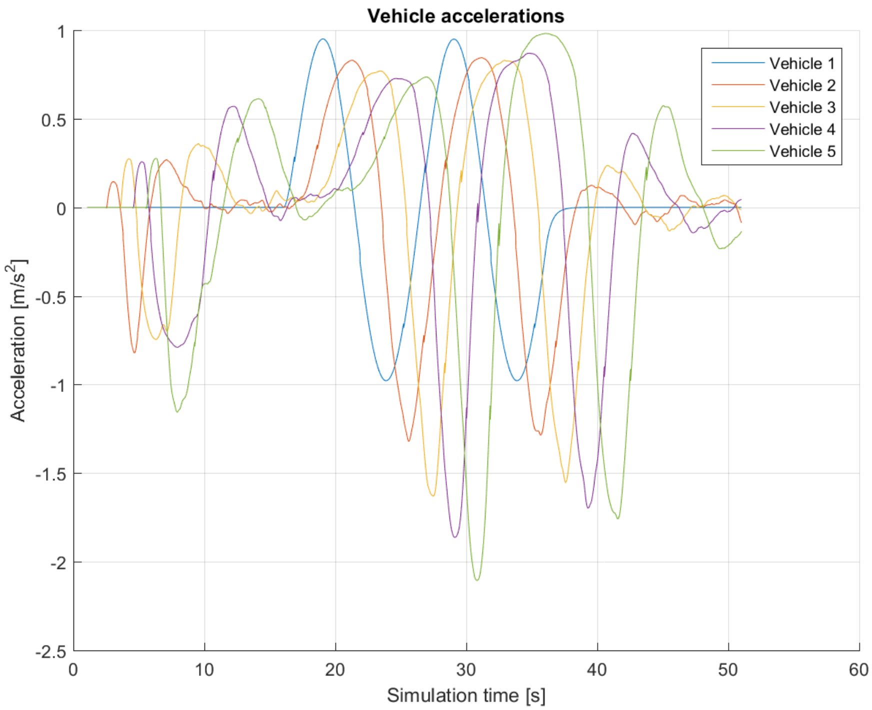
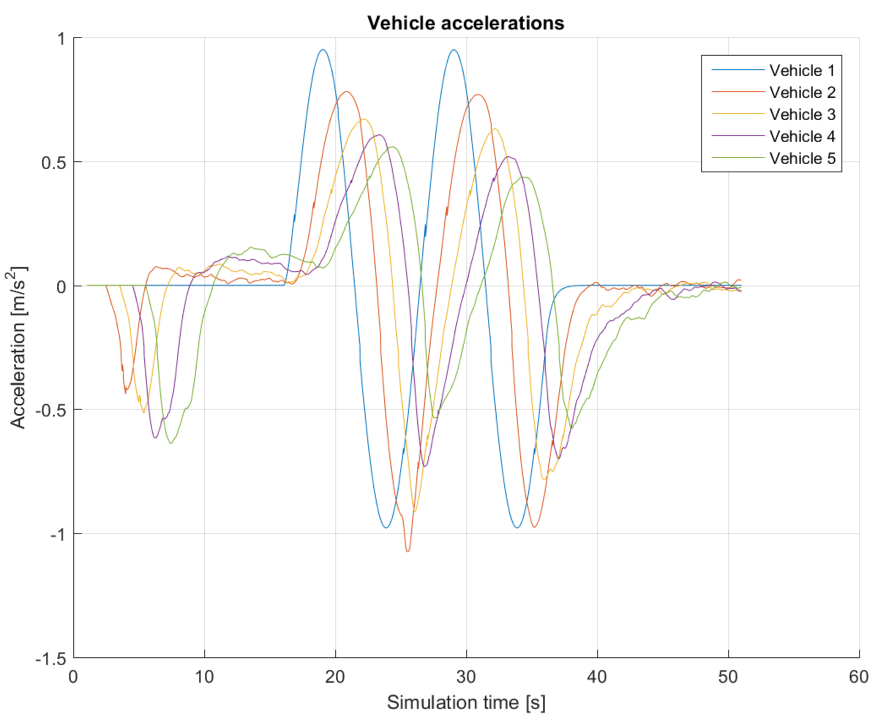
4.2.1 String Stability

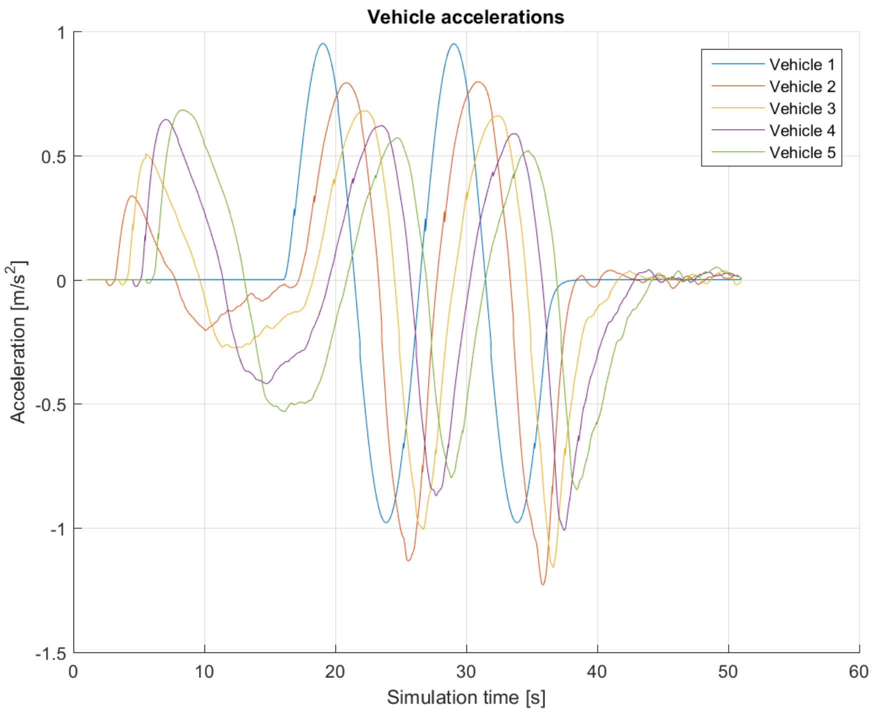
The stability of a vehicle string under automated control was evaluated to understand the effect of perturbations induced when the lead vehicle performs a sinusoidal deceleration maneuver, initiates hard braking and in response to a loss of communications within the string.

4.2.1.1 Comparison of ACC and CACC

A stable string of five vehicles traveling under ACC or CACC control at a set speed of 50 mph was subjected to a sinusoidal deceleration / acceleration maneuver performed by the lead vehicle. The maneuver was initiated 15 seconds into the simulation run and performed for two cycles with a period of 10 seconds and a peak of +- 1 m/s^2. Following vehicle response was assessed for three different time gaps settings within the string. Figure 49 compares following vehicle response under ACC and CACC control. For a time gap of 2s, the CACC algorithm demonstrates peak decelerations and accelerations decreasing from vehicle to vehicle indicating a stable string. The ACC system, however, is unstable under this condition as deceleration levels increase from vehicle to vehicle with peaks reaching ~ -1.5m/s^2.

<table>
<tr><th colspan="2">ACC vs CACC @ Time Gap</th></tr>
<tr><td>ACC
@ 2s</td><td>
</td></tr>
<tr><td>CACC
@ 2s</td><td>
</td></tr>
</table>

<table>
<tr><th colspan="2">ACC vs CACC @ Time Gap</th></tr>
<tr><td>ACC
@ 1s</td><td>
</td></tr>
<tr><td>CACC
@ 1s</td><td>
</td></tr>
</table>

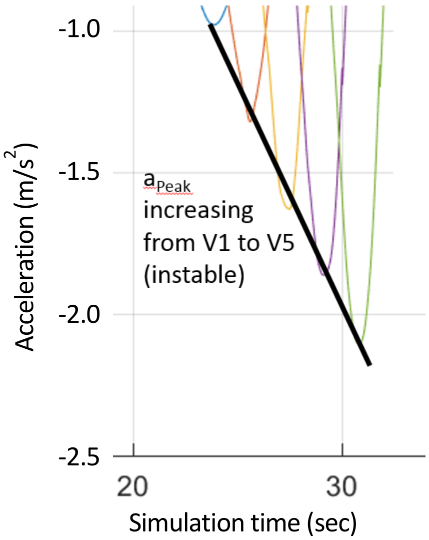
ACC vs CACC @ Time Gap	
ACC@ 0.5s	NA
CACC @ 0.5s	

Source: CAMP V2I Consortium

Figure 49 – String Stability Comparison

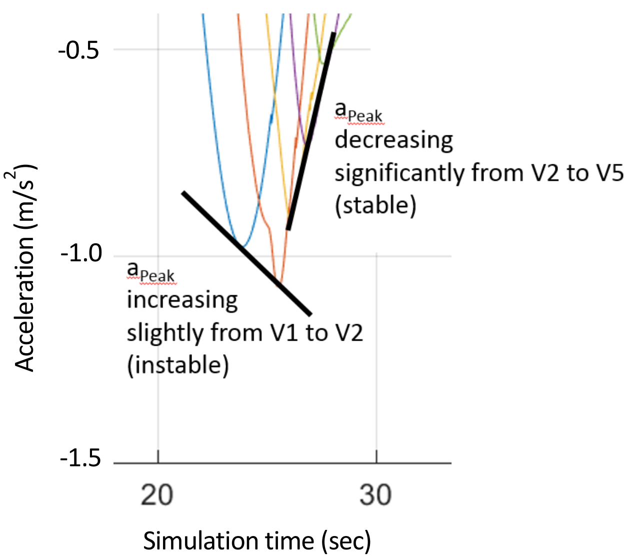
At a time gap of 1s, this effect increases under ACC control. Figure 50 provides an expanded view of string response to the first deceleration maneuver. Peak decelerations increase along the ACC string reaching ~ -2m/s^2. Comparing peak decelerations from vehicle to vehicle, a sharp negative slope can be seen indicating the instability of the ACC string under these conditions.

Figure 51 shows an expanded view of the same response region for CACC. Since vehicle 1 is following a static trajectory commanded by the simulation under "manual" control, it is not transmitting its acceleration forecast. As a result, Vehicle 2 can only rely on the reception of current acceleration information through the BSMs of vehicle 1. String stability is established under CACC control because vehicles 3-5 receive acceleration forecasts transmitted by the preceding vehicles. Comparing the performance of vehicles 2-5, a significant decrease in peak deceleration is observed along the string. Since the negative slope between vehicle 1 and 2 is still less than the same slope for ACC, it appears that CACC operation based on measured *current* acceleration performs better than sensor-based ACC and that CACC operation based on acceleration *forecasts* performs significantly better than ACC.



Source: CAMP V2I Consortium

Figure 50 – Expanded View of ACC Initial Peak Accelerations @ 1 sec Time Gap

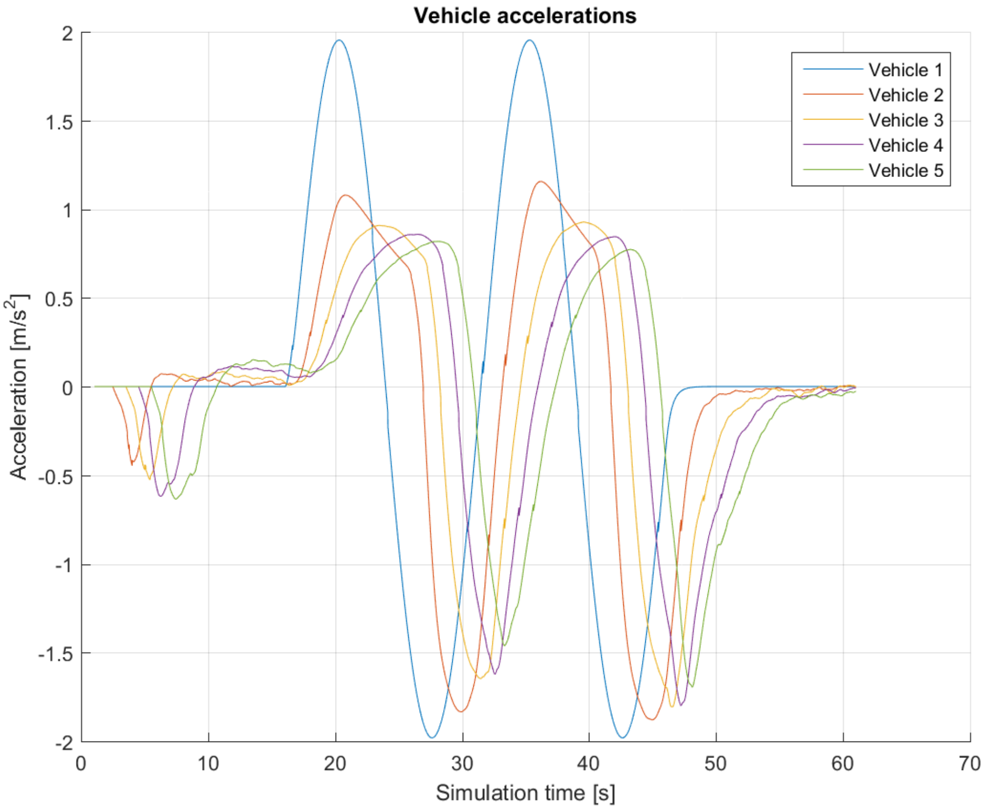


Source: CAMP V2I Consortium

Figure 51 – Expanded View of CACC Initial Peak Accelerations @ 1 sec Time Gap

Given the increasing instability of the ACC string with decreasing time gaps, only CACC string performance was evaluated with a time gap of 0.5s. The behavior of the string during this simulation run was similar to CACC operation at a 1s time gap with deceleration levels decreasing along the string in a stable manner.

CACC performance was also evaluated in response to a sinusoidal deceleration / acceleration amplitude of +-2m/s^2 at a 1s time gap between vehicles. Figure 52 shows that the performance of the CACC algorithm remains stable under this condition as well.

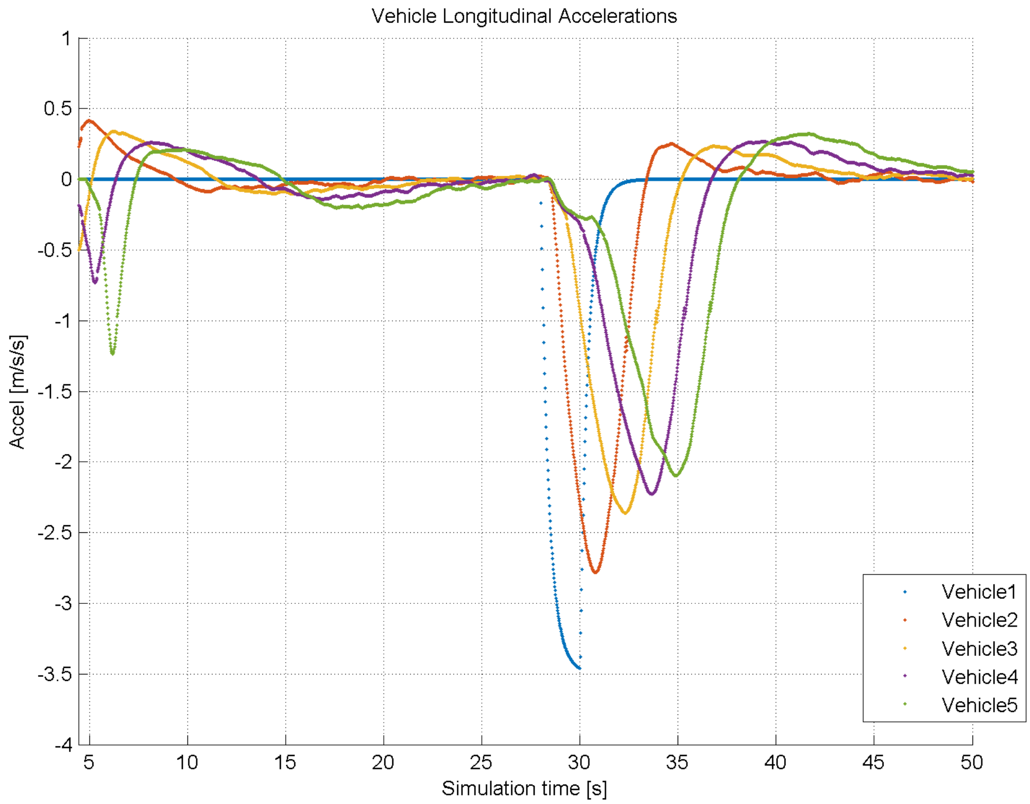


Source: CAMP V2I Consortium

Figure 52 - CACC String Response at +- 2m/s^2 over 15 s

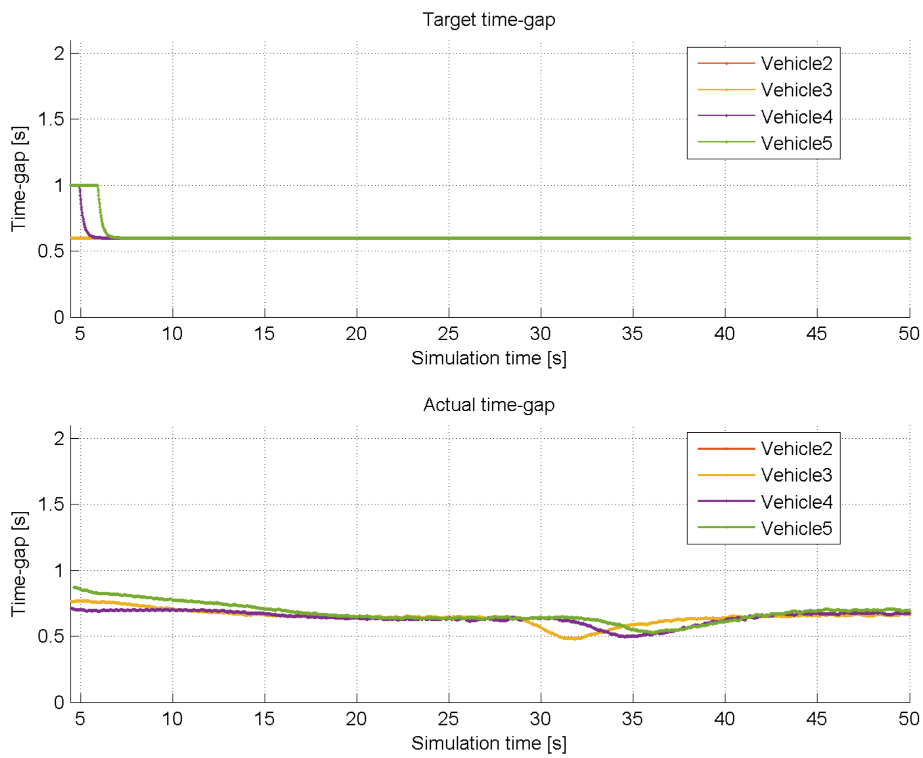
4.2.1.2 Time-Gap Adaptation during Hazard events

The effect of adapting time gap during a hazard event on string stability was evaluated. The scenario involves a sting of 5 vehicles traveling with a target time gap of 0.6s. The lead vehicle decelerates at -3.5m/s^2 for 2 seconds as shown in Figure 53. In absence of time gap adaptation, the vehicles in the string try to maintain the target set time gap of 0.6s as seen in Figure 54. As a result, the distance between vehicles decreases consistently along the string as shown in Figure 55.



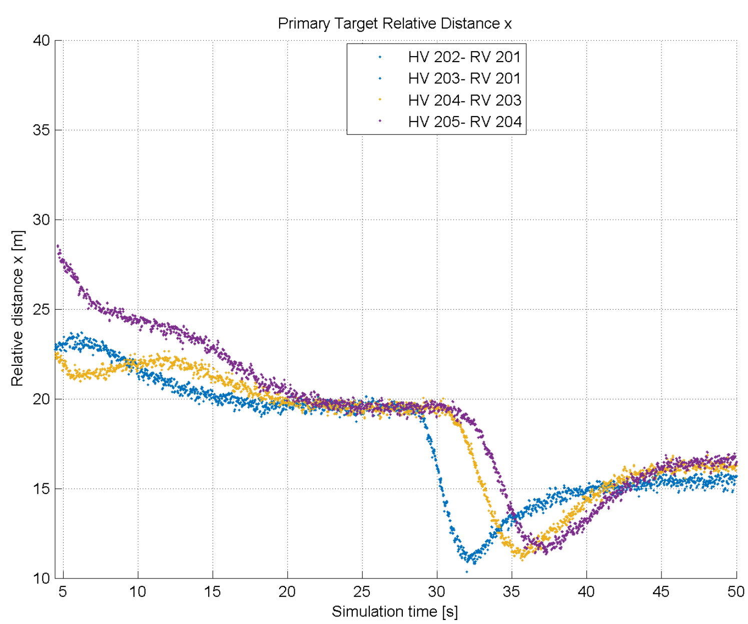
Source: CAMP V2I Consortium

Figure 53 - Deceleration Response with Constant 0.6s Time Gap



Source: CAMP V2I Consortium

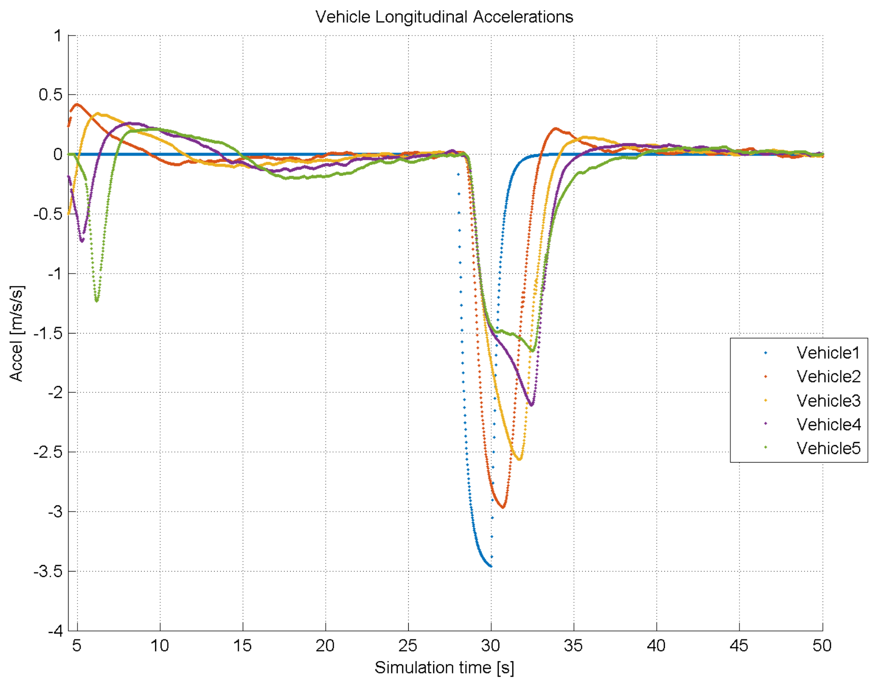
Figure 54 - Actual Time-Gap Change in Response to Hazard Flag



Source: CAMP V2I Consortium

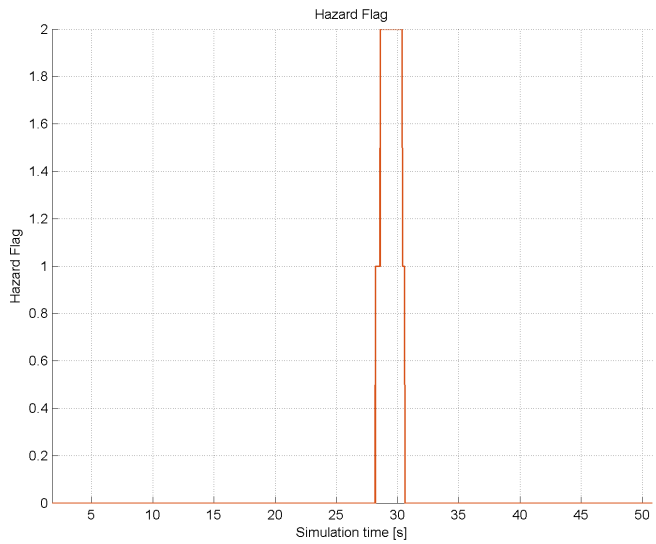
Figure 55 - Relative Distances with Constant 0.6 s Time Gap

When this simulation was repeated with time gap adaption, the deceleration by the lead vehicle triggered the Vehicle Behavior Estimation module of the following vehicles generating a hazard information flag as shown in Figure 57. As seen in Figure 58, the vehicles have a target time gap of 0.6s until vehicle 1 starts decelerating. For the duration of the lead vehicle deceleration, the hazard flag is set and the adaptive time gap module increases the target time gap to 1s. While the adaptation in the actual time gap is small, the reduction in distance between vehicles along the string during the deceleration is lessened and the vehicles return to a stable state more rapidly than with no time gap adaptation.



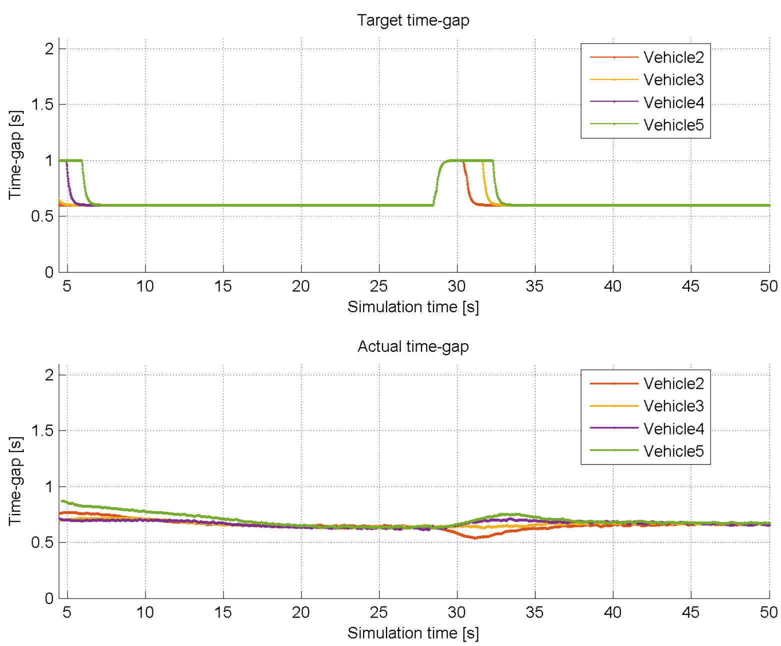
Source: CAMP V2I Consortium

Figure 56 - Deceleration Response with Time-Gap Adaptation to 1.0s



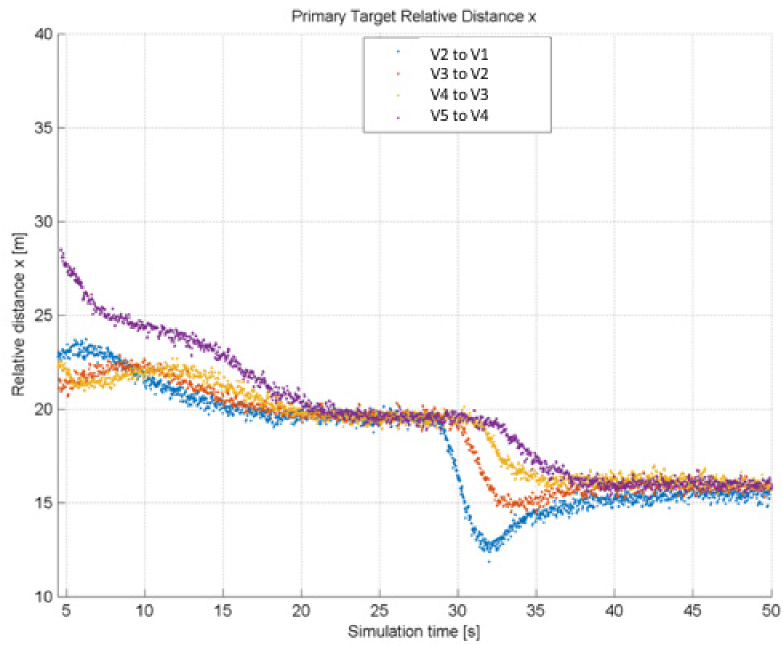
Source: CAMP V2I Consortium

Figure 57 - Hazard Flag Set by Vehicle 2



Source: CAMP V2I Consortium

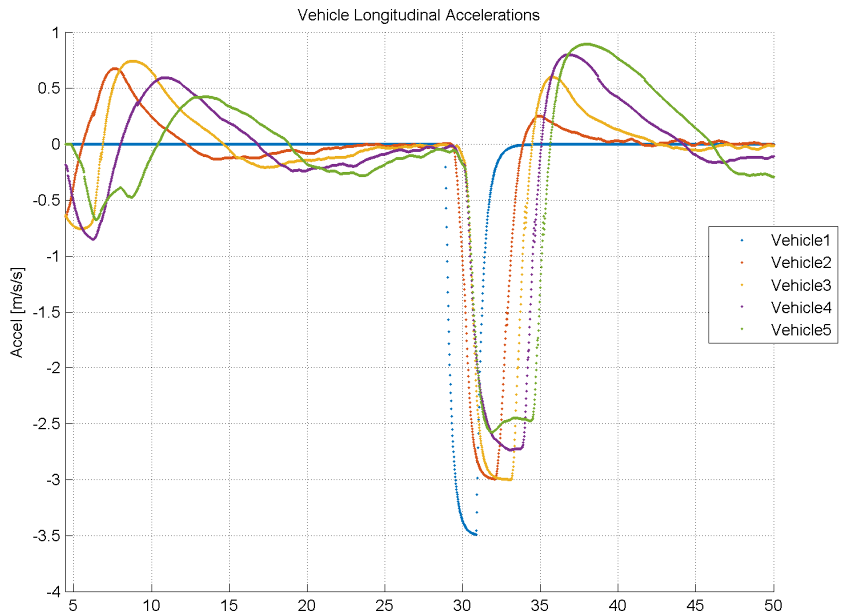
Figure 58 - Actual Time-Gap Change in Response to Hazard Flag



Source: CAMP V2I Consortium

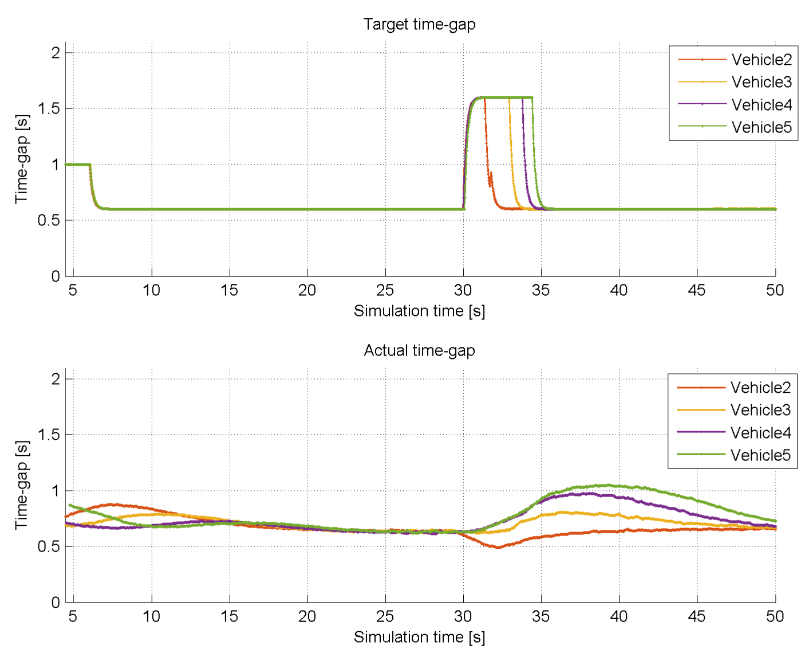
Figure 59 - Relative Distances with Time-Gap Adaptation to 1.0s

The simulation was repeated with the parameter set to increase the target time gap to 1.6s for the duration when the hazard is set. This causes a significant increase in the actual time gap as shown in Figure 60. As a result, the distances between vehicles increase in the latter portion of the string. However, the string takes longer to return to a stable state after the event.



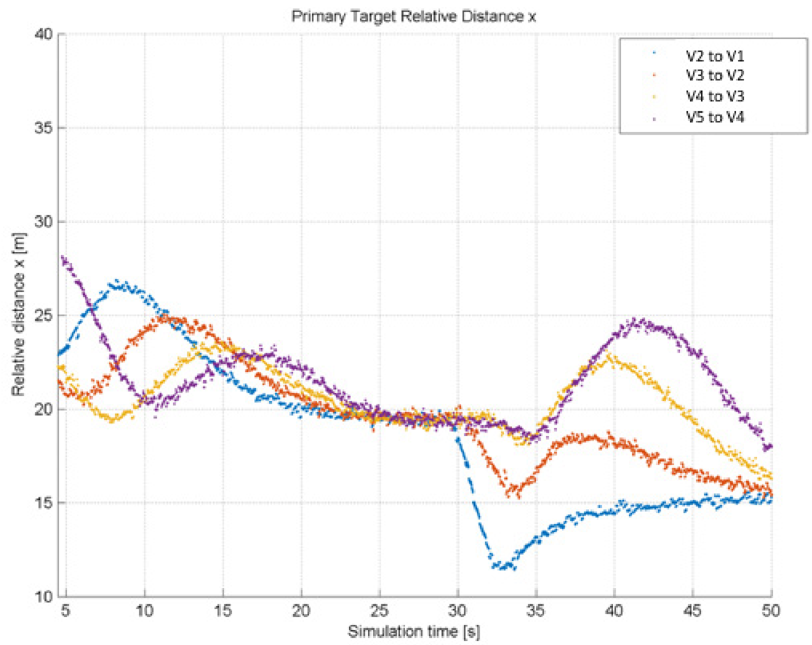
Source: CAMP V2I Consortium

Figure 60 - Deceleration Response with Time-Gap Adaptation to 1.6s



Source: CAMP V2I Consortium

Figure 61 - Actual Time-Gap Change in Response to Hazard Flag

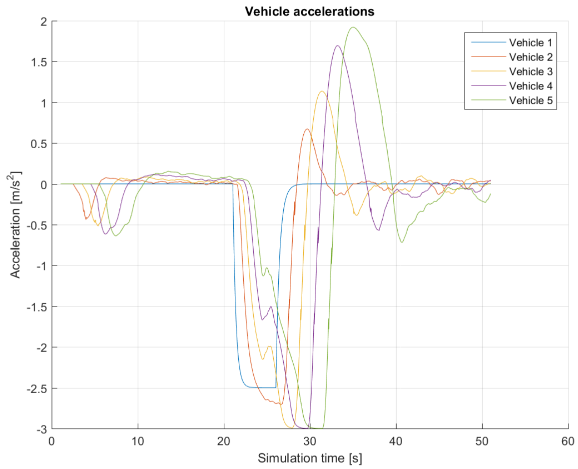


Source: CAMP V2I Consortium

Figure 62 - Relative Distances with Time-Gap Adaptation to 1.6s

4.2.1.3 Effect of Communication Loss on String Stability

The effects of a communication loss between CACC-equipped vehicles on string stability was assessed at a 1s time gap in the case where the lead vehicle performs two successive square-waveform deceleration / acceleration patterns of +- 2.5 m/s^2 with a 5s period for each and a time of 25s in between the two maneuvers. Figure 63 shows the string response when a communication outage occurs at the 23s of the simulation time while the vehicles are in the deceleration maneuver. The result is an unstable string exceeding the -3 m/s^2 limit.



Source: CAMP V2I Consortium

Figure 63 - CACC String Response with Communication Failure

4.2.2 Reaction Time

To study reaction times during deceleration and acceleration maneuvers, a string of ACC and CACC vehicles was exposed to scripted maneuvers with a negative and a positive acceleration of 2.5 m/s^2. The input perturbation is introduced through the acceleration of the first vehicle of the string. It represents a scenario where the first vehicle is manually driven and the remaining vehicles follow this vehicle. The set time gap for these simulations was 1s for both ACC and CACC to allow for a direct comparison. The CACC multi-vehicle look-ahead and the adaptive time-gap features were not used in this comparison.

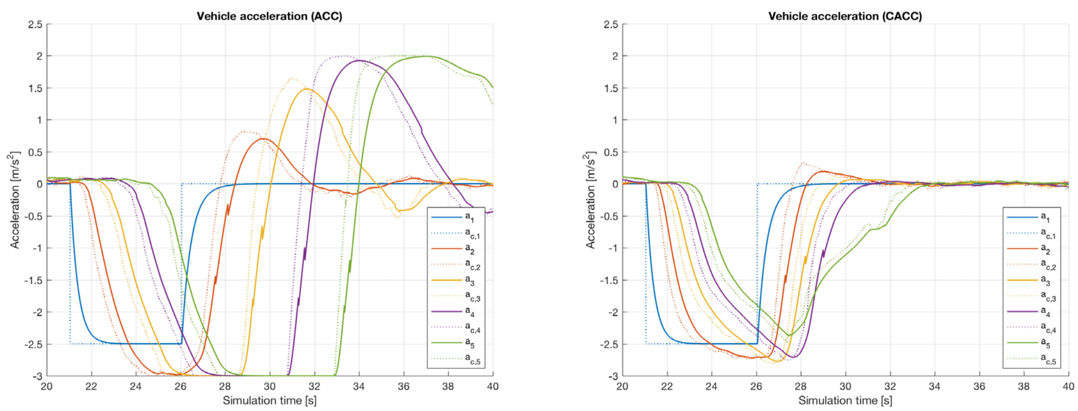
4.2.2.1 Reaction during Deceleration

Figure 64 shows the response of a string of simulated ACC and CACC vehicles, respectively. Dashed lines represent the acceleration command of a vehicle and solid lines represent the actual acceleration of the vehicle.

For vehicles under ACC control, deceleration levels increase along the string and each vehicle eventually reaches the maximum deceleration limit of the controller which is set to -3m/s^2. After the vehicles complete their deceleration, they accelerate again to close the increased time gap. This is an indication that the deceleration was unnecessarily high.

In contrast, vehicles under CACC control start decelerating significantly earlier thus requiring lower maximum deceleration which are beneath the controller deceleration limit. String recovery is significantly improved as well. With the minor exception of vehicle 2, there is no acceleration overshoot visible after the deceleration maneuver is completed. The entire CACC string becomes stable at 34 seconds, whereas the tailing ACC vehicles are still unstable significantly beyond 40 seconds.

The deceleration levels observed for vehicles under CACC control are slightly higher than the lead vehicle. However, this can be attributed to the simplified step input perturbation which is a harsher slope than is natural for the longitudinal controller.



Source: CAMP V2I Consortium

Figure 64 - ACC vs. CACC String Response to Lead Vehicle Deceleration

The longitudinal control system's reaction to preceding vehicle deceleration can be divided into the following two parts.

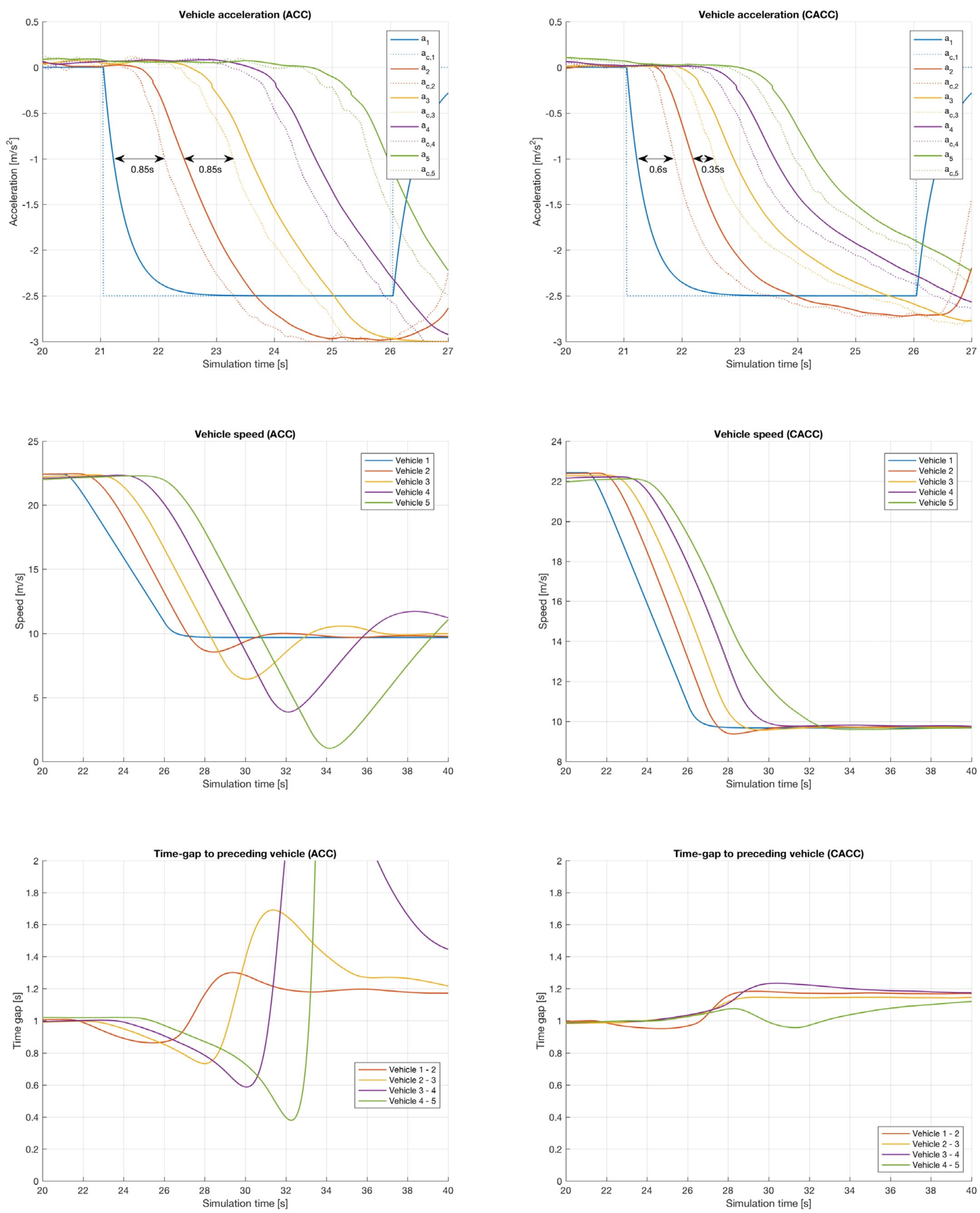
Detection delay: This is the delay from the preceding vehicle's deceleration to the host vehicle's acceleration command

Reaction delay: This is the delay from the host vehicle's acceleration command to the host vehicle's acceleration response

No modifications were made to any system components when implementing CACC that would lead to a change in the reaction delay. Therefore, no difference in reaction delay is visible between the ACC and the CACC simulations.

In this example, the detection delay for ACC is nearly identical for all vehicles in the string (0.85s at $1m/s^2$). The delay for the CACC vehicles differs between the first and the second vehicle (0.6s) and all remaining vehicles (0.35s). This can be attributed to the fact that the simulation operates the first vehicle like a manually controlled, DSRC-equipped vehicle in order to implement the prescribed deceleration. Vehicle 1 transmits current acceleration values but no acceleration forecasts. Therefore, vehicle 2 can't predict its behavior very far into the future and its response is delayed. In contrast, vehicle 3 receives acceleration forecasts from vehicle 2 and is better able to predict its motion, resulting in reduced response delay.

Figure 65 provides an expanded view of vehicle deceleration, speed and time gap during the each string's deceleration maneuver. ACC control exhibits significant overshoot for both speed and time gap with the minimum speed for vehicle 5 almost reaching 0 m/s and the time gap fluctuating between a minimum of 0.4s and a maximum of 8s. CACC on the other hand shows a stable response with speeds not dropping below 9 m/s and time gap fluctuating between 0.9s and 1.3s.



Source: CAMP V2I Consortium

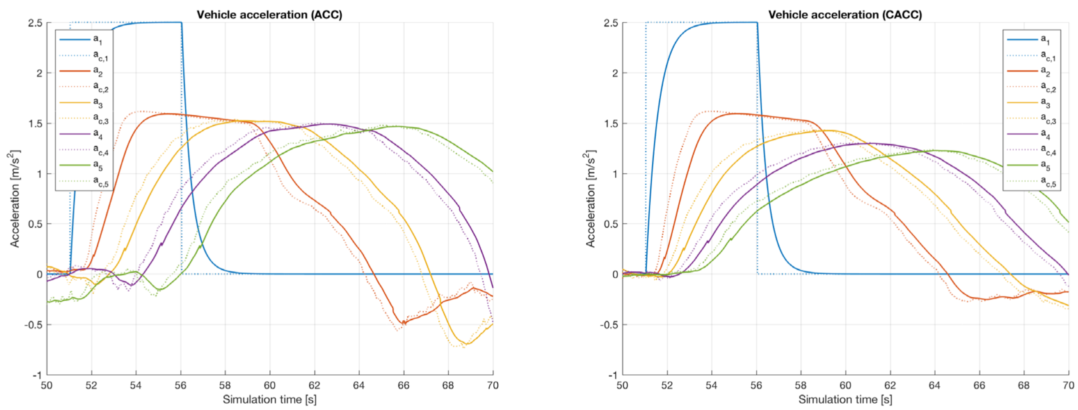
Figure 65 - ACC vs. CACC Deceleration Response Comparison

4.2.2.2 Reaction during Acceleration

The simulation was repeated with an acceleration maneuver of identical magnitude and duration. Figure 66 shows the response of a string of simulated ACC and CACC vehicles, respectively. In this case, the differences between ACC and CACC are not immediately obvious in the acceleration graph.

Vehicle 2 shows a very similar acceleration pattern with similar maximum values. For the tailing vehicles, a slight reduction in maximum acceleration can be observed.

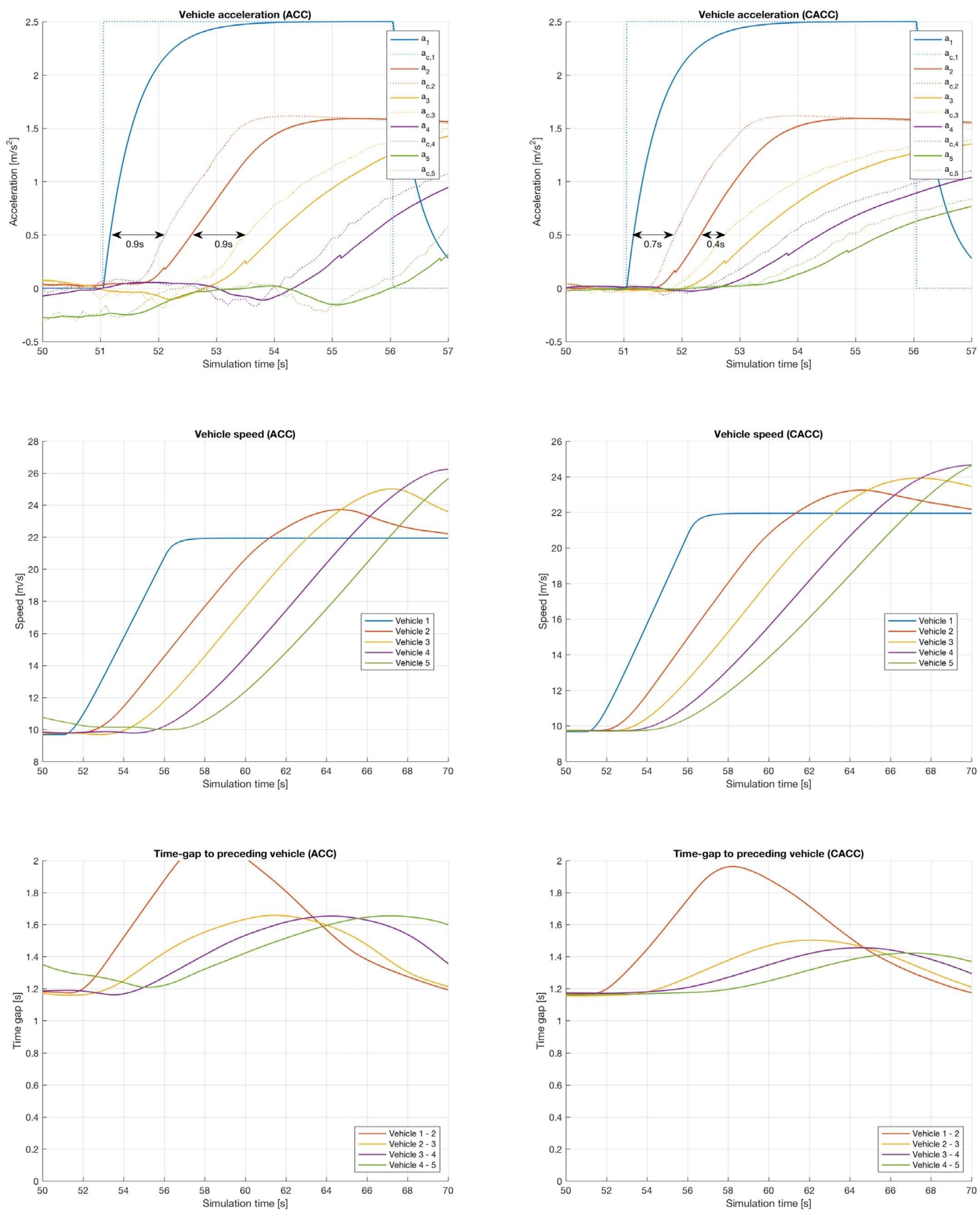
Notably, no vehicle reaches the acceleration level of the first vehicle. This is due to the conservative design of the longitudinal controller and the implemented limitation in maximum acceleration (around 1.5m/s^2). If these characteristics of the controller were modified, a sharper response could be realized in the future.



Source: CAMP V2I Consortium

Figure 66 - ACC vs. CACC String Response to Lead Vehicle Acceleration

Figure 67 provides an expanded view of vehicle acceleration, speed and time gap during each string's acceleration maneuver. A difference between ACC and CACC response can be observed in response time from vehicle to vehicle. A value of 0.9s can be observed for ACC while CACC reaches 0.7s between the first and the second vehicle and 0.4s for the following vehicles. A sample point of 0.5m/s^2 was chosen for comparison since the accelerations flatten out at 1m/s^2 (due to the controller parameterization) and therefore, the differences are less visible.



Source: CAMP V2I Consortium

Figure 67 - ACC vs. CACC Acceleration Response Comparison

The speed profiles don't show a significant difference between ACC and CACC. Only a faster initial response is notable: Vehicle 5 reaches 12.5m/s at 60s in case of ACC and 14m/s in case of CACC.

In the time gap graphs, the differences are more notable. For ACC, the time gap between vehicle 1 and 2 opens beyond 2s while CACC limits it to just under 2s. The remaining vehicles reach 1.65s in case of ACC and 1.5s - 1.4s for CACC.

4.2.2.3 Summary

When comparing the performance of ACC and CACC in isolated acceleration and deceleration maneuvers, significant performance improvements between ACC and CACC can be seen. A CACC system that has access to acceleration forecasts from the preceding vehicle can reduce the reaction time by almost 60% and a CACC vehicle that only has access to current vehicle-dynamics information over DSRC can reduce its reaction time by 30%. This finding highlights the importance of including acceleration forecast data as part of the communications exchange between CACC vehicles.

These results have been generated utilizing a conventional ACC longitudinal controller and optimizing its input data. The current design is limited in the responsiveness to acceleration maneuvers. If acceleration forecasts are integrated into the controller design itself, improved performance may be possible.

4.2.3 DSRC Messages to Support CACC

The prototype CACC algorithm developed uses data exchanged between vehicles via the SAE J2735 Basic Safety Message, with an additional extension required to implement the proposed functionality as described in the following sections.

4.2.3.1 Implementation Approaches

CACC relies on the exchange certain of data elements between vehicles in a string. Some of those data elements are a subset of the BSM, whereas others don't exist in current messages. To exchange the necessary data elements, CACC vehicles could either extend the BSM or transmit additional messages. Different possible scenarios are outlined in Table 13. This overview was created with the assumption that all vehicles would initially be transmitting BSMs on channel 172 in accordance with SAE J2945/1.

Table 13 - Implementation Scenarios for CACC Data Elements

Scenario	Messages on Channel 172	Messages on Side Channel	Advantages	Disadvantages
1	BSM with CACC extension	None	1. No requirement for multiple radios in the vehicle	• Impact on the channel load on channel 172
2	BSM with CACC extension (only when longitudinal control active)	None	• No requirement for multiple radios in the vehicle	• Some impact on the channel load on channel 172

Scenario	Messages on Channel 172	Messages on Side Channel	Advantages	Disadvantages
3	BSM	Additional CACC message	• No impact on the channel load on channel 172	• Requires tracking and matching of information on both channels • Dual radio requirement for the vehicle
4	BSM	Subset of BSM plus CACC extension	• No impact on the channel load on channel 172	• Requires tracking and matching of information on both channels • Dual radio requirement for the vehicle • Unnecessary channel load due to duplication

Source: CAMP V2I Consortium

Based on this analysis, scenario 2 was identified as providing the best combination of advantages and disadvantages and a BSM longitudinal control message extension was defined. For initial testing, this message extension was specified as a (private) regional extension (APPENDIX E: Regional BSM Extension ASN.1). For real-world deployment, this additional data would need to be included in the SAE J2735 standard as a BSM Part II extension. For other SDOs, such as the European Telecommunications Standards Institute (ETSI) with the Cooperative Awareness Message, a similar approach would be needed.

4.2.3.2 Required BSM Data Elements

The following data elements as shown in Table 14 are part of the current BSM per SAE J2735 2016.3. Most of them are required for CACC operation. The information in this table is used below to calculate the size of a typical BSM ("baseline") to determine the relative impact of adding a CACC extension on the size of a BSM.

Table 14 - BSM Data Elements Required for CACC

Data Element	Required per J2945/1	Data Type	Required by CACC	Use in CACC
Identifier of remote vehicle	yes	TemporaryID	yes	Used to communicate target vehicle information to other vehicles
Latitude	yes	Latitude	yes	Relative positioning and fusion with radar data
Longitude	yes	Longitude	yes	Relative positioning and fusion with radar data
Elevation	yes	Elevation	yes	Filtering of irrelevant vehicles (e.g., on an overpass)
GPS error ellipse	yes	PositionalAccuracy	yes	Assessment of positioning accuracy for weighting in fusion
Speed	yes	Speed	yes	Fusion with radar data
Heading	yes	Heading	yes	Relative positioning and fusion with radar data
Yaw Rate	yes	YawRate	yes	Detection of lane changes
Brake activation	no[2]	BrakeSystemStatus	yes	Estimation of behavior of the vehicle (early reactions to decelerations)
Vehicle width and length	yes	VehicleSize	yes	Fusion with radar data for physical object representation
Longitudinal acceleration	yes	Acceleration	yes	Estimation of the behavior of the vehicle
V2V event flags	yes	VehicleEventFlags	yes	Early reactions to emergency brake maneuvers

[2] Although SAE J2945/1 does not require transmitting the value of the brake activation state, this field has a fixed size and is always encoded.

Data Element	Required per J2945/1	Data Type	Required by CACC	Use in CACC
Turn signal status	no[3]	ExteriorLights	yes	Detection of lane changes
Path history	yes[4]	PathHistory	no	
Path prediction	yes	PathPrediction	no	

Source: CAMP V2I Consortium

The data elements containing the brake activation status and the turn signal status are not required to be transmitted per SAE J2945/1. Minimum Performance Requirements for CACC would need to be established including those data elements.

4.2.3.3 CACC Extension

Table 15 lists the additional data elements required by CACC. A definition and description of the purpose for each element is provided below.

Table 15 - Additional Data Elements Required for CACC

Data Element	Data Type
CACC state	LongitudinalControlState
Acceleration forecast	Acceleration
Tau	TimeConstant
Target vehicle temporary ID	TemporaryID

Source: CAMP V2I Consortium

4.2.3.3.1 Longitudinal Control State

Possible states of the equipped vehicle's automated longitudinal control system are:

1. Manual
2. CC
3. ACC

[3] For the purpose of establishing a baseline BSM, this field is included, given that in a modern vehicle one or more exterior lights are usually on.

[4] For the purpose of establishing a baseline BSM, three path history points are included, as this has been found to be a typical number of path history points.

4. CACC (One-Vehicle Look-Ahead)
5. CACC (Multi-Vehicle Look-Ahead)
6. Higher levels of automation (sensor based)
7. Higher levels of automation (V2V data-fusion based)
8. Manual Override

This information is used by a receiving vehicle to adjust expectations with regards to the maneuvers that this vehicle will be performing.

4.2.3.3.2 Acceleration Forecast

When the host vehicle's longitudinal controller is issuing an acceleration command to brake and/or engine control, the current value is communicated to other vehicles as a forecast of the future behavior of the vehicle. Receiving vehicles can use this information to adapt their own accelerations.

4.2.3.3.3 Tau

In addition to the acceleration forecast, the host vehicle transmits an estimation of its response to the current acceleration command using the first-order lag model constant tau.

4.2.3.3.4 Target Vehicle Temporary ID

When the host vehicle is currently considering another vehicle as its target and that remote vehicle is transmitting BSMs, the host vehicle transmits the Temporary ID of that remote vehicle in this data element. This enables the linked-list algorithm to compile a list of vehicles that are part of the same string.

4.2.3.4 Impact on Message Size

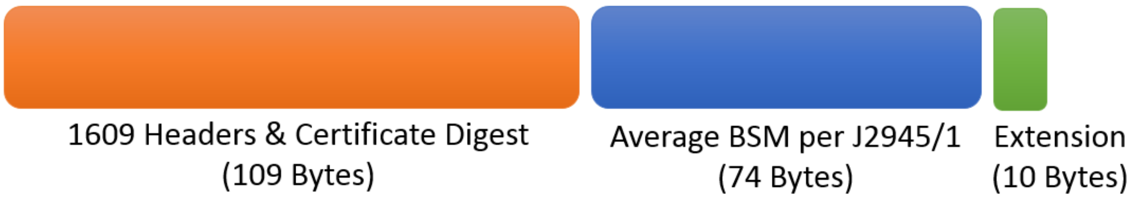
Table 16 provides a size comparison between the CACC message payload and a BSM only baseline.

Table 16 - CACC-Payload-Size Comparison

Scenario	Description	BSM Payload size (UPER encoded)
Baseline J2945/1	The BSM includes all the data elements that are required by J2945/1 as well as the exterior lights and three path history points	74 bytes
With extension	The BSM also includes a longitudinal control extension	84 bytes

Source: CAMP V2I Consortium

To put the CACC extension in perspective to the overall message size, the additional headers and security certificate need to be considered as well. Per J2945/1, a vehicle will transmit a full certificate with every fifth message and only include a digest for intermediate messages. Figure 68 shows a proportional visualization of the message headers, the BSM payload and the added size through the extension.



Source: CAMP V2I Consortium

Figure 68 - CACC Extension Message Size Comparison

Compared to the rest of the message, the extension represents an increase in message size of 5%. Since the full extension would only need to be transmitted for vehicles with active longitudinal control, the impact on the communication channel is further reduced.

4.2.3.5 Transmission Rate

While the CACC algorithm operates with an update rate of 50Hz, the BSM transmission frequency was kept at the typical 10Hz. CACC relies on communication with the immediate preceding vehicle. Close proximity provides high-reception probabilities so that in low to medium channel load scenarios the packet error rate will be very low. A receiving vehicle can extrapolate the movement of the remote vehicles based on the received dynamics data to generate intermediate results until the next message from that vehicle is received. No problems were identified with this approach.

4.2.3.6 Congestion Control

If the proposed CACC extension to the BSM is transmitted on channel 172, its transmission would be governed by SAE J2945/1. The standard requires the implementation of a congestion control algorithm that starts to reduce transmission power and increase transmission intervals as soon as 25 stations are identified in 100m proximity of the host vehicle. Assuming that deployment rates will eventually increase to nearly 100% of vehicles, this point can be reached relatively easily even in free-flowing traffic on a highway. If all vehicles travel at 55 mph and leave a time gap of 1s, one vehicle roughly follows the other every 30m. On a freeway with three lanes in each direction, this means that roughly 6 lanes with 200m length each are within the 100m omnidirectional range of one vehicle. The approximate number of stations in range can be calculated as follows:

$$n = n_{lanes} \times l_{lane} \times k$$

$$n \cong 6 \times 200m \times \frac{1}{30m} = 40$$

This means that even in free-flowing traffic the congestion control algorithm would already be active. Therefore, its effects need to be considered for CACC.

The algorithm would:

1. Decrease transmission power from the original 20dBm to (in the worst case) 10dBm
2. Increase the transmission interval from 100ms to (in the worst case) 600ms

Since CACC mainly relies on communication with the immediate preceding vehicle, no significant decrease in performance is expected from the transmission power reduction. However, the transmission interval increase would likely affect CACC operation. If that interval increases significantly, algorithm performance would degrade. In the example case, this would lead to a transmission interval of 160ms. However, in congested traffic the value would rise further.

4.2.4 System Set Speed

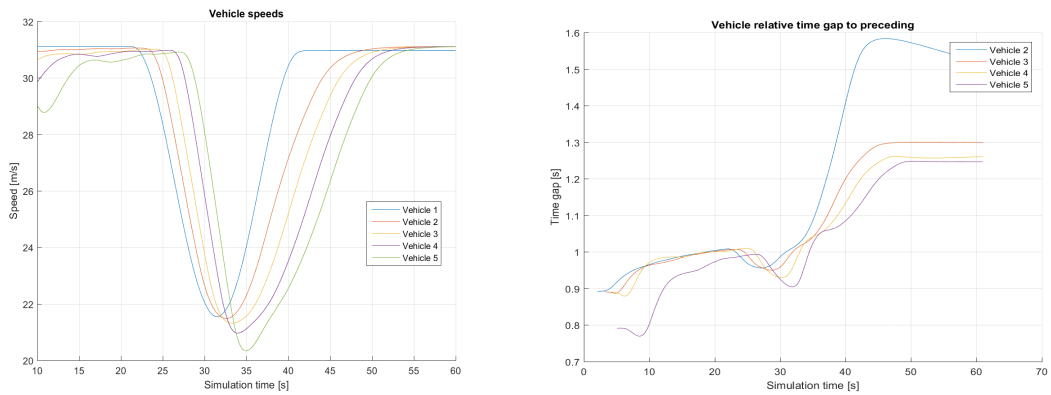
Conventional Cruise Control and ACC systems allow the driver to select the set speed of their vehicle. The same approach was followed for the prototype CACC system developed in this project. However, there are certain aspects of the this approach that may need to be reevaluated when implementing the system.

ACC is designed around individual vehicle operation. CACC introduces the concept of strings of vehicles. Improvements in the response times of vehicles in the string enable them to follow in close proximity.

Consider the case where five ACC vehicles are traveling in a string unobstructed on a freeway that has a posted speed limit of 70 mph at a time gap of 1s, each with a set speed of 70 mph . If the string slows down due to a traffic perturbation and then accelerates afterwards, the time gaps after the maneuver will have increased due to the lag in reaction time between the vehicles. As soon as the first vehicle reaches 70 mph, it will stop accelerating. Each following vehicle will reach 70 mph at a later point in time and, therefore, fall slightly behind the preceding vehicle. Since each vehicle is restricted by its own set speed, the vehicles won't automatically close the time gap back to the original 1s string spacing. These effects could increase over time and lead to time gaps that are higher than intended. This behavior was observed in the prototype ACC vehicles built and tested in this project. For the purposes of testing, this issue was mitigated by providing the following ACC vehicles with a higher set speed than the lead vehicle, knowing that they would be slowed down by the lead vehicle once the gap was restored.

Simulations were performed to examine this issue first with ACC to replicate observed test track behavior and then with CACC to understand how performance is impacted. In this scenario, five vehicles travel along a freeway at a speed of 70 mph (31m/s). At 20s into the scenario, the string has stabilized with a time gap of 1s. The first vehicle then performs a sinusoidal deceleration / acceleration maneuver with an amplitude of +- 1.5 m/s^2.

The results of this scenario when the vehicles operate in ACC mode are shown in Figure 69.



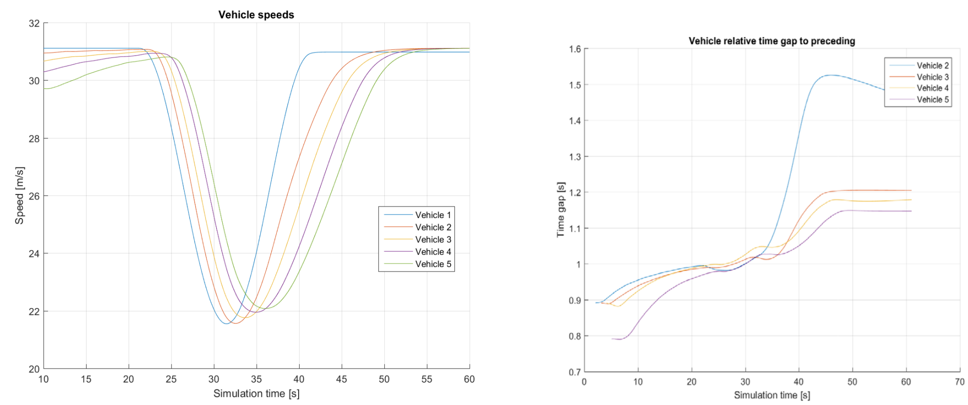
Source: CAMP V2I Consortium

Figure 69 – ACC String Speed and Time-Gap Response

In the phase from 0s to 20s, the vehicles adjust their initial speeds and time gaps to establish the string since those parameters can only be controlled within limits in the simulation environment. Between 20s and 40s, the deceleration maneuver is performed. After that, the following vehicles try to catch up to the leading vehicle.

During the recovery portion of the maneuver, the time gap between the first and second vehicle increases significantly. This is an artifact of the simulation approach with vehicle 1 adhering to the acceleration profile provided (e.g., operating in ‘manual mode’) while vehicle 2 operated in ACC mode with a more conservative acceleration limit. The performance of the ACC string is indicated by observing vehicles 2 to 5. The time gap between those vehicles increases to 1.25 - 1.3s from the original target of 1s. Since the vehicles reach their set speed at around 55s, the time gaps don't change anymore at that point. The vehicles would continue driving with these time gaps until the next perturbation occurs which would (temporarily) reduce the time gap.

The simulation run was repeated with vehicles operating in CACC mode. The resulting can be seen in Figure 70. The same effect can be seen here but the magnitude was slightly reduced with the resulting time gaps after the maneuver between 1.15 - 1.2s.



Source: CAMP V2I Consortium

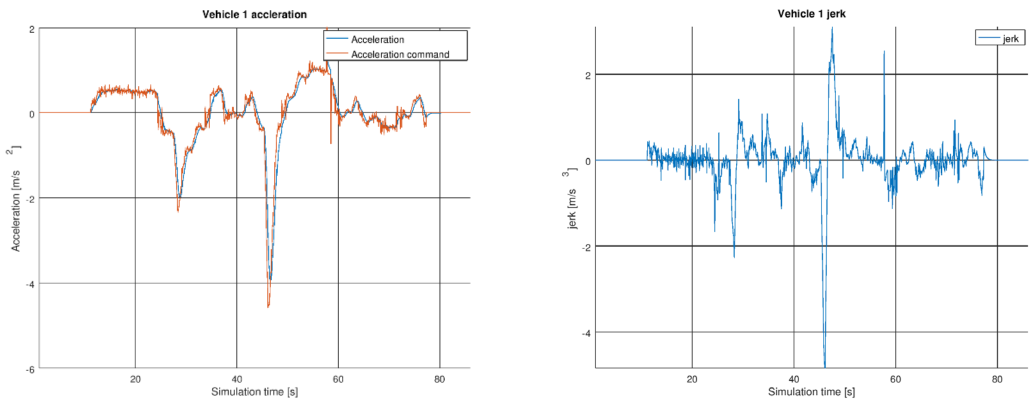
Figure 70 – CACC String Speed and Time-Gap Response

The ACC simulation results reproduce the effects that were observed during vehicle testing. The CACC algorithm simulation shows similar behavior with the magnitude of the time gap increase slightly reduced. Maintaining string time gaps as specified while traveling through traffic may require additional adjustments or alternative algorithm approaches.

4.2.5 Jerk Comparison

Vehicle acceleration and the time rate of change of the acceleration (jerk) have a great impact on driver satisfaction and traffic flow. The acceleration and braking profiles of the CACC and ACC vehicles were investigated to study the vehicle jerk effects under different situations and with different vehicles in the string. The results show that the CACC system can reduce the amount of jerk for each vehicle in a CACC string and enhance the quality of the vehicle performance.

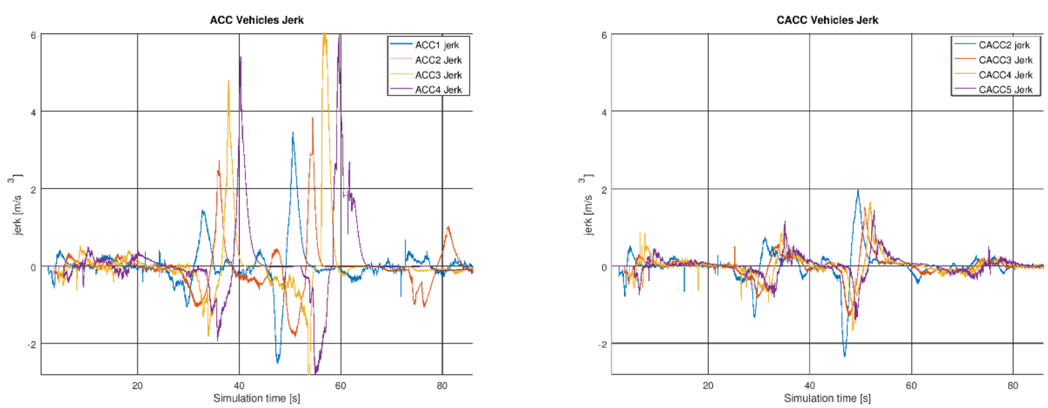
The study was conducted using a five-vehicle string under a freeway driving scenario approximately 2 minutes in duration. The scenario was created by using a naturalistic driving pattern from SPMD as an input perturbation to the string of vehicles. The pattern was collected during highway driving of naïve subjects and includes two braking events that bring the vehicle from free-flowing traffic to a significantly reduced speed. In the simulation, the first vehicle of the ACC and CACC strings respectively mimics the collected acceleration profile and the following vehicles act as if they were driven behind that vehicle. The vehicle acceleration and deceleration maneuver and the jerk profile used for this analysis is shown in Figure 71.



Source: CAMP V2I Consortium

Figure 71 - Lead Vehicle Acceleration and Jerk Profile

Figure 72 shows a comparison of the resulting jerk in ACC and CACC vehicle strings during the execution of this scenario. Momentary excessive jerk values (sharp peaks) are observed in both strings. These unusual jerk values are an artifact resulting from a state transition between two vehicle different vehicle-dynamics models used for acceleration and deceleration in the simulation.

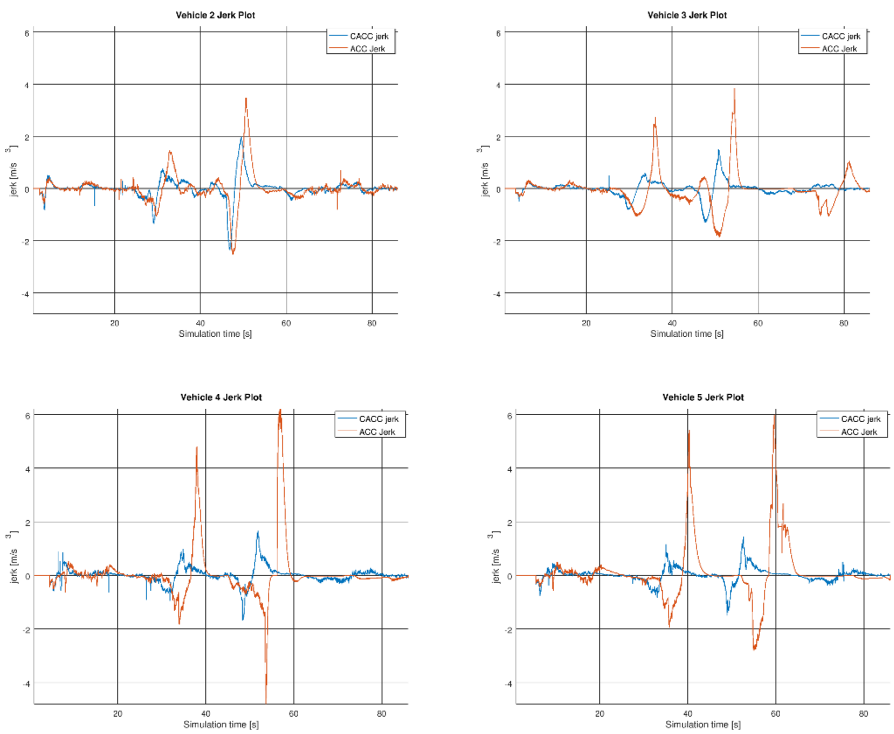


Source: CAMP V2I Consortium

Figure 72 - Excessive Momentary Jerk Levels in ACC and CACC Strings

These excessive momentary values do not reflect real vehicle performance. Therefore, before conducting the jerk analysis, an averaging filter was used to eliminate these artifacts from both the ACC and CACC simulation results. The acceleration, jerk and Root Mean Square Error (RMSE) values in the remainder of this section reflect the results of this filtering process.

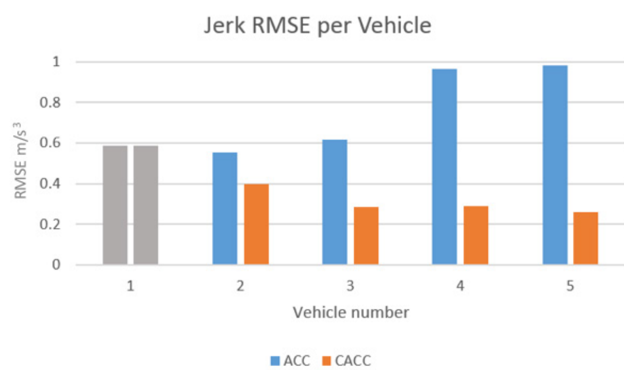
Looking at the resulting string behavior in Figure 73, jerk increases from vehicle to vehicle along the ACC string while a significant decrease in jerk levels is observed along the CACC string. The jerk level observed for vehicle 5 in the ACC system is 6 m/s^3, while the maximum jerk in vehicle 5 in CACC system is 1.5 m/s^3. This is likely due to the acceleration forecasts transmitted by vehicles under CACC control eliminating unnecessary accelerations and decelerations for the following vehicles.



Source: CAMP V2I Consortium

Figure 73 - Comparison of Jerk in ACC and CACC Strings

The RMSE was calculated for both ACC and CACC strings. Figure 74 provides a comparison of these results which shows a reduction in the jerk RMSE using the CACC system. While the jerk RMSE in ACC vehicle 5 is about 0.98 m/s^3, the jerk RMSE in CACC vehicle 5 is only about 0.26 m/s^3.



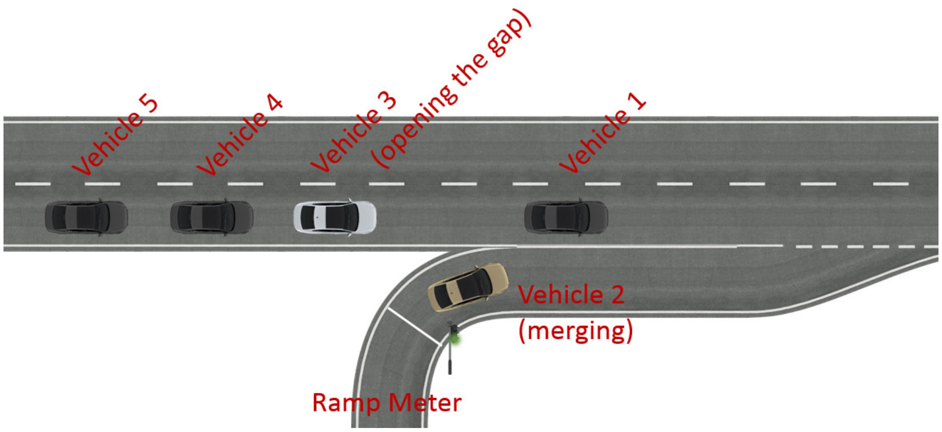
Source: CAMP V2I Consortium

Figure 74 - Jerk RMSE for ACC and CACC Strings

Based on the findings, it is anticipated that, in contrast to ACC, CACC control can reduce jerk levels in the string thereby improving driver satisfaction and providing smoother traffic flow which is expected to enhance lane capacity.

4.2.6 Merging Performance

Merging algorithm performance was evaluated using a simple on-ramp scenario with a single approach lane merging into the rightmost lane of the freeway as illustrated in Figure 75. The ramp is equipped with a ramp meter that releases a single vehicle. A string of four CACC vehicles is traveling along the simulated freeway, reacting to the merging request. The scenario is timed so that the merging vehicle (vehicle 2) arrives just in front of vehicle 3. Therefore, vehicle 3 is selected by the infrastructure algorithm to provide a gap in the string.



Source: CAMP V2I Consortium

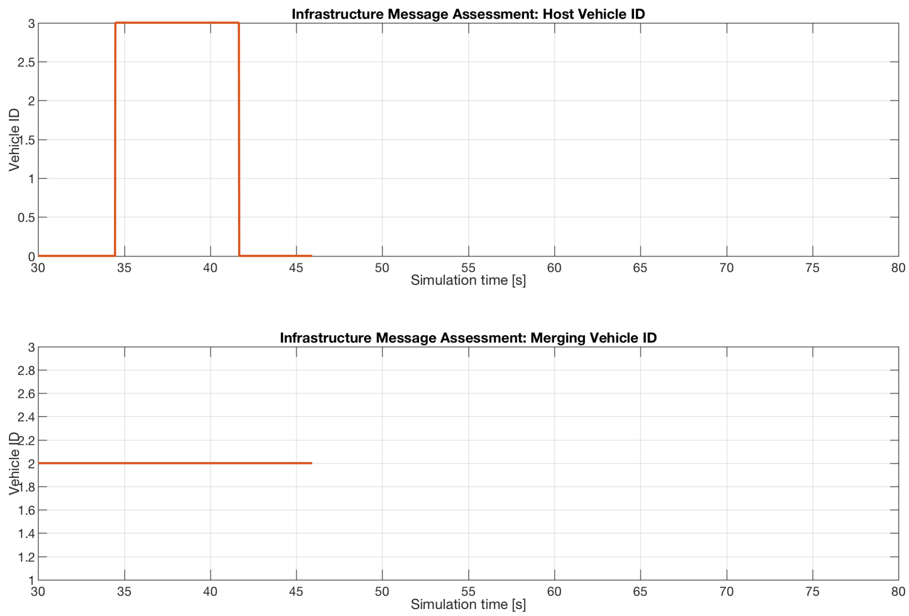
Figure 75 - Merging Scenario Setup

The merging scenario was set up with freeway vehicles traveling at 70 mph and a merging vehicle that reaches 50 mph at the time of the lane change. The setup represents a challenging scenario where the string needs to accommodate a slow merging vehicle, reducing the speed beyond what would be necessary under normal conditions. The following modifications were made to the algorithm during the evaluation:

Deactivation of Lateral Filtering
Since the merging algorithm needs to receive BSMs from vehicles on the on-ramp, those messages cannot be filtered out by other software modules. The algorithm was modified so that the merging modules would receive all BSMs.

Limitation of Controller Response
The longitudinal controller is very sensitive to speed differentials with the target vehicle. A second unmodified controller was initially used for the merging scenario. However, the speed differential with the merging vehicles was initially very high due to the ramp meter. This caused the controller to respond harshly causing unnecessary deceleration. The deceleration limit for the merge controller was modified to limit response to $-1.5 m/s^2$.

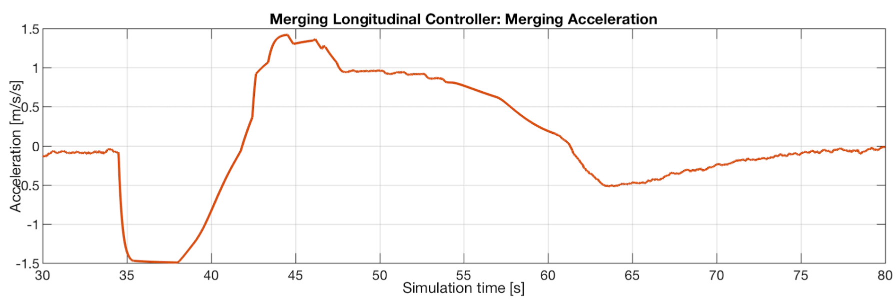
The merge scenario begins 32s into the simulation when vehicle 2 is released from the ramp meter and accelerates to 50 mph. At 34.5s, the simulated Roadside Unit (RSU) begins transmitting a merge request message addressed to vehicle 3. This request continues till 42s where the merging maneuver is completed as shown in Figure 76.



Source: CAMP V2I Consortium

Figure 76 - Infrastructure Generated Merge Request

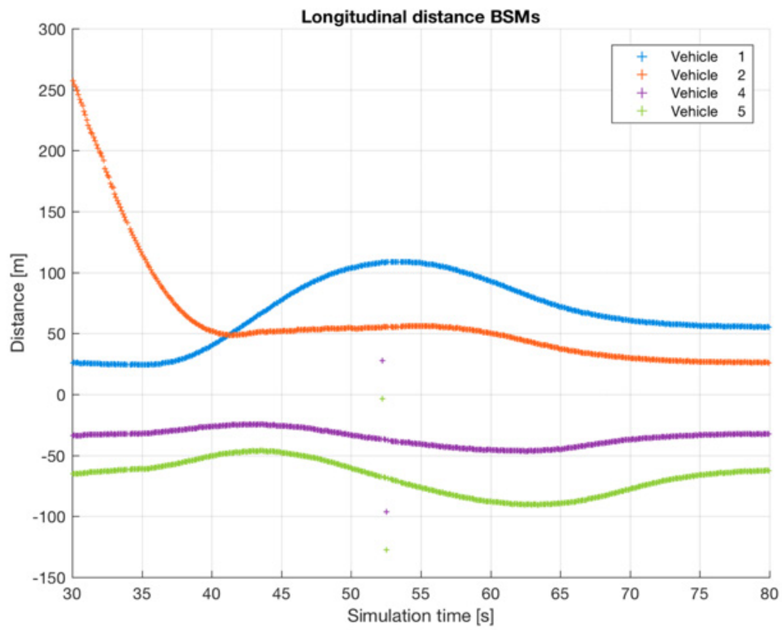
Throughout the merging maneuver, vehicle 3 receives BSMs from vehicle 2. As soon as the merging algorithm becomes active, the longitudinal controller starts issuing a negative acceleration command, almost immediately reaching the -1.5m/s2 limitation. This is due to the high speed differential of more than 5m/s between the vehicles at that point in time. The deceleration continues for around 5s and then turns into a positive acceleration.



Source: CAMP V2I Consortium

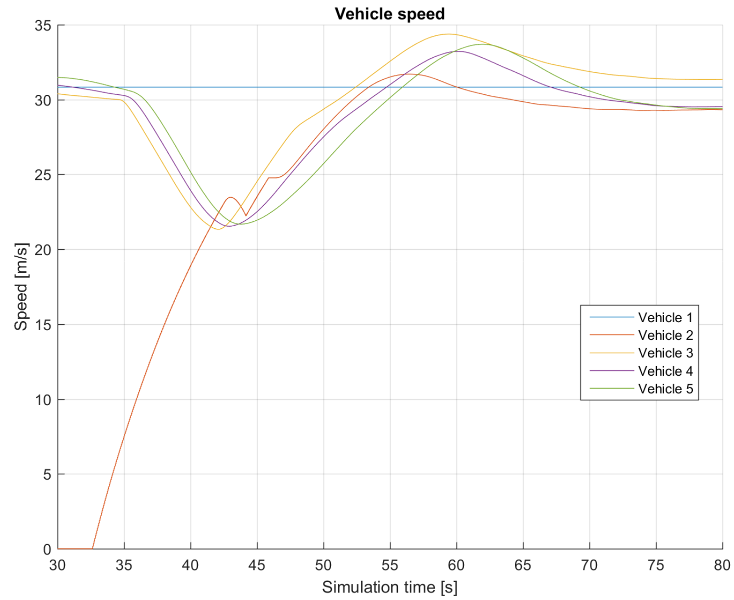
Figure 77 - Requested Acceleration by the Merging Controller

At 42s, the relative speed between the vehicle 1 and vehicle 3 is almost 0m/s with a time gap of 2s and the merge request is terminated. Vehicle 2 performs the cut-in maneuver between 44s – 47s and becomes part of the string. After the completion of the lane change, the gaps between the vehicles are larger than necessary and the vehicles continue accelerating to close the gaps. At 80s, all time gaps are restored to the target of 0.8s. At this point in time, vehicle 2 activates the CACC functionality and the algorithm takes over longitudinal control. Figure 78, Figure 79 and Figure 80 show the relative distances, speeds and accelerations within the trailing portion of the string during the maneuver.



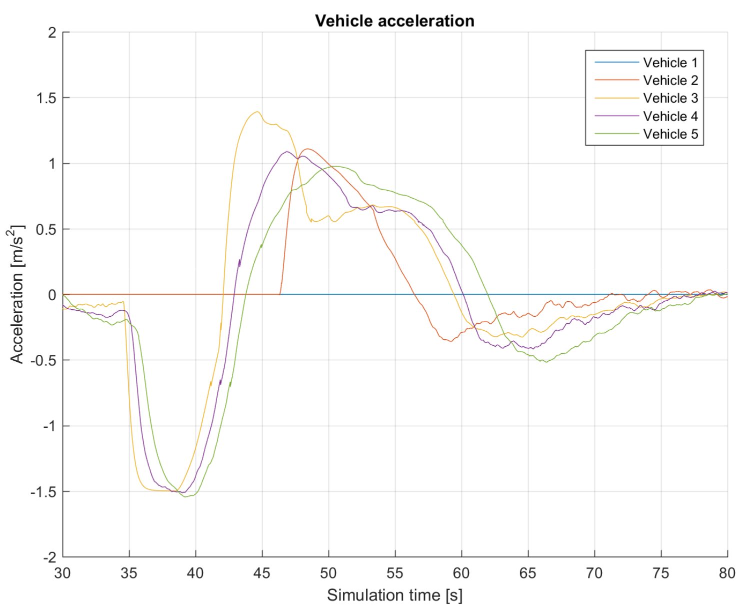
Source: CAMP V2I Consortium

Figure 78 - Longitudinal Distance from Vehicle 3 to the other Vehicles



Source: CAMP V2I Consortium

Figure 79 - Vehicle Speeds during the Merging Maneuver



Source: CAMP V2I Consortium

Figure 80 - Vehicle Acceleration during the Merging Maneuver

The speeds of vehicles 3, 4 and 5 were temporarily reduced from the initial 31m/s (70 mph) to 22m/s (50 mph) by vehicle 2. After the merging maneuver, the vehicles accelerate back to the initial speed. The accelerations performed by the individual vehicles are very similar. No increase in required deceleration from one vehicle to another is visible. For vehicle 2, the acceleration is only available after 47s when the CACC system is activated. Prior to 47s, its acceleration is scripted.

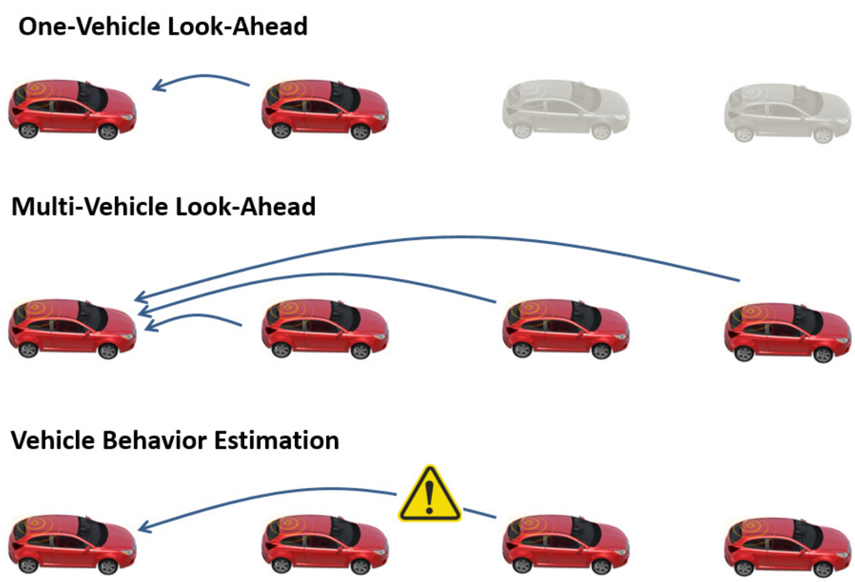
4.2.7 Evaluation of Look-Ahead Concepts

To explore the potential benefits of receiving information from vehicles more than one position ahead in the CACC string, different algorithm features were implemented and evaluated. Figure 81 depicts these scenarios.

One-Vehicle Look-Ahead (OVLA): The simplest form of vehicle control where only data from the immediate preceding vehicle in the string is considered, like ACC. A perturbation downstream will propagate sequentially from one vehicle to the next through the string.

Multi-Vehicle Look-Ahead (MVLA): This algorithm feature adjusts the Virtual Target based on data received from several preceding vehicles in a CACC string. This enables vehicles to react earlier to downstream perturbations.

Vehicle Behavior Estimation: This algorithm feature assesses the braking activity of vehicles ahead in the string. If a vehicle ahead is performing a harsh deceleration maneuver, the feature immediately increases the target time gap and applies a fixed amount of deceleration to improve response.

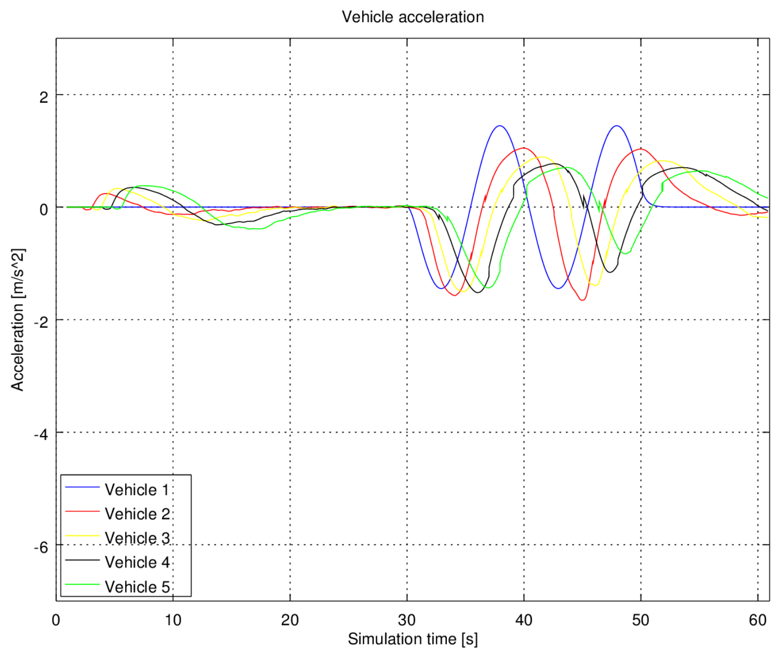


Source: CAMP V2I Consortium

Figure 81 - Overview of Look-Ahead Features Evaluated

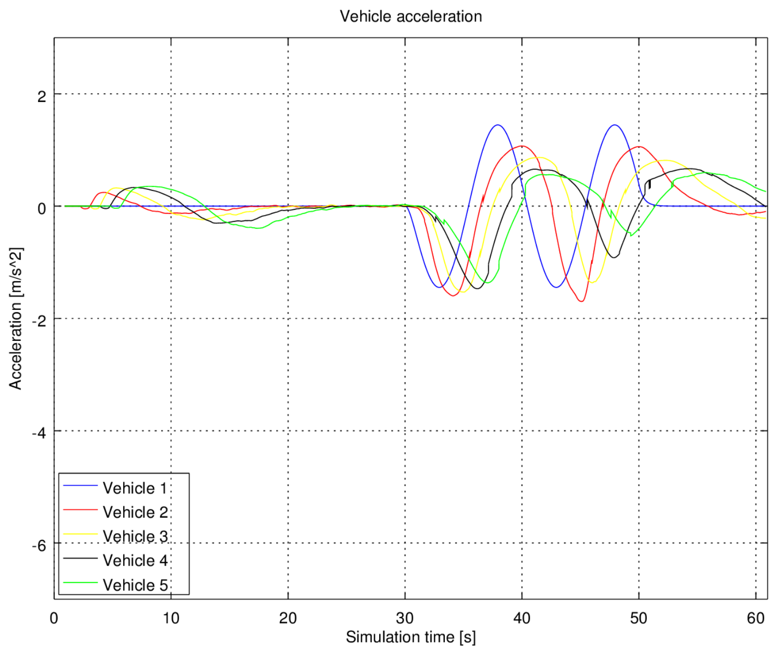
In the following example, a CACC string consisting of three compact cars followed by two large SUV's is traveling along a roadway. The target time gap for the vehicles was set to 0.5s to evaluate the algorithm performance under close following conditions.

After the string stabilizes, the lead vehicle performs a sinusoidal acceleration / deceleration maneuver of +- 1.5 m/s². Figure 82 and Figure 83 show the resulting string accelerations with and without MVLA, respectively. An improvement in acceleration response along the string with MVLA can be observed. In particular, vehicles 4 and 5 show a decreased acceleration amplitude during the end of the maneuver (around 45 – 50 sec).



Source: CAMP V2I Consortium

Figure 82 – CACC String Acceleration with OVLA (Sinusoidal)

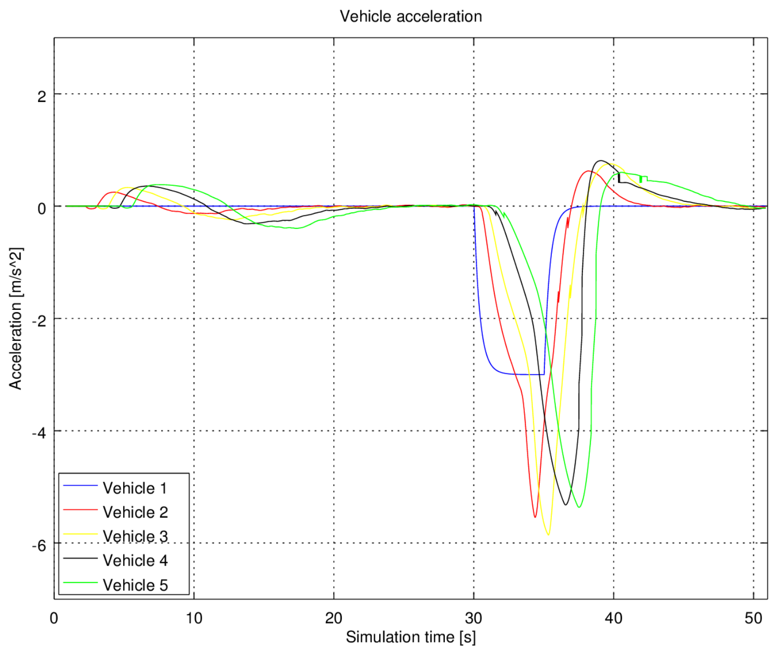


Source: CAMP V2I Consortium

Figure 83 - CACC String Acceleration with MVLA (Sinusoidal)

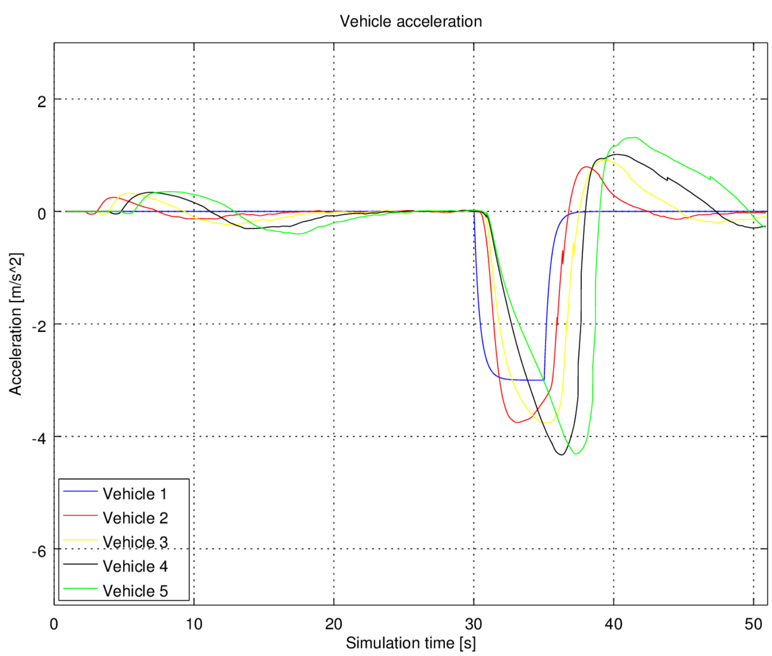
In the following example, the analysis was continued for a stronger deceleration maneuver. This is essential since the CACC algorithm needs to operate effectively under various conditions. A step function with an amplitude of -3 m/s^2 for a duration of 6s was used to simulate a short but hard braking maneuver of a downstream vehicle. Figure 84 and Figure 85 provide a comparison between the OVLA and the MVLA features. The improvement provided by MVLA is clear. The maximum deceleration in the OVLA case is close to -6m/s^2 while in the MVLA case, the decelerations are reduced to a maximum of -4.5m/s^2.

In addition, the accelerations performed by the vehicles are increased after 40s when the string starts to recover from the deceleration maneuver. This is an effect of the time gap increase by the Vehicle Behavior Estimation (VBE) algorithm. The vehicles are recovering from the increased time gap to the original target time gap.



Source: CAMP V2I Consortium

Figure 84 - CACC String Acceleration with OVLA (Step Deceleration)



Source: CAMP V2I Consortium

Figure 85 – CACC String Response with VBE (Step Deceleration)

Multiple simulations were conducted comparing the different look-ahead features in different situations. Table 17 provides an overview of the performance of the different features for a moderate time gap of 1s and a significantly reduced time gap of 0.5s.

Table 17 – Look-Ahead Feature Performance Summary

Feature	1s Time gap	0.5s Time gap
One-Vehicle Look-Ahead	Sufficient for string stability and maintaining set time gap.	Sufficient for uniform strings of identical vehicles and light braking but insufficient for moderate or harder braking.
Multi-Vehicle Look-Ahead	Limited improvement from one-vehicle look-ahead.	Useful for strings of different vehicles and light braking. Insufficient for moderate to hard braking.
Vehicle Behavior Estimation	Causes exaggerated responses by unnecessarily increasing time gap.	Useful to maintain set time gap during braking and improve string stability. Provides, drivers more time to react in emergency braking scenarios

Source: CAMP V2I Consortium

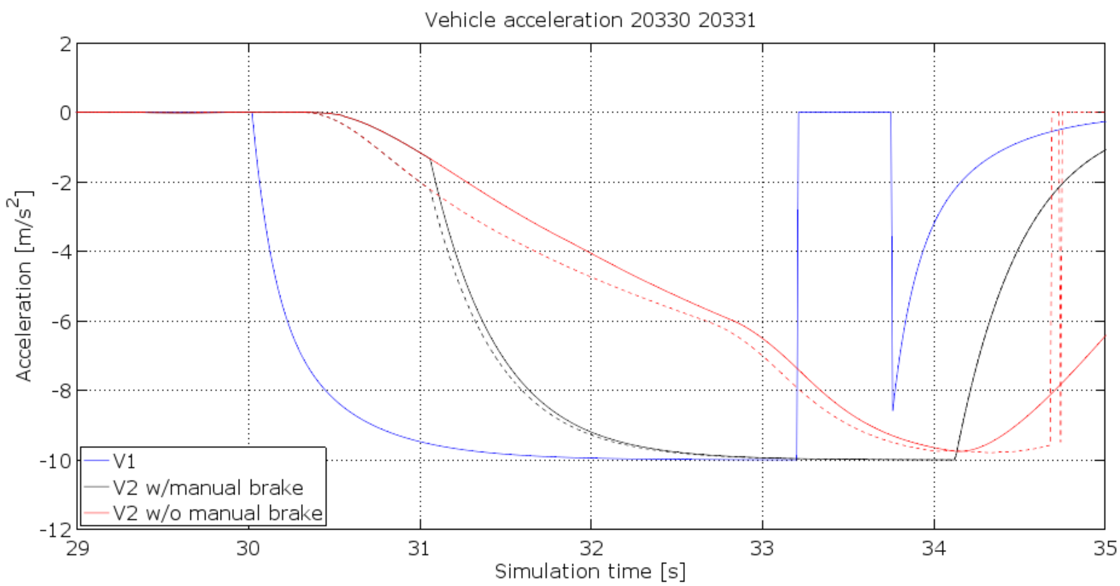
The look-ahead feature evaluation shows a different performance based on the time gap selected. Consideration should be given to dynamically adapting algorithm parameters based on the time gap selection and implementation of a longitudinal controller design that gradually transitions between the different concepts to realize the full benefits of CACC.

4.2.8 Emergency Braking Events

Whenever the capabilities of the ACC or CACC longitudinal controller are exceeded, the driver is expected to take over control of the vehicle. A series of simulation runs were conducted to study string behavior when the lead vehicle performs a ‘harsh’ deceleration of 10 m/s^2 at a time gap of 1s. Figure 86 and Figure 87 show acceleration profiles and trajectories of vehicles in ACC and CACC strings during a harsh braking event initiated by the leading vehicle. Both strings are operating with time gap of 1s, which is specified as the minimum for ACC operation (ISO 22179). For both ACC and CACC, the deceleration limit was extended up to -10m/s^2, although this exceeds the value specified in the standard. The simulation assumed no driver intervention takes place.

The blue line represents the deceleration profile of the lead vehicle (v1) and the red lines represent the response of the following vehicle (v2) for ACC (solid) and CACC (dashed) operation. A collision occurs with both ACC and CACC after 33s. However, due to the faster reaction, CACC delays the time of collision by 0.14s and reduces the relative speed at the time of collision by 2.8m/s.

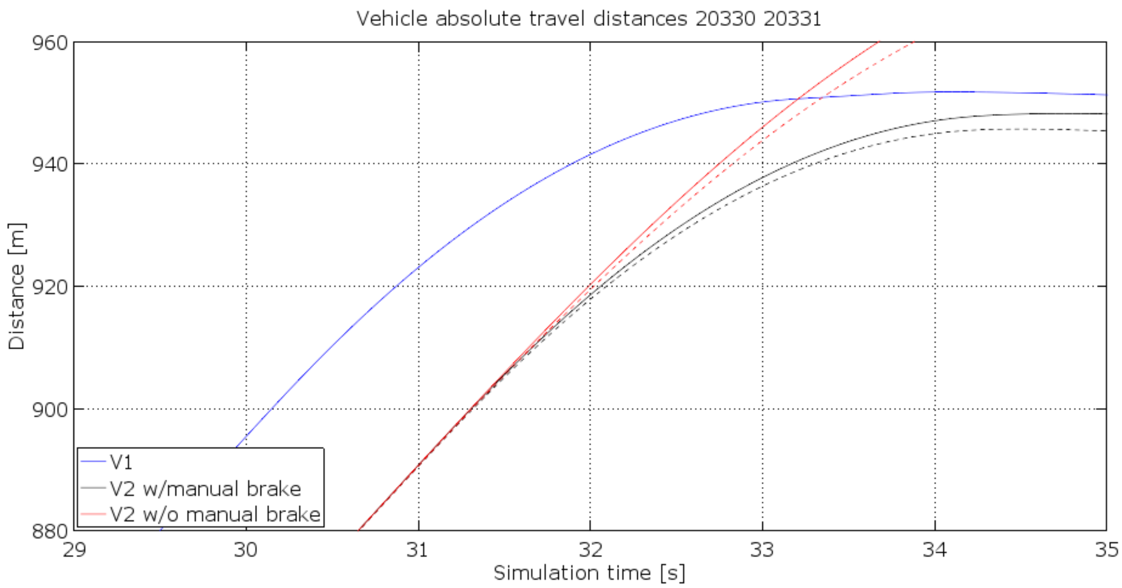
A second simulation was conducted which assumed the driver is notified when system capabilities are exceed and assumes control, applying additional braking after a reaction time of 1s. The results of the modified scenario with manual intervention by the driver are shown with the black lines also in Figure 86 and Figure 87. With manual braking, the collision is avoided for both ACC and CACC. This is consistent with the fact that time gap of 1 second is set as a limit of ACC operation in the standard. With CACC, the collision can be avoided with an increased distance margin (2.8m) to the preceding vehicle.



Source: CAMP V2I Consortium

Figure 86 - Acceleration Levels for Harsh Braking with a Time Gap of 1s

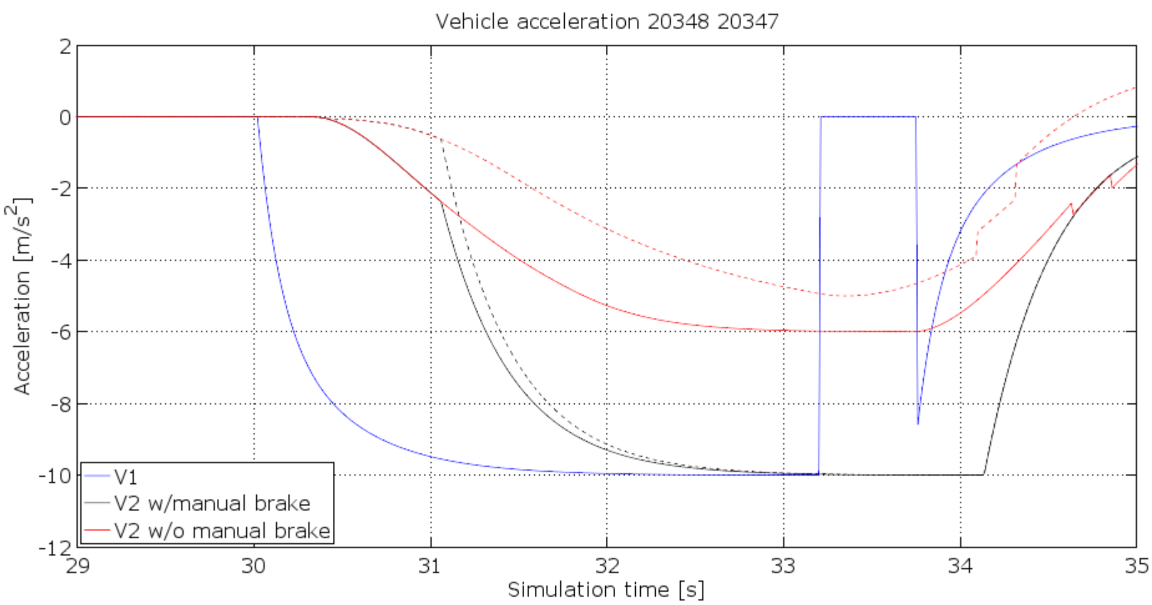
Vehicle 1 artifacts in the acceleration plots after 33s should be ignored since they result from the collision of vehicle 1 and vehicle 2 where, in the simulation environment, the vehicles travel through each other.



Source: CAMP V2I Consortium

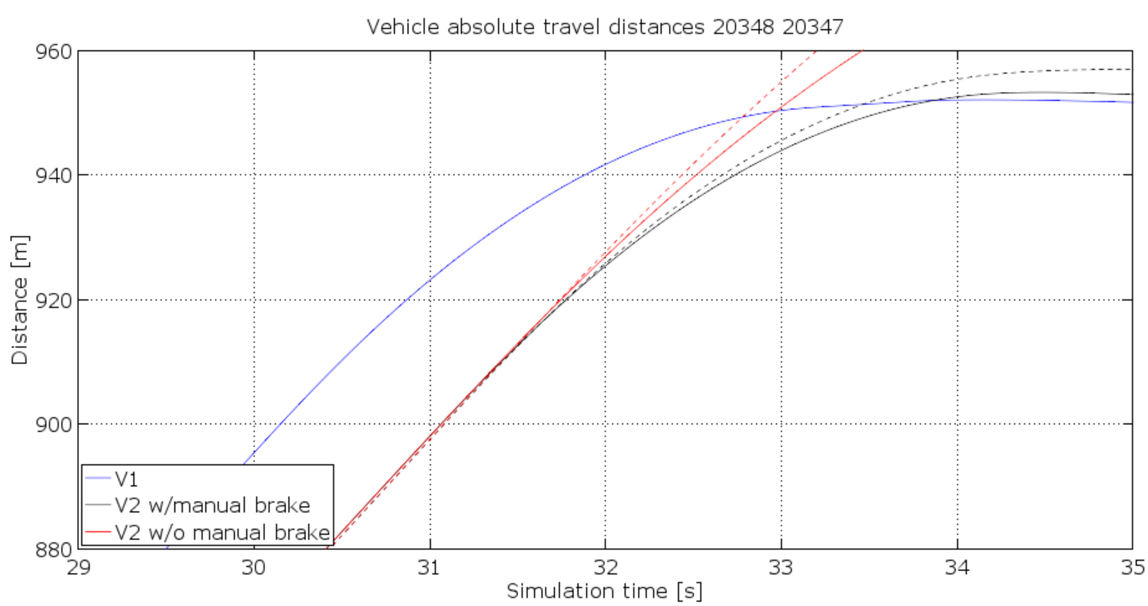
Figure 87 - Trajectories for Harsh Braking with a Time Gap of 1s

The same simulation was repeated with the time gap set to 0.75s for CACC only using two different vehicle-dynamics models, one with a faster deceleration response (Compact hatch - solid line) and one with a slower deceleration response (Full-size SUV - dashed line). All other conditions are identical. Results are shown in Figure 88 and Figure 89. Even with driver intervention, a slight collision occurs in this case. This simulation was repeated with different time gaps and 0.75s represents the edge case between collision and no collision for the vehicle with a faster response. The vehicle with the slower response experiences a slightly earlier collision with a higher relative velocity. This suggests that time gap should be adapted based on the reaction capabilities of the host vehicle.



Source: CAMP V2I Consortium

Figure 88 - Acceleration Levels for Harsh Braking with a Time Gap of 0.75sec



Source: CAMP V2I Consortium

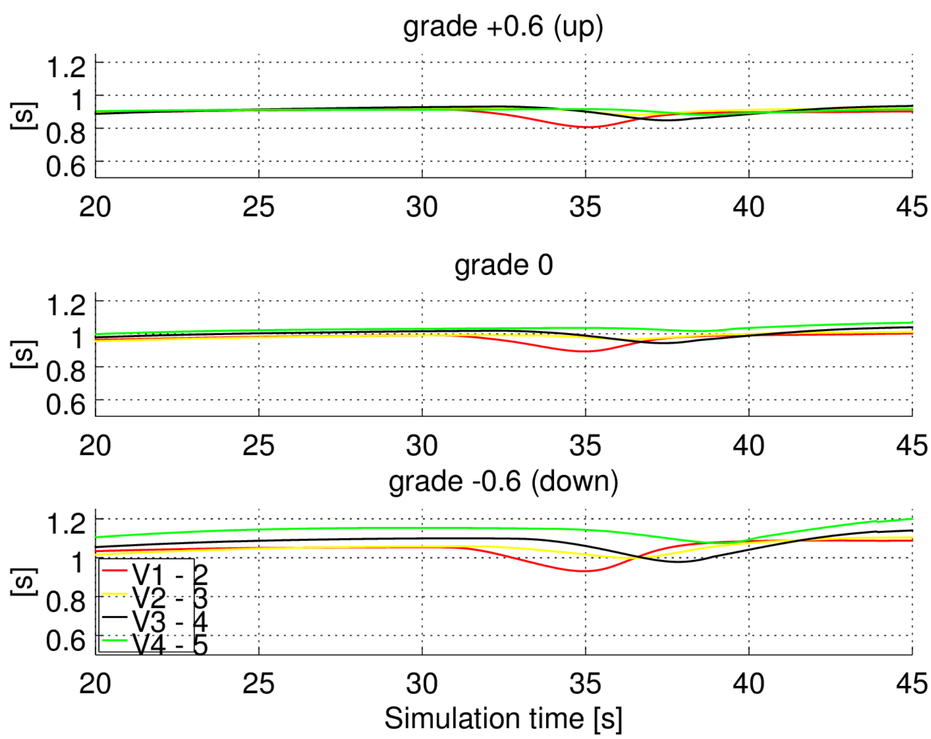
Figure 89 - Trajectories for Harsh Braking with a Time Gap of 0.75s

The analysis suggests that driver assumption of control may be necessary for harsh braking events in both ACC and CACC modes. Compensation of time gap for vehicle response characteristics may mitigate this need. It should be noted that only the deceleration limits of the ACC controller were modified in this analysis. Other control parameters such as a gradient limitation were not modified and may provide means of improving system performance.

4.2.9 Grade Effects

If the acceleration information received in the BSM of preceding vehicles does not account for acceleration due to road grade, CACC operation may be affected by the error as discussed in Section 2.3.4 Impact of Grade. Simulations were conducted to explore this effect. It was assumed that the vehicles would automatically compensate for the effects of grade on acceleration in their own brake and engine control systems but that the acceleration information communicated in their BSM data would not include this compensation.

Simulations were conducted with fixed grades of -6%, 0%, and 6% to show the worst-case effects to be expected on freeways. The effects were exposed by introducing a slight sinusoidal input perturbation into the string during the middle of the simulation run. The CACC string simulated consists of three small hatch backs followed by two large SUV's with the string time gap set to 0.5sec. Figure 90 shows the time gaps for CACC operation in the different grade scenarios utilizing the BSM extension. In this case, the longitudinal control algorithm utilizes both the current measured acceleration in the BSM and as well as the acceleration forecast in the BSM extension. Since these forecasts would not be affected by the grade errors, the impact on the CACC algorithm should be limited.

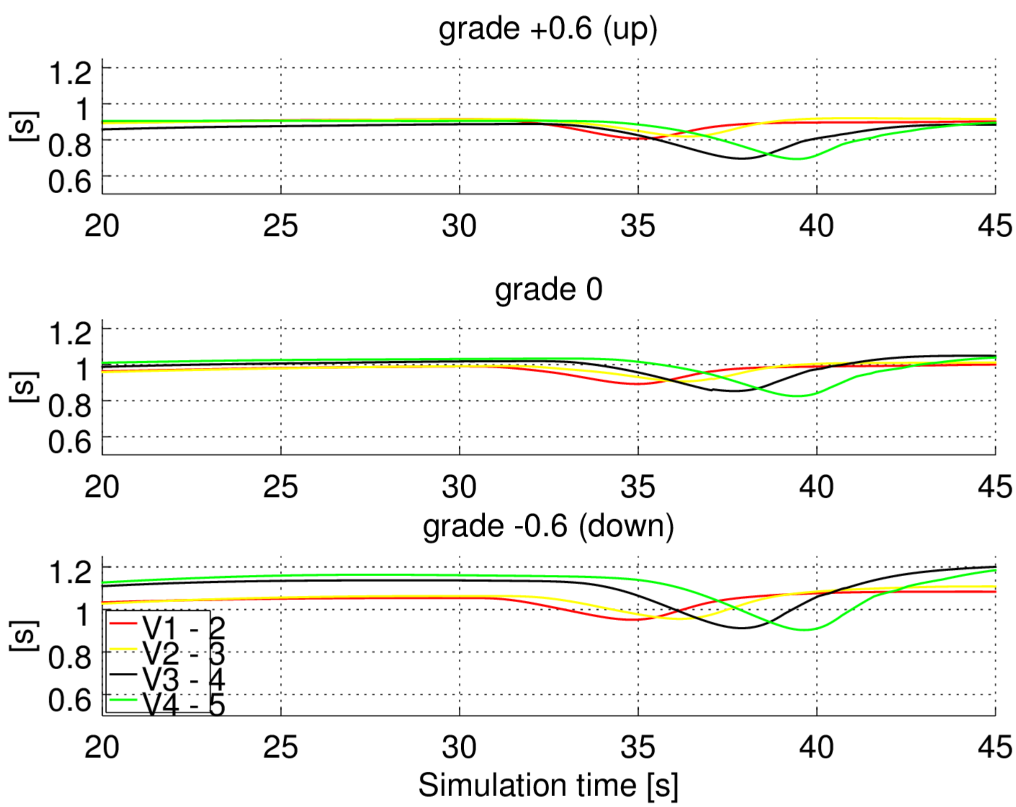


Source: CAMP V2I Consortium

Figure 90 – Effect of Grade on Time Gap for CACC with BSM Extension

Using the zero-grade scenario as a baseline, the effect of grade induced errors on CACC performance can be assessed. In the case of a positive grade, the time gap is reduced during the perturbation, particularly between vehicle 1 and vehicle 2. This is because positive grade leads to a positive error in perceived acceleration of the vehicles. This information is transmitted through the BSM to the following vehicle which calculates virtual target information based on that. The positive error will lead to a virtual target vehicle that will be positioned further away than the actual target vehicle position and, therefore, the longitudinal controller will keep a closer than desired distance.

In the negative grade scenario, time gap throughout the scenario increases, causing the vehicles to keep larger than necessary distance. This can be explained as follows. On a down-grade, the acceleration in the BSM always has an error which is interpreted as a decelerating maneuver of the RV. With that incorrect information, the virtual target becomes closer than the right position. The HV tries to keep a set time gap to this incorrect virtual target, resulting in a longer time gap than expected.



Source: CAMP V2I Consortium

Figure 91 – Effect of Grade on Time Gap for CACC without BSM Extension

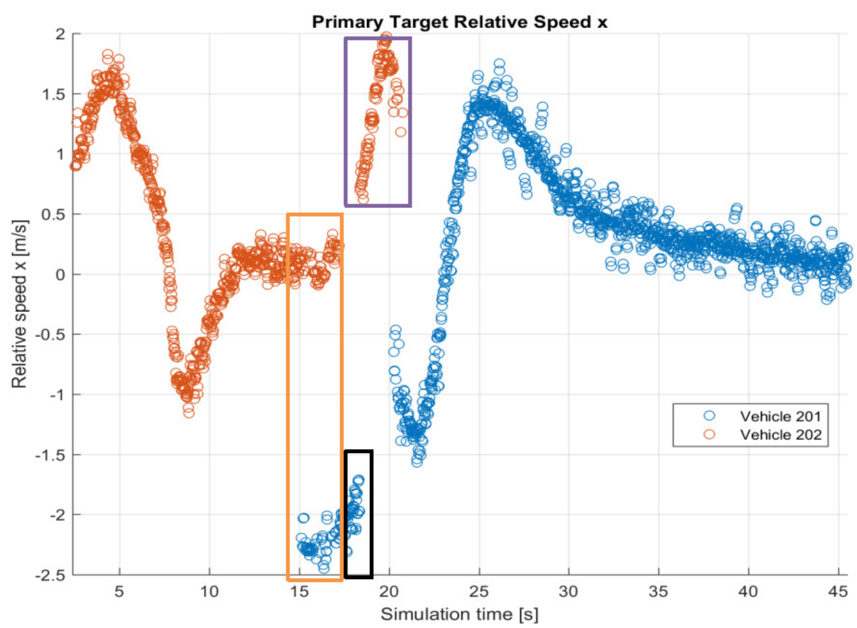
Without the BSM extension, the algorithm only relies on the current acceleration information in the BSM, which is affected by the grade. The resulting behavior can be seen in Figure 91. Since the algorithm doesn't receive acceleration forecasts, the performance in the base-line scenario is reduced. As expected, the effects on a positive and a negative grade are further increased. On the positive grade, the time gap between two vehicles is smaller and on the down grade the time gap between two vehicles is larger.

Thus, lack of grade correction in BSM acceleration data does have an impact on CACC algorithm performance. This effect is increased without acceleration forecast information, which is not impacted by grade.

4.2.10 Lane-Change Detection

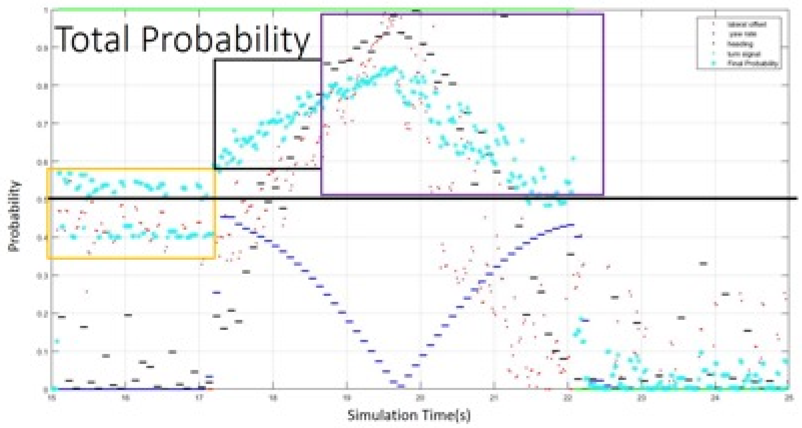
The Lane-Change Detection Algorithm is responsible for calculating the probability that a remote vehicle is performing a either a ‘cut-in’ or a ‘cut-out’ lane-change maneuver with respect to the lane of the host vehicle. The current implementation considers relative yaw-rate, relative heading, lateral offset and turn signal activation. The probability of a lane change is calculated as a weighted sum of the contributions of these individual factors. If the final probability calculated is greater than a set threshold, the lane-change flag is set indicating that a lane change is detected.

Initial results indicate a fluctuation in selection of the primary target vehicle. Figure 92 depicts the way the primary target of the host vehicle changes between two of the vehicles in front of it, one vehicle that cuts in and the other that is already traveling in front of the HV. Figure 93 shows the total probability of lane change as calculated by the lane-change detection system. The time around when the lane change occurs is broken into three distinct regions. The yellow box highlights the time when the vehicle from the adjoining lane begins the cut-in maneuver ahead of the HV. The black box indicates the time frame when the adjoining vehicle has very nearly finished the cut-in maneuver. The purple box indicates the time when the new vehicle in front of the HV has finished the cut-in maneuver and may be orienting itself in the center of the lane.



Source: CAMP V2I Consortium

Figure 92 - Fluctuation in Target Selection with Lane-Change Detection



Source: CAMP V2I Consortium

Figure 93 - Probability of a Lane Change

Fluctuations in the net probability can be attributed in part to the fact that the calculations were performed on raw sensor data and the selection of 0.5 as the threshold, since 0.5 indicates essentially uncertainty. Increasing this threshold will make the system certain in its detections but will also result in delayed detections. In addition, while vehicles cutting in from another lane were detected, there was no settling period to allow the vehicle to remain in the lane. Instead, the system immediately started to indicate a vehicle cutting out from the lane. There are variables in the algorithm responsible for 'timing-out' data if a certain time passed between data samples. These thresholds have an impact on the how early/late a lane change is recognized.

Thus, the behavioral interaction between the lane-change detector, in-lane classifier and primary target evaluation module is not performing accurately as currently modeled. Further work is needed to improve the performance of the lane-change detection algorithm. Various threshold choices and buffering schemes should be investigated. Machine learning approaches should be evaluated for their performance as a lane-change detector. Performance should be evaluated on various road geometries, with a greater number of cars, and considering multiple/simultaneous cut-in/out maneuvers.

4.3 Performance Requirements

4.3.1.1 Motivation

When a CACC vehicle is following another vehicle, it needs to make assumptions about the expected behavior and performance of that vehicle. Especially when close time gap following is considered, the accuracy of the received information and the anticipated acceleration or deceleration performance.

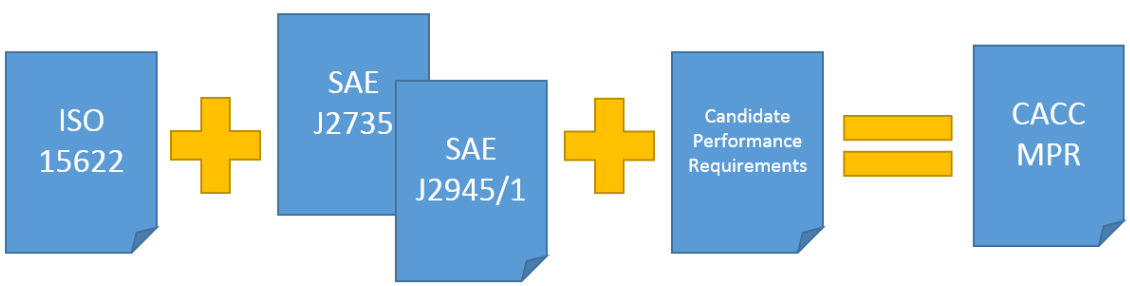
The following is a list of examples where Minimum Performance Requirements (MPR) become crucial for CACC operation:

1. CACC realizes improvements in performance through the availability of BSM extension elements (e.g., improvements in string stability through communication of acceleration forecasts from the preceding vehicles and the MVLA feature which relies on a remote vehicle's assessment of whether the vehicle preceding it is 'in-lane' or not).
2. ISO standards for ACC only set maximum limitations for acceleration and deceleration of ACC vehicles. The decision how fast a vehicle accelerates or decelerates is made by the individual OEMs. In the project's test campaign, it became evident that significant differences exist between vehicles of different makes and models in their acceleration response. Especially at a grade, this led to the brake-up of strings which would have undesired effects on the traffic flow. In scenarios with designated CACC lanes, single vehicles could limit the acceleration of all following vehicles and waste valuable time and space on the freeway.
3. As shown in the functional safety concept design, the CACC system needs to retain control of the vehicle for longer periods of time when certain safety-relevant situations occur. To design for those situations, the behavior of the remote vehicles needs to be considered. These design assumptions can be made, only if the data from the remote vehicle can be trusted and the implemented behavior falls within bounds.

4.3.1.2 Candidate Performance Requirements

During the course of the project, a list of performance requirements for a vehicle implementing CACC were defined (see Figure 94). At this point, this is not a comprehensive list of all requirements, but it is intended as an addition to the existing standards that define BSM transmission (SAE J2945/1) and ACC performance (ISO 15622).

Some of the requirements developed here are new requirements, whereas other requirements are intended to supersede existing requirements in other standards.



Source: CAMP V2I Consortium

Figure 94 - Overview of CACC Performance Requirements

The following is the list of Candidate Performance Requirements defined by the project based on the findings from the preliminary vehicle testing and the simulations. These requirements could be categorized and separated into the three categories as vehicle-dynamics requirements (Table 18), message transmission requirements (Table 19), and sensor performance requirements (Table 20).

Table 18 – Vehicle-Dynamics Requirements

Summary	Description
Adherence to ISO 15622	Vehicles implementing CACC functionality shall adhere to the ISO 15622:2010 performance requirements and test procedures.
CACC acceleration limit	CACC Control Unit shall ensure that a (positive) acceleration command does not exceed MAX_ACCEL_CACC when the system is in 'CACC' mode.
CACC deceleration limit	CACC Control Unit shall ensure that a (negative) acceleration command does not exceed MAX_DECEL_CACC when the system is in 'CACC' mode
Control strategy	The control strategy in CACC mode shall be based on maintaining a time gap (in contrast to maintaining a fixed distance).
Minimum time gap in CACC mode	In CACC mode, the CACC control unit shall never allow selection of a time gap below the minimum time gap, TAU_MIN_CACC for operation.
Maximum time gap	In CACC mode, the CACC control unit shall never allow selection of a time gap above the maximum time gap, TAU_MAX_CACC for operation.
Following performance	At speeds between 10mph and 70mph, when the lead vehicle is accelerating with 2m/s2 or less, keeping the average jerk less than 2.0m/s3, starting from steady-state conditions, the actual time gap to the preceding vehicle shall not exceed 200% of the target time gap.
Jerk limitations	In CACC mode, the average rate of change of positive and negative jerk (over a time window of 1s) shall not exceed 2,0 m/s3

Source: CAMP V2I Consortium

Table 19 - Message Transmission Requirements

	Description
Adherence to SAE J2945	Vehicle implementing CACC functionality shall transmit Basic Safety Messages in accordance with the minimum performance requirements defined in SAE J2945/1.
Transmission of exterior lights	Vehicle implementing CACC shall populate the ExteriorLights data frame with the correct values when transmitting a Basic Safety Message. Note: This data frame is optional per SAE J2945/1
Transmission of brake status	Vehicle implementing CACC shall populate the BrakeSystemStatus data frame with the correct values when transmitting a Basic Safety Message. Note: This data frame is optional per SAE J2945/1

	Description
Transmission of the CACC extension	Vehicle shall transmit BSMs with the CACC extension when it is under automated longitudinal control.
Transmission of CACC state	The CACC state data element shall be set to the current state that the longitudinal control system is operating in.
Transmission of state change	The CACC state data element shall be changed to the new value within 100ms when the longitudinal control state changes.
Transmission of Acceleration forecast	A vehicle under automated longitudinal control shall transmit an acceleration forecast of its future acceleration.
Transmission of tau	The vehicle shall transmit the time constant tau of the vehicle response to the acceleration forecast when an acceleration forecast is transmitted.
Transmission of the acceleration over ground	Longitudinal acceleration of the vehicle and acceleration forecast shall be transmitted "over ground" with potential measurement errors due to grade accounted for.
Transmission of prediction accuracy	When a CACC vehicle follows a preceding vehicle, which accelerates and decelerates in a sine wave perturbation. The actual acceleration of the following vehicle shall follow a response calculated from the forecast acceleration by a 1st order lag filter whose time constant tau is transmitted in the BSM, with a tolerance of +/- 0.3m/s/s. And the time constant tau shall be 0.2s or larger. Sine wave perturbation condition: Cycle time = 8.0 sec, Amplitude = +/- 1.0 m/s/s (Δv = 11mph) This requirement applies to grades ranging between -6% and 6%
Transmission of target vehicle identifier	Vehicle shall transmit the BSM temporary ID of the remote vehicle as the target object temporary ID when it is currently considering the remote vehicle as its longitudinal control target and the remote vehicle is sensed through both DSRC and the non-communication based sensing technique.
Transmission of primary target change	The primary target ID data element in transmitted messages shall be changed to the new value within 100ms when the primary target of the vehicle changes

Source: CAMP V2I Consortium

Table 20 - Sensor Performance Requirements

Summary	Description
Object fusion	In the CACC state, the vehicle shall select a primary target only if it was received through DSRC and validated using non-communication based sensing techniques.
Sensor blindness	The system's non-communication sensing system shall detect sensor blindness (e.g., through damage, dirt, etc.)

Source: CAMP V2I Consortium

4.4 Vehicle Software Integration

Phase 2 of the CACC research plan, if conducted, would integrate the proposed system design into the prototype ACC vehicles built during Phase 1 and perform controlled test and evaluation. In preparation for the transition from simulation to vehicle implementation, the status of the individual algorithm modules was analyzed.

No major issues were identified with the algorithms. Based on this analysis, Software Version 3 should be used for vehicle implementation. The final algorithm parameters from simulation provide a starting point for the vehicle calibration. However, modifications are to be expected as vehicle performance is evaluated. Table 21 provides an overview of each algorithm module's status and any potential modifications required.

Table 21 - Algorithm Module Performance Assessment

Module Name	Status	Comments
Input Data Receivers and Output Data Transmitters	Needs replacement	All modules handling inputs and outputs need to be converted from simulated data interfaces to in-vehicle interfaces (e.g., through CAN).
MoveData Extractor	O.K.	No known problems - can likely stay unmodified.
Communication Quality Observer	Potential minor adjustments	Real-world communications data might require additional parameterization.
Coordinate Transformation	O.K.	No known problems - can likely stay unmodified.
MRR Object Validation	O.K.	Was originally developed using real Radar data and, therefore, can likely stay unmodified.
Path Prediction	Potential minor adjustments	No known problems from the simulation. However, real-world testing may require additional parameterization.

Module Name	Status	Comments
		Specifically, the use of the steering wheel angle in addition to the yaw rate will need to be evaluated.
Longitudinal Classification	Potential minor adjustments	No known problems from the simulation, However, real-world testing might require additional parameterization.
Object Fusion	Potential minor adjustments	No known problems from the simulation. However, additional parameterization will need to occur when sensor data with true errors is available. CPU load will also need to be monitored for this module.
Lane Classification	Potential minor adjustments	No known problems from the simulation. However, real-world testing may require additional parameterization.
Lane-Change Detection	Additional work necessary	This module requires improvements in the event separation. The behavior can be improved through the addition of detection hysteresis. These changes should be made when CACC vehicles are available and tests based on real data can be conducted.
Primary Target Validation	O.K.	No known problems - can likely stay unmodified.
In-lane Assessment	O.K.	No known problems - can likely stay unmodified.
State Machine	O.K.	No known problems - can likely stay unmodified.
Vehicle Behavior Estimation	O.K.	There are no known issues with this module, which implements reaction time improvements necessary during short time-gap operations.
Time Gap Determination	O.K.	This module is required for dynamic time-gap adjustments in CACC mode. Adaptation for safety considerations during the vehicle testing are likely.
First Order Lag Look-Up	O.K.	There are no known issues with the module. It's impact on the performance is likely very low. Its usefulness should be evaluated during vehicle testing.
Virtual Target Creation	O.K.	There are no known issues with the module. Real world sensor data may show potential issues with the current calculations. The current calculation is based on both radar and GPS. If the impact of GPS errors is too large, the calculation may need to be modified.

Module Name	Status	Comments
Longitudinal Controller	Potential minor adjustments	There are no known issues with this module. However, vehicle implementation may require additional parameterization and tuning for comfort and performance.
BSM Transmitter	Needs replacement	Need to establish connection to the vehicle's DSRC radio.
Logging Output Transmitter	Minor adjustments	In the vehicle, the cloud-based and simulation environment based logging systems won't exist. Therefore, the logging concept needs to be adapted. A live view of key parameters as well as a logging output for post-processing is envisioned.
Infrastructure Message Assessment	Not planned for continuation	Implementing the merging assistant functionality in vehicles would require: • significant changes in the real-time platform since it would need to host two longitudinal controllers instead of one. • creation of the infrastructure component which does not presently exist Therefore, this functionality is not recommended for vehicle implementation.
Merging Target Modifier		
Merging Target Creation		
Merging Longitudinal Controller		

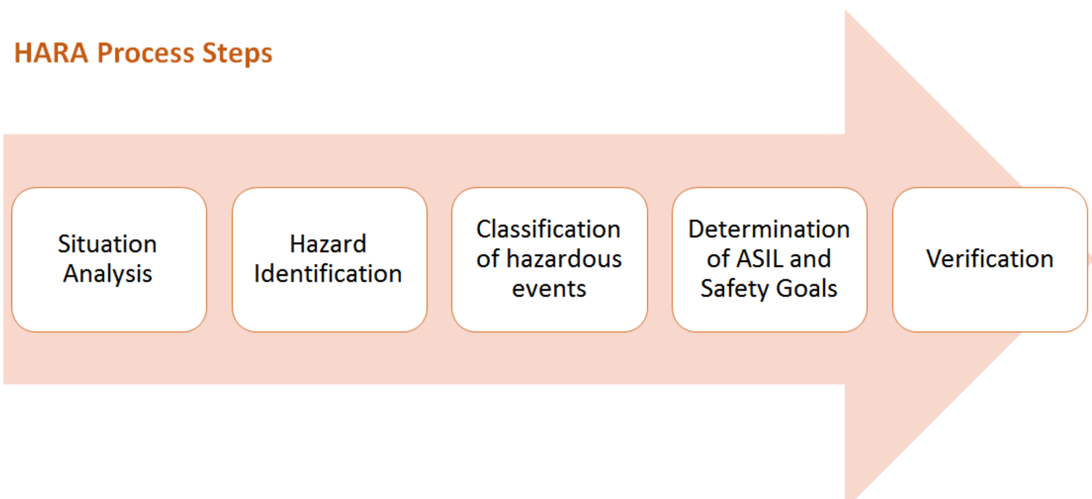
Source: CAMP V2I Consortium

5 Hazard Analysis & Safety Concept

Functional safety of the prototype CACC system was evaluated using a formal hazard analysis. Safety requirements were established and means to realize those requirements established in a Safety Concept developed for the experimental system. The methodology used and key outcomes are outlined in the following sections. This analysis does not reflect any specific OEM implementation of ACC or CACC, which may differ from these findings.

5.1 Hazard Analysis

The Hazard Analysis and Risk Assessment (HARA) process is defined within ISO26262, which provides a standard for functional safety in the production of vehicles as illustrated in Figure 95. The process encapsulates the gathering of a group of situations, assigning a rating level to each situation according to the Automotive Safety Integrity Level (ASIL) scale. ASIL ratings are then defined according to Severity (S1-3), Exposure (E1-3), and Controllability (C1-3) for each given situation.



Source: kVA

Figure 95 - HARA Process Steps

5.1.1 Situation Analysis

The scope of the HARA was the CACC system. The assessment was conducted considering three different operating scenarios to identify potential differences under these conditions. The longitudinal control operation of CACC does not change significantly across the following scenarios.

5.1.1.1 Scenario 1: Designated CACC Lane on a Freeway

In this scenario, it is assumed that vehicles would be operated in CACC mode only on a designated lane on a freeway. A physical separation between this lane and the other driving lanes is possible and lane-change maneuvers should either be impossible or very unlikely. When entering and leaving the CACC lane, either the system automatically handles activation and deactivation or the driver performs this task.

5.1.1.2 Scenario 2: CACC Operated on a Multi-Lane Freeway

In this scenario, CACC would be operated throughout the whole freeway, and it would be the driver's responsibility to activate and deactivate the system whenever appropriate. Since this would include operation in a multi-lane environment, the system would need to handle cut-in maneuvers by other vehicles as well as lane changes initiated by the host vehicle's driver.

5.1.1.3 Scenario 3: CACC Operated on Non-Freeway Roads

Scenario 3 considers CACC operation on non-freeway roads such as secondary or country roads, but it does not include city streets. Operational speeds and traffic densities are assumed to be lower than the first two scenarios.

5.1.1.4 Additional Parameters

Additional parameters covering situations a CACC vehicle may encounter in any of the operating scenarios were identified and analyzed. These include:

- Road conditions (dry, wet, icy)
- Road profile (straight, curved)
- Traffic conditions (normal, heavy, transition from normal to heavy)
- CACC string operation (normal, slowdown of preceding vehicle, cut-in maneuver)
- Time gap (600ms, 3s)

For time gap, values were chosen lower and higher than a typical ACC time gap of 1s to explore the effect on system operation.

5.1.2 Hazard Identification & Classification

5.1.2.1 Assumptions

The Hazard Analysis was conducted considering the assumptions listed in Table 22.

Table 22 - CACC HARA Assumptions

Assumption Underlying the CACC Hazard Analysis
• Regarding the classification of malfunctions, when the system is in Manual state, unintended activation of CC, ACC or CACC produce "unintended" acceleration and deceleration commands. However, when in the ACC, CC or CACC state due to driver activation, undesired acceleration or deceleration provided by the system is no longer "unintended" but is considered "incorrect" since they are computed by the system.
• While defining vehicle level hazards, separate malfunctions are consolidated / combined for similar situations.

Assumption Underlying the CACC Hazard Analysis
• Regarding controllability rating, the arbitration of control between the driver and the CACC system is performed by vehicle controllers such as brake controller and/or engine controller in the same manner as in a traditional ACC-equipped vehicle. Therefore, brake commands from the driver are provided priority over commands received from CACC system by the vehicle controllers.
• Unintended insufficient acceleration (in the worst case) is assumed as a removal of acceleration i.e., constant speed or gradual reduction in speed due to aerodynamic drag or other losses.
• The minimum selectable CACC time gap allowed is 0.6 seconds.
• Typical driver perception-reaction time is 1.5 seconds.
• The maximum deceleration rate for remote vehicles during "normal string operation" is limited by CACC system capabilities at 5 m/s^2.
• The maximum deceleration rate for remote vehicles outside of "normal string operation" is 9.8m/s^2 resulting from an emergency brake maneuver initiated by the driver of the remote vehicle or other system outside CACC.
• In the event of a malfunction of the host vehicle CACC system, maximum brake and acceleration capabilities are possible (this could mean the acceleration and deceleration limits could not be enforced on the vehicle)
• When there is a malfunction of the leading CACC vehicle in a string creating unintended deceleration, the trailing vehicle's driver is the only entity to react to the situation, taking over control from that vehicle's CACC system and applying brakes and/or steering to avoid/ mitigate the hazard. The 'CACC' system of the trailing vehicle is conservatively assumed not to have the capability to react to this situation.
• Since the CACC system does not have lateral authority, operation on exit ramps/ sharp curvatures/ mountain roads, which may lead to lateral instability, are not considered as a malfunction created by the system itself, even it leads to lateral instability. Since the driver is responsible for lateral control, it is his/her decision to keep the CACC system activated in these conditions.
• Curved roads follow national and state road design manuals for radius and superelevation. Road curvature refers to the smallest radii allowed for each road profile and the speeds assumed [10]: – Highway (>55 mph) – Secondary/ Country Roads (>30 mph && <55 mph) – City Roads (<30 mph)

Source: CAMP V2I Consortium

5.1.2.2 Hazard Identification

The ASIL rating is defined in terms of 3 criteria and their associated scale. These criteria, Exposure, Severity and Controllability, are defined in ISO26262 and shown in Table 23.

Table 23 - ASIL Rating Criteria and Scales

	E1 very low probability	E2 low probability	E3 medium probability	E4 high probability
Value	**0.001**	**0.01**	**0.1**	**1**
Frequency / Duration	Situations that occur **less often than once a year for the** great majority of drivers	Situations that occur **a few times a year** for the great majority of drivers	Situations that occur **once a month or more often for an** average driver	All situations that occur during **almost every drive on** average
	n.a.	<1% of average operating time	1% – 10% of average operating time	> 10% of average operating time

S1	Light and moderate Injuries
S2	Severe injuries, possibly life-threatening, survival probable
S3	Life threatening injuries (survival uncertain) or fatal injuries.

	C1 simply controllable	C2 normally controllable	C3 difficult to control or uncontrollable
Value	**0.01**	**0.1**	**1**
De-finition	More than **99%** of average drivers or other traffic participants are usually able to control the damage	More than **90%** of average drivers or other traffic participants are usually able to control the damage.	The average driver or other traffic participants is usually unable, or barely able, to control the damage

Source: kVA

Safety ratings are defined as ASIL A, B, C, or D, with D being the highest or most serious, or Quality Managed (QM), a classification that indicates the situation is handled via "Quality Management" systems, with no need for a safety rating as shown in Table 24. The rating is assigned by initially assuming each situation is at ASIL D, and then de-rating one level for each reduction in severity, exposure, or controllability as follows:

- Ratings of S4, E4, and C3 combine to yield ASIL D, the highest level.
- Ratings of S3, E4, and C3 yield ASIL C, due to severity S3.
- Ratings of S3, E2, and C3 yield ASIL A as three reductions are noted.

Table 24 - ASIL Determination

Difficulty to Control →

Greater Severity ↓ / Higher Probability Of Exposure ↓

Severity Class	Exposure Class	Controllability Class C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

ASIL RATING

81

Source: kVA

The hazard identification process for the prototype CACC developed in this project produced 1,076 Hazardous Event entries. An example of the resulting compilation is shown in Figure 96 for Scenario 2: CACC Operating on a Multi-lane Freeway with the Hazard 4: Incorrect Insufficient Acceleration. Note the resulting classification levels assigned to example event 'HE657' rated at "E4," "S1," and "C1."

Vehicle Hazard: Scenario 2		Hazard H_4 - Incorrect Insufficient Acceleration CACC operated on multi-lane freeway				
Hazardous Event ID	Hazard	SCENARIO: Road Conditions	Road Profile	Traffic Conditions	Time Gap	CACC String
HE657	[H_4] Incorrect Insufficient Acceleration	Dry pavement	Straight road	Normal freeway traffic	600 ms	Normal string operation

Exposure Probability		Severity		Controllability	
Exposure Probability	E - note	Severity	S - note	Controllability	C-Note
E4	This exposure is considered since the intended functionality for the CACC system is on the freeways with short time-gaps in normal conditions (>10% of the operating time)	S1	At freeway speeds, the relative speed between the host vehicle and the following vehicle is less. Also, a coasting event does not lead to a collision with following vehicle with enough relative speed to cause severe injuries. Hence, a S1 rating is chosen.	C1	Since the host vehicle coasts, the following vehicle (along with driver) has the ability to avoid collision by removing acceleration, or apply brakes and/or steering. Even with the shorter time-gap, this is a very controllable event

Source: CAMP V2I Consortium

Figure 96 - HARA Table Excerpt

5.1.3 Verification

While the Hazard Analysis and Safety Concept share a direct connection via the ASIL ratings, they also drive requirements related to the Safety Concept. Given that these requirements are testable, a direct connection then exists to the verification process for a specific system implementation. Due to the experimental nature of the prototype CACC system developed in this project, instead of testing, the technical team addressed verification by reviewing each HARA table entry in detail to verify the content in relation to the overall Safety Concept.

5.1.4 Outcomes

The maximum ASIL levels identified for each of the CACC operational scenarios at different time gap are summarized in Table 25. The reduced operating speeds and lower traffic densities in scenario 3 lead to a lower maximum ASIL ratings compared to scenarios 1 and 2. A discussion of possible scenario modifications and their effects on the results of the analysis follows.

Table 25 - Maximum ASIL Based on CACC Operational Scenarios

CACC Scenario	Maximum ASIL 0.6s time gap	Maximum ASIL 1.0s time gap
1: Designated Lane on a Freeway	ASIL C	ASIL B
2: Operated on a Multi-Lane Freeway	ASIL C	ASIL B
3: Operated on Non-Freeway Roads	ASIL B	ASIL A

Source: CAMP V2I Consortium

Designated Lane: Operation on a designated freeway lane does not lead to the anticipated safety benefits resulting from physical separation from other traffic lanes. This is because the severity of the failure situations is largely the result of potential longitudinal collisions with high speed differentials. Lateral collisions resulting from lane-change maneuvers play a secondary role. As a result, safety levels for the CACC system did not change with the use of designated lane, regardless of the type of separation (markings, soft barriers, strong barriers).

Also, scenarios 1 and 2 have the same maximum ASIL levels, even though one assumed mixed-mode operation and the other didn't. Therefore, while the ASIL ratings for some situations may vary, the maximum ASIL for Scenario 1 is not expected to change in the case of mixed-mode operation on the designated lane.

Reduced Time Gap: Increasing the time gap reduced the maximum ASIL level for every scenario. As expected, following at lower time gaps increases the safety requirements for the systems involved.

5.1.5 CACC Safety Goals

The safety goals identified for the prototype CACC system are summarized in Table 26. When the CACC system identifies a malfunction, it transitions into a ‘safe state’ to minimize the potential to cause harm. The CACC system safe state is described by the following criteria:

1. The system is disengaged, and no acceleration or deceleration requests are issued (e.g., it is in 'manual state')
2. The driver assumes longitudinal control responsibilities
3. The time gap is sufficient for the driver to perform the longitudinal control task

The system transition to a safe state shall occur within a 'fault tolerant time interval' (FTTI) to limit potential exposure to unsafe control actions. The vehicle following situation should be controllable by the driver while transitioning into the safe state. Tentative values were assumed for the prototype CACC system shown in Table 26. These assumptions should be revisited for specific OEM implementations.

Table 26 - Safety Goals for CACC System Malfunction(s)

Safety Goal	ASIL	FTTI
Prevent Incorrect Excessive Deceleration	C	150 - 200 milliseconds
Prevent Incorrect Insufficient Deceleration	C	350 - 400 milliseconds
Prevent Incorrect Excessive Acceleration	C	450 - 500 milliseconds

Source: CAMP V2I Consortium

5.2 Safety Concept

5.2.1 Comparison between ACC and CACC

This section outlines differences between typical ACC safety concepts and special considerations for CACC that lead to the development of the project CACC safety concept.

5.2.1.1 ACC Safety Concept

Schaeffner et.al. [5] present an exemplary ACC safety concept derived from hazard analysis. Their analysis presents (among others) the following safety goals:

Goal 1: Hazardous, inappropriate braking shall be prevented (ASIL C)

Goal 2: Hazardous, inappropriate braking that destabilizes the vehicle shall be prevented (ASIL B)

Goal 3: Hazardous, inappropriate acceleration shall be prevented (ASIL B)

Using these goals, a functional safety concept is presented considering an architecture consisting of sensing, acceleration determination and acceleration implementation. Multiple variants of applying these safety goals to the ACC system architecture are presented. Variant C introduces a new functional module that always prioritizes driver inputs over ACC inputs and limits decelerations to maximum levels. This approach is attractive since it assigns the higher ASIL to the additional functional module(s), which are relatively simple to implement. Sensing and acceleration determination modules can be developed with QM, which is important since sensing errors cannot be eliminated.

The system does not prevent inappropriate braking, but it ensures that the driver can still control the vehicle in those situations and reestablish normal operation. Using this approach:

- The driver is expected to be attentive, constantly monitoring the situation
- The system is operating at time gaps that provide the driver enough time to identify that the system is behaving inappropriately and transition the vehicle to manual control.

5.2.1.2 CACC Safety Concept

The safety concept proposed for CACC is designed in a similar fashion to the ACC concept, with the sensing, acceleration determination, acceleration implementation modules, as well as the communications module, all implemented with QM. However, this is only feasible when the system is operating at time gaps that provide the driver with enough time to perform the monitoring and mitigation tasks. Since CACC is designed to allow lower time gaps than typical in ACC, down to 0.6 seconds in this project, the CACC safety concept must also provide for transition from short time gap following to a state controllable by the driver.

5.2.2 Safety Assumptions

The assumptions on which the proposed CACC safety concept is based are summarized in Table 27.

Table 27 - CACC Safety Concept Assumptions

Number	Assumption
A1	ACC is developed independently to a level of safety integrity that assures controllability by the driver [hypothetically ASIL B].
A2	Radar sensor information integrity can't be assured. Hence acceleration and deceleration limits, as well as warnings in ACC systems, become crucial (assured). The ACC controller is designed to always ensure driver controllability to the required integrity level.
A3	If the system encounters a situation (including faults) that requires a transition from CACC to ACC while operating in conditions outside the capabilities/ design for ACC, the system shall first transition to an intermediate Recovery state to make conditions suitable for ACC operation. While in Recovery state, a TBD level of deceleration will automatically be applied over a specified period, depending on lead vehicle behavior and the surrounding environment, to establish appropriate conditions for ACC operation.

Source: CAMP V2I Consortium

5.2.3 CACC Safety Architecture

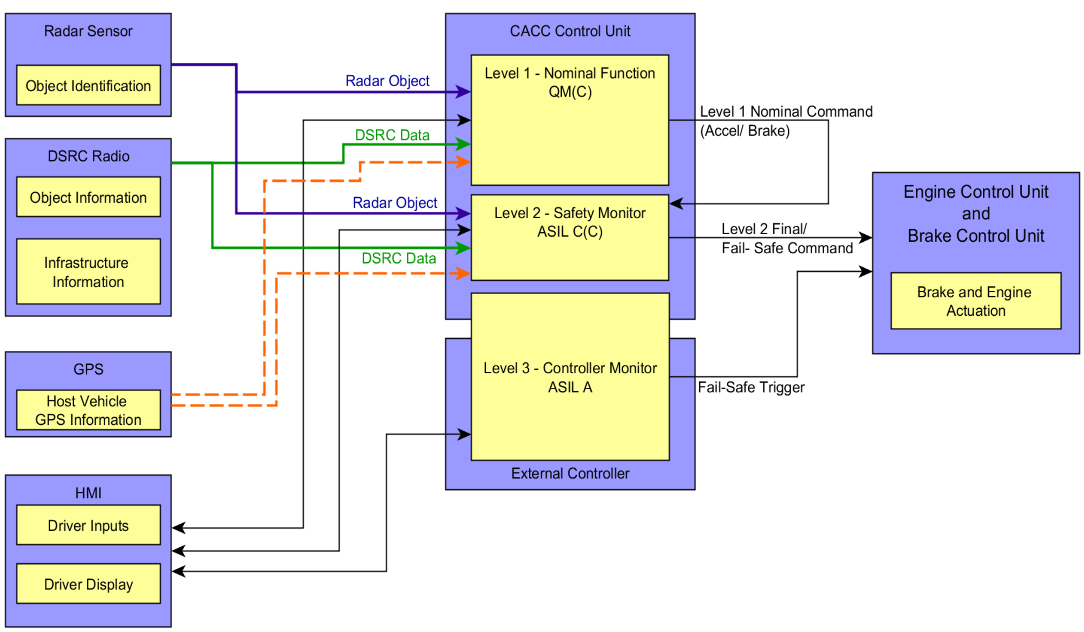
The goal of the approach selected is to make ASIL decomposition feasible, supporting partitioning of different levels of functionality and oversight. This allows different levels of risk to be viewed as separate components, each supporting their own set of requirements. The design of the CACC control unit was decomposed into three levels:

Level 1 carries out basic processing to achieve the more obvious goals of vehicular control.

Level 2 acts as a higher-level monitor of the system. It takes in some of the same inputs as Level 1 (e.g., DSRC, Radar or Vision Sensor data) and processes these inputs in real time, but in a wholly different way, to provide oversight in the form of a providing boundary and limit checking. The key is to perform processing that is completely independent of that done in Level 1, such as using independent equations to provide a system solution. Level 2 provides a 'sanity check' that the input and output values for Level 1 are within known limits.

Level 3 operates on yet a higher level. It performs startup diagnostic checks and continuously provides "watchdog" functions, e.g., monitoring whether hardware and software components can provide a specific signal (a "heartbeat") that indicates the module is still functional.

The hardware is partitioned such that Level 2, and Level 3 are implemented on separate microprocessors. These processors are chosen partly based on the ASIL level they are intended to support (i.e., ISO 26262 compliance). This hardware approach brings with it system design choices that determine how the Level 2 output is used to provide oversight to Level 1, as well as the interaction between Level 3 and the other parts of the system. The controller architecture configuration proposed is shown Figure 97. For the design selected, Level 1 output is fed into the Level 2 sub-system and is thus "gated" based on Level 2 criteria before being passed to the engine and brake controllers. Thus, the engine and brake controllers will never see an out-of-bounds torque request from Level 1.



Source: CAMP V2I Consortium

Figure 97 – CACC Controller Architecture with Three Monitoring Levels

5.2.3.1 Level 1 - Nominal Function

Level 1 fulfills the primary need for a CACC controller.

- The nominal functionality of the system is developed at QM(C) integrity
- Level 1 takes in all the relevant inputs to calculate appropriate system state, time gap and provide the required acceleration / deceleration command output
- Level 1 functionality is defined by the functional requirements specification.

5.2.3.2 Level 2 - Safety Monitor

Level 2 continuously monitors the functionality of Level 1 to provide an independent means to verify in real-time, whether the input to and output from Level 1 are within acceptable ranges. If Level 2 confirms that Level 1 functionality is outside the expected limits for a specified period, it initiates a transition to an appropriate safe state.

- Level 2 safety monitor is developed to ASIL C integrity
- Level 2 safety software independently receives the radar objects and DSRC information and, using a diverse method, calculates the appropriate limits for time gap and acceleration / deceleration commands.
- Level 2 independently assesses the appropriate system state.

5.2.3.3 Level 3 - Controller Monitor

Level 3 provides diagnostics, continuous supervision of hardware and software, and the ability to move the system to a lower level of automation, if needed.

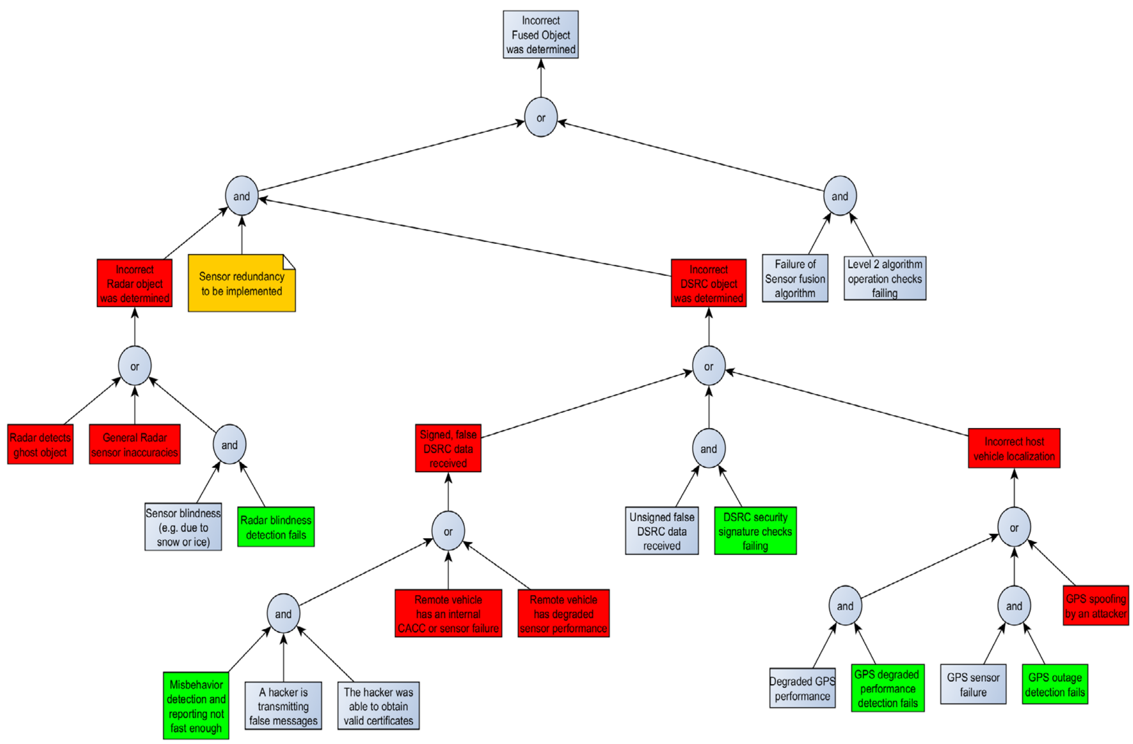
- Level 3 controller monitor is developed at ASIL A integrity
- Level 3 performs diagnostic checks on the primary controller to ensure that Level 2 safety monitor is available for protection and that a fault of Level 2 does not remain latent / silent.
- Level 3 implements safety checks on the primary microcontroller hardware as well as Level 2 software, including, but not limited to:
    - Program flow check (Q&A)
    - Memory / ALU check
    - Sequence check
    - Shutdown path tests
    - A/D converter checks

5.2.4 Sensor Performance

The impact of degraded sensor performance on the safety of the CACC nominal function is not covered by ISO 26262 functional safety analyses. The sensor performance fault tree shown in Figure

98 was constructed to examine potential sensor based causes for an incorrect fused object that could lead to incorrect accelerations or decelerations of the CACC system.

Misbehavior detection (MBD) is intended to address/filter malicious or misconfigured messages within a vehicular network. To reach this capability, the MBD is divided into two sub-processes of local misbehavior detection (LMBD) and global misbehavior detection (GMBD). LMBD targets the misbehavior detection at a vehicle level utilizing in-vehicle algorithms and applications. On the other hand, GMBD makes use of vehicle-level misbehavior reports inside Misbehavior Authority (MA) within Security Credential Management System (SCMS) to realize, validate, and confirm misbehavior detected and reported at the vehicle level as well as detection of attacks not realizable at the vehicle level [11, 12].



Source: CAMP V2I Consortium

Figure 98 - Sensor Performance Fault Tree

Sensor based faults that by their nature cannot be detected or eliminated are shown in red. In this analysis, potential performance issues propagate from the sensing of both radar objects and DSRC objects. The additional, high-level system requirements listed in Table 28 were created to mitigate this potential.

Table 28 - CACC System Requirements to Mitigate Sensor Faults

Requirement	Component	ASIL	Description
Sensor Redundancy for Reactions	Level 1	QM	CACC control unit Level 1 shall not react to individual Radar objects or individual DSRC objects. Level 1 shall always perform reactions based on a Level 1 fused object.

Source: CAMP V2I Consortium

Sensor performance issues that can be detected and mitigated are shown in green. Additional, high-level system requirements created to address these situations are listed in Table 29.

Table 29 - CACC System Requirements to Address Sensor Performance Issues

Requirement	Component	ASIL	Description
Disallow CACC operation if GPS performance is insufficient	Level 1	QM	CACC control unit Level 1 shall prevent state transitions to the CACC mode if GPS performance is considered insufficient.
Reaction to insufficient GPS performance when in CACC mode	Level 1	QM	CACC control unit Level 1 shall transition to ACC Recovery mode if GPS performance is considered insufficient.
GPS Sensor Diagnostics - Localization Sufficiency	CACC Control Unit	ASIL C	CACC control unit shall consider localization as 'insufficient' if either: 1. no GPS data is provided 2. if the time stamp of the last received GPS fix is older than specified maximum **3.** if the estimated localization error is greater than specified maximum
DSRC Message Authenticity Check	DSRC Module	QM	The DSRC module shall validate authenticity of received DSRC messages using checks of message signatures and the SCMS chain of trust.
DSRC Module - SCMS Certificate Revocations	DSRC Module	QM	The DSRC module used for CACC shall receive SCMS certificate revocations and use them to discard received messages.
Sensor Blindness	Radar Module	QM	The radar sensor shall detect sensor blindness (e.g., through damage, dirt, etc.).

Source: CAMP V2I Consortium

5.2.5 Recovery Transitions

As noted in CACC Safety Concept, because CACC is designed to allow lower time gaps than typical in ACC, down to 0.6 seconds in this project, the CACC safety concept must also provide for transition from short time gap following to a state controllable by the driver. Recovery transitions from the CACC state to the ACC state and the Manual state address this need. The purpose of these transitions is to bring the vehicle into the operational limits of the target state before performing the actual transition. If these operational limits are already satisfied, the system will immediately transition into the requested end state.

5.2.5.1 ACC Recovery State

The purpose of the ACC recovery state is to ensure that the transition from CACC to the ACC is only allowed when the time gap, acceleration and deceleration parameters are within designed operating limits for ACC. This is done by applying limited braking until all necessary conditions are satisfied. Since the radar subsystem is operational, time gap information can be computed. The control strategy implemented is to continue to operate within CACC acceleration and deceleration limits and attempt to achieve the following (ordered) goals:

1. Increase the time gap to the minimum time gap supported by ACC
2. Reduce the commanded deceleration to the maximum deceleration supported by ACC
3. Reduce the commanded acceleration to the maximum acceleration supported by ACC

As soon as all these goals are met, the transition to the ACC state can be made.

5.2.5.2 Manual Recovery State

The purpose of the Manual Recovery state is to ensure that the time gap supports controllable driver operation before transitioning to Manual state. The driver shall be notified about the expected take-over as soon as the recovery state is entered.

The time the system remains in Manual Recovery depends on operating conditions preceding the transition. The control strategy implemented is to assume constant acceleration of the target vehicle using the last known sensor data and calculate required deceleration rate and time for a linear deceleration by the host vehicle with the following (ordered) goals:

1. Attain the minimum allowable ACC time gap at the end of the deceleration
2. Limit deceleration rates to CACC operational limits
3. Limit maximum deceleration time to 3s

As soon as all these goals are met, the transition to the Manual state can be made.

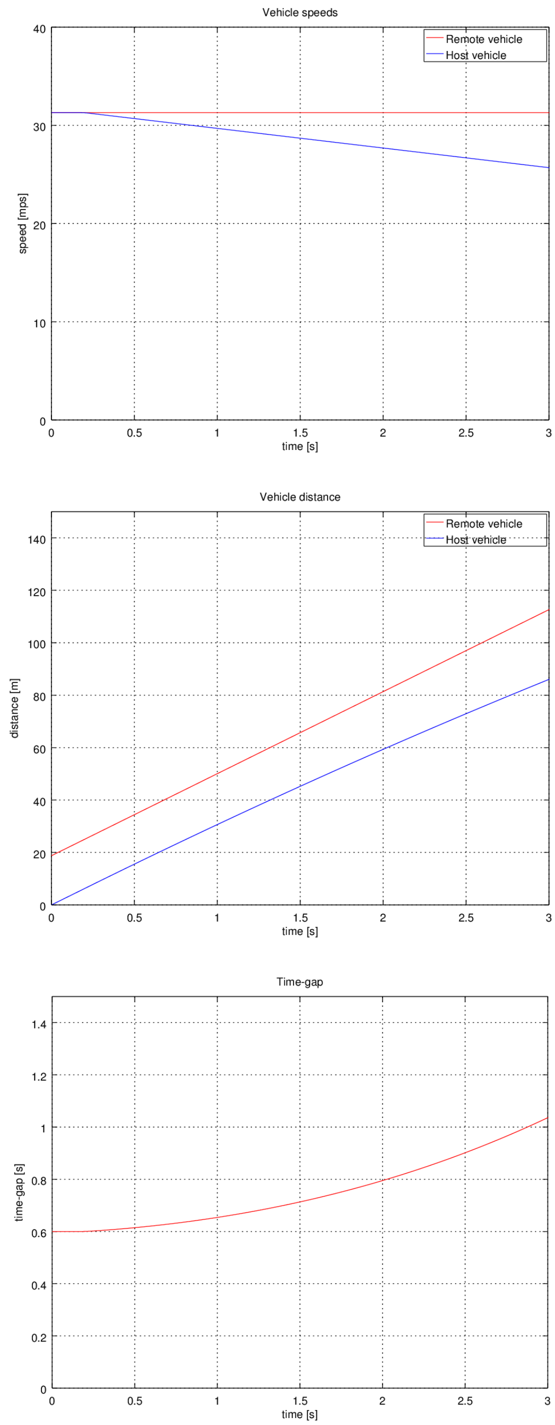
5.2.5.3 Recovery State Transition Examples

The following recover state transition examples were examined to provide a preliminary look what happens when the proposed recovery strategies are applied using a simplified vehicle-dynamics model with the following assumptions:

1. The component failure occurs at t=0
2. The failure is identified and a recovery state entered within 100ms
3. The time delay to initiate braking due to communication latency and mechanical latency is 200ms
4. The CACC maximum deceleration limit is -6 m/s^2
5. The driver reaction time is 1s
6. The driver braking capability is up to -9.81 m/s^2

5.2.5.3.1 Example 1 – ACC Recovery during Steady State Following

The host vehicle is following a remote vehicle at 0.6s time gap with a constant speed of 70 mph when the DSRC radio fails. Vehicle behavior during the transition is shown in Figure 99. The remote vehicle speed remains constant. The host vehicle CACC system transitions into ACC recovery state and decelerates until the time gap reaches 1s then continues operation in ACC mode. After 2.8s, the transition is completed without intervention by the driver.

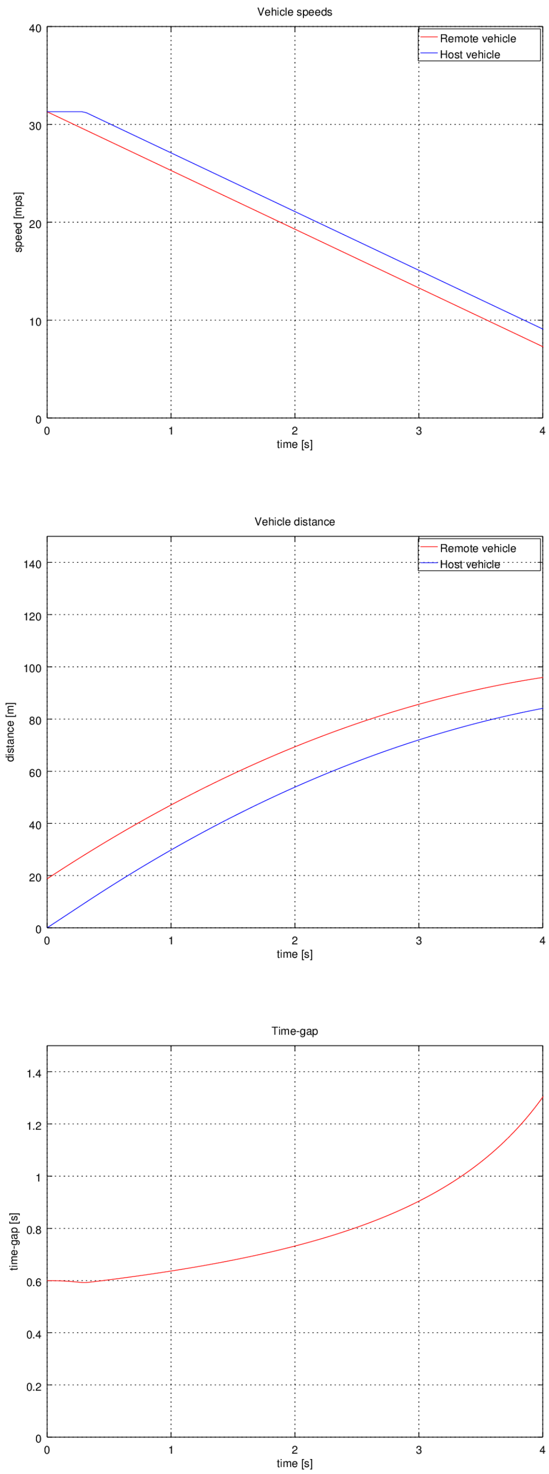


Source: CAMP V2I Consortium

Figure 99 – ACC Recovery during Steady State Following

5.2.5.3.2 Example 2 – ACC Recovery during Remote Vehicle CACC Braking

In this example, the host vehicle is once again following a remote vehicle at 0.6s time gap with a constant speed of 70 mph when the DSRC radio fails. However, this time the remote vehicle simultaneously decelerates at a rate of -6 m/s2. This causes the host vehicle to also brake with the same CACC maximum deceleration rate while in ACC recovery state. Vehicle behavior during the transition is shown in Figure 100. Since both vehicles are reducing their speeds at the same time, the time gap increases even though the distance between the vehicles stays almost constant. After ~3.3s, the time gap reaches 1s which marks the end of the transition to ACC mode.

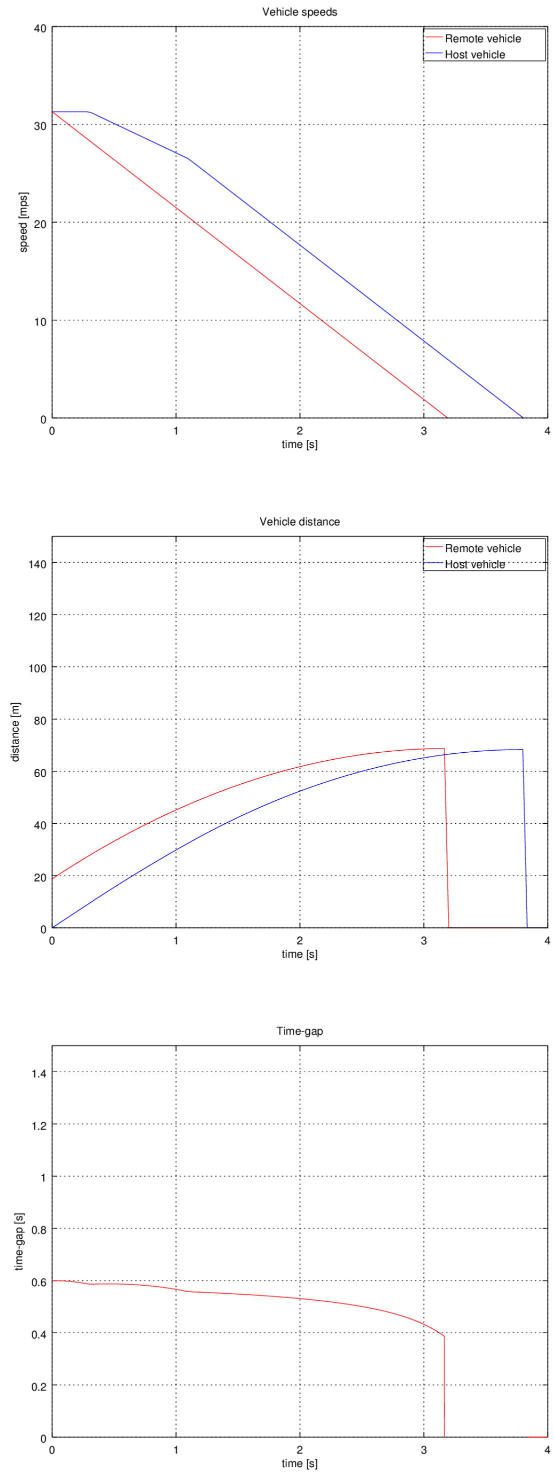


Source: CAMP V2I Consortium

Figure 100 - ACC Recovery during Remove Vehicle CACC Braking

5.2.5.3.3 Example 3 – Manual Recovery during Remote Vehicle Emergency Braking

In Figure 101, the host vehicle is once again following a remote vehicle at 0.6s time gap with a constant speed of 70 mph when a CACC component fails and the driver of the remote vehicle simultaneously initiates an emergency brake maneuver of -9.81 m/s2. This causes the host vehicle to brake with the CACC maximum deceleration rate of -6 m/s2 while in the recovery state and to notify the driver that they need to assume control. After the anticipated reaction time of 1s, the driver takes over and increases the braking force to also attain -9.81 m/s2. In the end, both vehicles come to a stop having just barely avoided a collision.



Source: CAMP V2I Consortium

Figure 101 – Manual Recovery during Remote Vehicle Emergency Braking

5.2.6 CACC System Safety

Preliminary analysis of the proposed CACC safety concept suggests that it is feasible to safely operate the prototype CACC system developed in this project at time gaps as low as 0.6s. This is dependent on implementing:

1. A three-level monitoring concept to handle higher ASIL levels and unavoidable sensor malfunctions
2. Recovery transitions to mitigate risks after component failures
3. A maximum allowable system deceleration rate of $-6m/s^2$ to provide sufficient time during the recovery transitions for the driver to assume control

6 Conclusions & Recommendations

The focus of the CACC-SST Project is to develop and implement CACC functionality as an extension of conventional ACC technology leveraging DSRC communications between vehicles and with the infrastructure. During Phase 1 of the research plan (Figure 2), a reference ACC system was implemented in four prototype vehicles of different makes and models and baseline performance established through structured vehicle testing in a controlled environment. These test results were used to parameterize the simulation environment which was established to model the behavior of vehicle strings under automated longitudinal control in freeway traffic. CACC algorithms were developed and evaluated in simulation. A preliminary hazard analysis was performed, and a safety concept established for DSRC-enabled CACC.

Overall it was shown that, through use of data exchanged via DSRC, improvements in string-stability may be realized. Reduced time gaps within a string of equipped vehicles may also be feasible, if close attention is paid to the additional functional safety requirements. These results were obtained in simulation and will need to be verified through vehicle implementation in Phase 2 of the research plan.

Significant progress was made on each of the specific technical goals established at the outset of the project.

Technical Goal 1: Increase Situational Awareness
The CACC algorithm developed demonstrated enhanced awareness of and reaction to downstream traffic perturbations beyond the immediately preceding vehicle. Software modules that identify which vehicles are part of the same string were implemented and a concept for the anticipation of cut-in and cut-out maneuvers was tested.

Technical Goal 2: Reduce System Latency
In comparison to baseline performance of the reference ACC system, the CACC algorithms implemented showed slightly improved vehicle string response times using knowledge of the current state of preceding vehicle(s) and significantly improved response using future state (acceleration) forecast(s) exchanged using DSRC.

Technical Goal 3: Optimize Time Gap
CACC algorithms were characterized using reduced time gaps and were shown to perform appropriately under most conditions. An algorithm that dynamically adjusts time gap based on current performance conditions was implemented and evaluated.

The following sections summarize the key findings discussed in the body of the report, provide recommendations to further evolve CACC research grouped by topic, and recommend next steps necessary for potential deployment of CACC:

1. ACC Baseline Performance
2. CACC Algorithm Development
3. DSRC Messaging
4. Functional Safety
5. Next Steps

6.1 ACC Baseline Performance

6.1.1 Response Lag

For ACC vehicles driving in a string, a reaction time from one vehicle to another of ~1.5s was identified for the reference system implemented. The first half of this lag appears to be the result of sensing and processing delays. The second half is the result of implementing the desired system reaction. DSRC-enabled CACC can improve system performance by reducing the first half of the observed response delay. For more details, see Section 2.3.1 Response Lag Analysis. .

6.1.2 Performance Harmonization

Characterization testing of the prototype ACC vehicles revealed that, even with a uniform ACC algorithm implemented in each vehicle, following performance differs significantly. ACC strings were observed breaking up during acceleration maneuvers. These effects were amplified by road grade.

This behavior was the result of differences in the way each OEM manages their production ACC interface with the vehicles' brake and engine control systems and restrictions intentionally placed on system response.

Although CACC is expected to improve string behavior, a certain level of harmonization is needed across individual vehicle acceleration / deceleration performance. The importance of this harmonization increases with reduced time gaps. For this purpose, minimum performance requirements for CACC vehicles are proposed in Section .4.3 Performance Requirements.

6.1.3 Road-Grade Effect

The longitudinal control performance of prototype ACC vehicle strings was significantly impacted by road grade, as individual vehicle systems did not compensate for the acceleration / deceleration due to grade. Prototype ACC string performance became unstable as a result. These findings are discussed in detail in Section 2.3.4 Impacts of Grade.

6.2 CACC Algorithm Development

6.2.1 Extending ACC

The project implemented CACC using an existing ACC longitudinal controller without any modifications. Benefits were realized by optimizing the input variables sent to the ACC controller based on the additional knowledge in the CACC platform (Section 4.1.2.5 Virtual Target Creation). This approach may enable adaptation of longitudinal control systems found in ACC or automated driving vehicles to CACC.

6.2.2 Vehicles as Individual Agents

The prototype CACC system developed in this project understands vehicles as individual agents that form their own decisions. The situation is always analyzed from the perspective of the host vehicle considering driver inputs and downstream vehicle behavior(s). At a minimum, the behavior of the immediately preceding vehicle is addressed, but vehicles further down the string may be considered as well. This approach allows for autonomous operation with information received from equipped vehicles nearby. By avoiding the need to determine and communicate with a string ‘leader; this approach is less affected by potential communication issues (e.g., string length is not limited by available DSRC range) and the risk of responding to third party commands that cannot be verified with local sensors is eliminated.

6.2.3 Look-Ahead Concepts

Simulation results (Section 4.2.7 Evaluation of Look-Ahead Concepts) suggest that CACC implementation based on OVLA, where each vehicle evaluates information only from the immediate preceding vehicle, can provide string-stable performance. Using acceleration status and forecasts from the preceding vehicle, it appears feasible to realize the benefits of CACC using a simple OVLA approach at a 1s time gap.

When considering information received over DSRC from MVLA, accurate lane assessment is necessary to reduce false positives and false negative responses. Prior research suggests that this can be accomplished by concepts where a sensor data is exchanged between vehicles and the results of downstream vehicles' object fusion algorithms can be received and evaluated by the host vehicle [13].

The prototype CACC system proposed utilizes a simpler method to make this determination without sensor data exchange as described in Section 4.1.2.3 In-lane Assessment. This approach utilizes the BSM temporary ID of the preceding vehicle's target vehicle to build a linked list of the vehicles in the string. This establishes a verified list of string members, where each member is validated through sensor fusion. This concept relies on adding target vehicle ID to the BSM data transmitted rather than sensor data, minimizing the impact on message size.

6.2.4 Lane-Change Detection

Analysis of data collected during prototype ACC vehicle testing (Section 2.3.3 Lane-Change Detection Analysis) found that assessment of individual parameters is insufficient for reliable lane-change detection.

An algorithm that estimates lead vehicle lane-change probability based on multiple weighted parameters was implemented in simulation. The resulting performance suggests that a multi-parameter lane-change detection may be feasible but that additional testing and improvements beyond this project are required as the current implementation is not robust.

The following steps were identified to potentially improve multi-parameter lane-change detection performance:

1. The weights and parameters of the lane-change detection require additional tuning based on simulations or, preferably, vehicle testing.
2. The algorithm needs to separate individual lane-change maneuvers and allow vehicles to settle after a lane change to improve reliability.
3. The algorithm should be tested in additional scenarios such as curved roads, greater number of cars, multiple / simultaneous cut-in / cut-out maneuvers.
4. Machine learning approaches should be evaluated for their potential to improve lane-change detection performance.

6.2.5 Reduced Time Gaps

Simulations of the proposed CACC algorithm show string-stable behavior at a time gap of 1s or more, even for the simplest OVLA mode of operation (Section 4.2.7 Evaluation of Look-Ahead Concepts). However, for shorter time-gap operation, additional restrictions need to be considered:

1. Obtaining current measured acceleration from the preceding vehicle through its BSM improves performance compared to ACC but doesn't support a reduction in time gap. Time gaps below 1s should only be selected if an acceleration forecast is received from the preceding vehicle which is also under CACC control.
2. When operating with a reduced time gap, early responses are desired but harsh responses degrade string-stability. Concepts such as MVLA and adapting time gap based on a preceding vehicles' brake activation can significantly improve string stability and adherence to the set time gap. Careful parameterization of these features is required to maintain stability.
3. Vehicles with slower responses to deceleration commands should restrict selectable time gaps accordingly.
4. Analysis suggests that driver assumption of control may be necessary for harsh braking events in both ACC and CACC modes (Section 4.2.8 Emergency Braking Events). Restricting allowable minimum time gap for vehicle response characteristics may mitigate this need, especially for vehicles with slower response characteristics.

6.2.6 Set Speed

The concept of set speed may need to be revisited for CACC strings. Traditional CCC and ACC systems are designed to maintain a driver selected speed. In addition, ACC systems perform gap control. However, neither system is designed to exceed the driver selected speed. Simulation of CACC system performance (Section 4.2.4 System Set Speed) suggests that gaps between CACC vehicles in a string increase during dynamic driving when their target speeds are set to the same value. If a tighter cohesion in a string is desired, the traditional concept of set speed needs to be revisited.

6.2.7 Vehicle Jerk

Analysis of vehicle jerk levels was conducted by introducing a naturalistic driving pattern as an input perturbation into a string of ACC / CACC vehicles (Section 4.2.5 Jerk Comparison). The resulting jerk patterns for ACC and CACC strings indicate that jerk increases from vehicle to vehicle in case of ACC and decreases from vehicle to vehicle in case of CACC. The maximum jerk level in the ACC string was 6 m/s^3 observed at vehicle 5 compared to 1.5 m/s^3 for CACC vehicle 5. The maximum jerk level in the CACC string was 2.5 m/s^3 observed at vehicle 2 compared to 3.5 m/s^3 for ACC vehicle 2.

6.2.8 Road-Grade Effect

The need to report true acceleration over ground is expected to be an important consideration for CACC. If lead vehicle acceleration levels reported over DSRC, both current and forecast, are not adjusted for road grade then uncompensated error(s) are introduced in the following vehicle's longitudinal controller. This effect was explored in simulation in Section 4.2.9 Grade Effects. It was identified that CACC is affected by this issue, particularly if the lead vehicle only transmits current vehicle-dynamics data such as when a manually driven DSRC-equipped vehicle is at the head of a string.

Based on the effects of road grade on prototype ACC vehicle performance and CACC algorithm simulations, the following actions are proposed:

1. SAE J2945/1 should be modified to require grade compensation for longitudinal acceleration transmitted in the BSM. This would provide a more consistent interpretation of the BSM describing the true motion of the vehicle and ensure consistency with acceleration values reports by ASDs (ASDs that calculate acceleration from GPS won't experience grade induced error).
2. CACC vehicles should transmit acceleration forecasts based on target acceleration without any compensations for grade. This way, the forecast describes the true desired motion of the vehicle.
3. CACC vehicles' brake and engine control systems should adjust requested accelerations to avoid unintended speed up or slow down on a grade.

6.3 DSRC Messaging

6.3.1 BSM Extension and Channel Selection

The proposed CACC system was implemented in simulation using BSMs with a small message extension containing necessary data elements transmitted at 10Hz.Section 4.2.3 DSRC Messages to Support CACC) Use of the extension would effectively increase the message size of BSMs from CACC-enabled vehicles by 5%. This lightweight extension would allow the application to "piggyback" on the anticipated deployment of BSMs on channel 172. However, the congestion control algorithm specified in SAE J2945/1 might be inappropriate for CACC. Additional research is required in communication channel selection and congestion control implementation. The outcome of this study should lead to a recommendation to standards bodies on how to proceed for the CACC message definition.

6.3.2 Acceleration Forecast

Acceleration forecasts play an important role in improving CACC performance (Section 4.2.1 String Stability). While CACC implemented using current BSM content improved the reaction time of the control system in simulation, the improvement did not lead to a string-stable, prototype algorithm at time gaps ≤ 1s. However, when the preceding vehicle is CACC enabled and transmits the proposed BSM message extension including its acceleration forecast, significant improvements were realized. Transmitting acceleration forecast data via DSRC appears essential to implementing CACC.

6.4 Functional Safety

The results of the Hazard Analysis (Section 5.1 Hazard Analysis) indicate that the reduced 0.6s time gaps envisioned for CACC operation drives higher system safety requirements requiring a different safety concept for CACC (Section 5.2.1 Comparison between ACC and CACC). Compared to ACC, the concept requires:

1. A three-level monitoring concept to handle higher ASIL levels and unavoidable sensor malfunctions
2. Recovery transitions to mitigate risks after component failures
3. A maximum allowable system deceleration rate of -6m/s^2 to provide sufficient time during the recovery transitions for the driver to assume control

In addition, it was determined that the concept of using dedicated lanes to shield CACC vehicles from surrounding traffic does not lead to relaxed system safety requirements.

6.5 Next Steps

To further evolve the research on CACC and to lay the path for a potential production vehicle implementation, the following next steps are recommended:

1. The algorithm performance of the designed CACC algorithm should be validated in vehicle testing. While the simulation environment used in the project was helpful in designing the algorithms, testing with vehicles will allow for final parameterization.
2. Standardization of a BSM message extension adding additional data elements to support CACC operation should be initiated. In this report, specific data elements, as well as a formal definition of a potential extension, are provided. The implications of congestion control on DSRC channel utilization for CACC remains an open topic that needs further research.
3. Performance requirements for CACC-equipped vehicles are needed to ensure interoperability. A list of potential requirements is provided as a starting point for discussion.
4. The concepts developed in this research to improve string stability may be useful in other sensor-based vehicle automation systems. The applicability of these concepts to other longitudinal control systems beyond CACC should be explored.

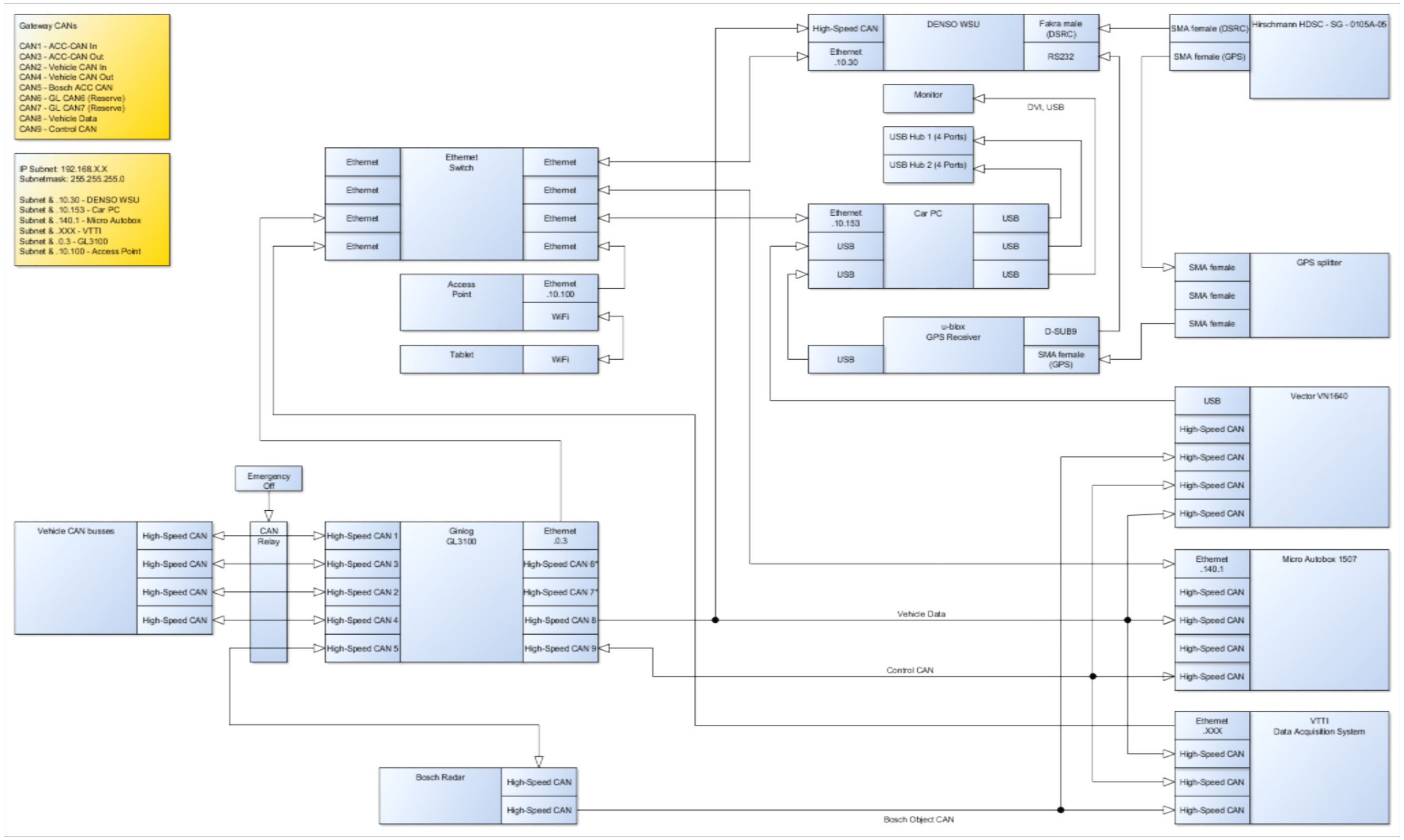
APPENDIX A. List of Acronyms

ACC	Adaptive Cruise Control
ADTF	Automotive Data and Time-Triggered Framework
ASD	Aftermarket Safety Device
ASIL	Automotive Safety Integrity Level
AASHTO	American Association of State Highway Transportation Officials
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CACC-SST	Cooperative Adaptive Cruise Control – Small-Scale Test
CAMP	Crash Avoidance Metrics Partners LLC
CAN	Controller Area Network
CC	Cruise Control
CITE	Communication Induced Tracking Error
CPU	Central Processing Unit
DOP	Dilution of Precision
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communications
ETSI	European Telecommunications Standards Institute
FHWA	Federal Highway Administration
FTTI	Fault Tolerant Time Interval
GMBD	Global Misbehavior Detection
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
HARA	Hazard Analysis and Risk Assessment
HMI	Human-Machine Interface

HOV	High-Occupancy Vehicle
HV	Host Vehicle
I2V	Infrastructure-to-Vehicle
IA	Information Age
ITS	Intelligent Transportation Systems
LMBD	Local Misbehavior Detection
MA	Misbehavior Authority
MAC	Media Access Control
MAP	SAE J2735 Map Message
MBD	Misbehavior Detection
MLVA	Multi-Vehicle Look-Ahead
MPR	Minimum Performance Requirements
MRR	Mid-range Radar Sensor
ns-3	Network Simulation (open source software version 3)
OEM	Original Equipment Manufacturer
OVLA	One-Vehicle Look-Ahead
QM	Quality Managed
RMSE	Root Mean Square Error
RSU	Roadside Unit
RTK	Real-Time Kinematics
RV	Remote Vehicle
SAE	SAE International
SCMS	Security Credential Management System
SDO	Standards Development Organizations
SPMD	Safety Pilot Model Deployment
SST	Small-Scale Test
USDOT	United States Department of Transportation

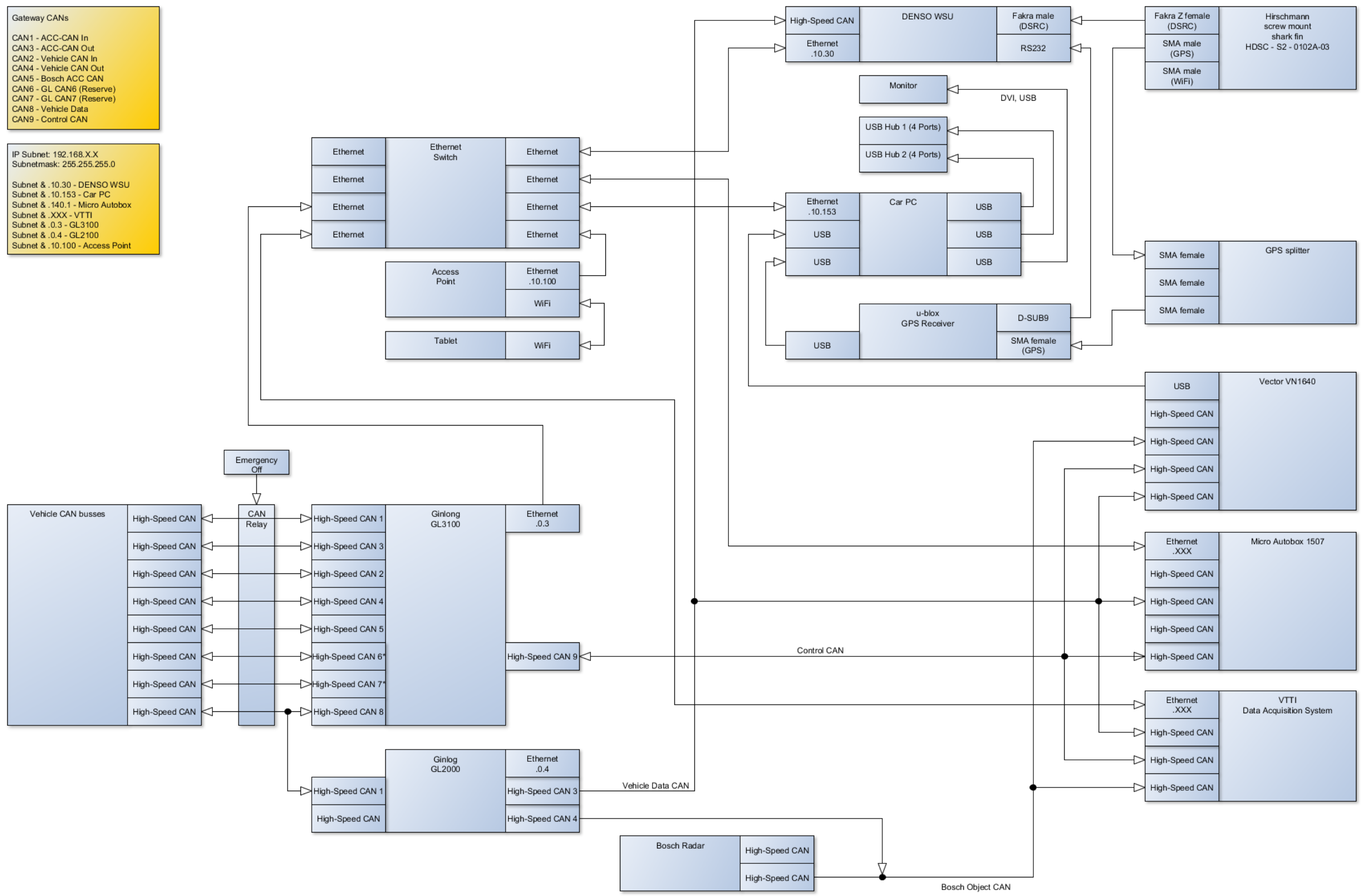
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VCC	Virginia Connected Corridor
VBE	Vehicle Behavior Estimation
VISSIM	Verkehr In Städten – SIMulationsmodell (A Traffic Flow Simulation)
VTTI	Virginia Tech Transportation Institute
WAVE	Wireless Access in Vehicular Environments

APPENDIX B. Hardware Architecture Detail



Source: CAMP V2I Consortium

Figure 102 - Hardware Architecture: Hatchback and Sedans



Source: CAMP V2I Consortium

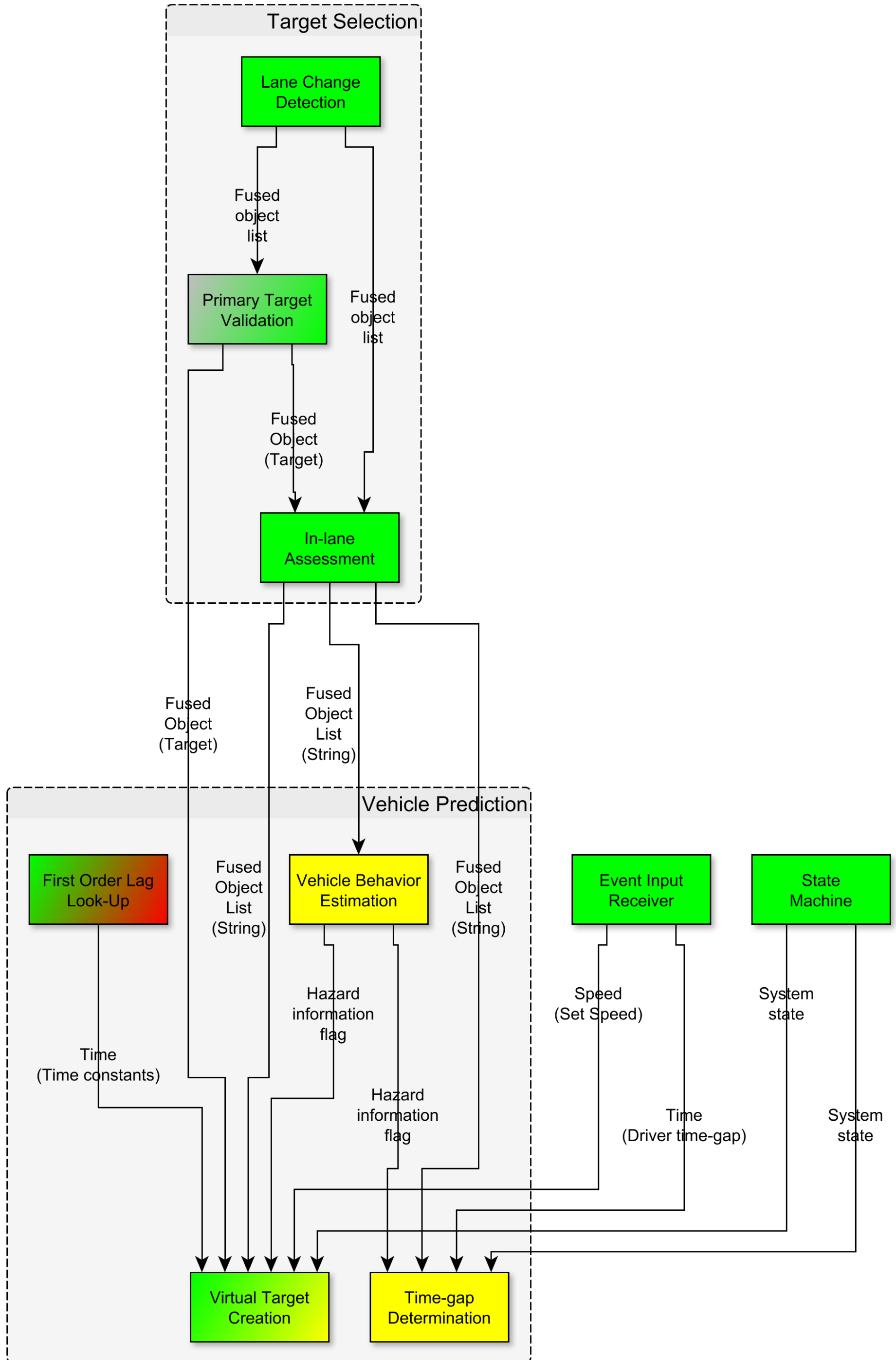
Figure 103 - Hardware Architecture: Large SUV

Table 30 - Vehicle System Hardware Components

Component	Description
Vehicle CAN bus	Proprietary OEM CAN buses that provide access to vehicle status data such as vehicle speed or acceleration
Vector GL3100	A tool for logging the necessary CAN data and Radar data while testing. Vehicle CAN data and Radar data is communicated with Micro Autobox.
Vector VN 1640	Provides access to vehicle CAN network through Car PC
MicroAutobox 1507	Computation unit providing real-time execution of the (C)ACC longitudinal controller software
VTTI Data Acquisition System	During the testing, VTTI's data acquisition system was installed to collect relevant vehicle status data as well as a video feed from four cameras for the later evaluation
Ethernet Switch	Provides access to Vector GL3100
Access Point	Allows tablet to be connected to CACC system wirelessly
Tablet	Display for the Car PC that can display system status information to the driver
Car PC (Spectra PowerBox model 1290Mini-PC)	X86 based automotive ready computing platform
Bosch MRR	Radar sensor used to identify target vehicles
DENSO WSU	DSRC radio that is transmitting and receiving BSMs
Hirschmann Screw-mount Antenna	Combined DSRC and GPS roof-top antenna that replaces or supports the vehicle's main antenna
u-Blox GPS Receiver (model EVK-M8N)	Global Navigation Satellite System (GNSS) Evaluation Kit

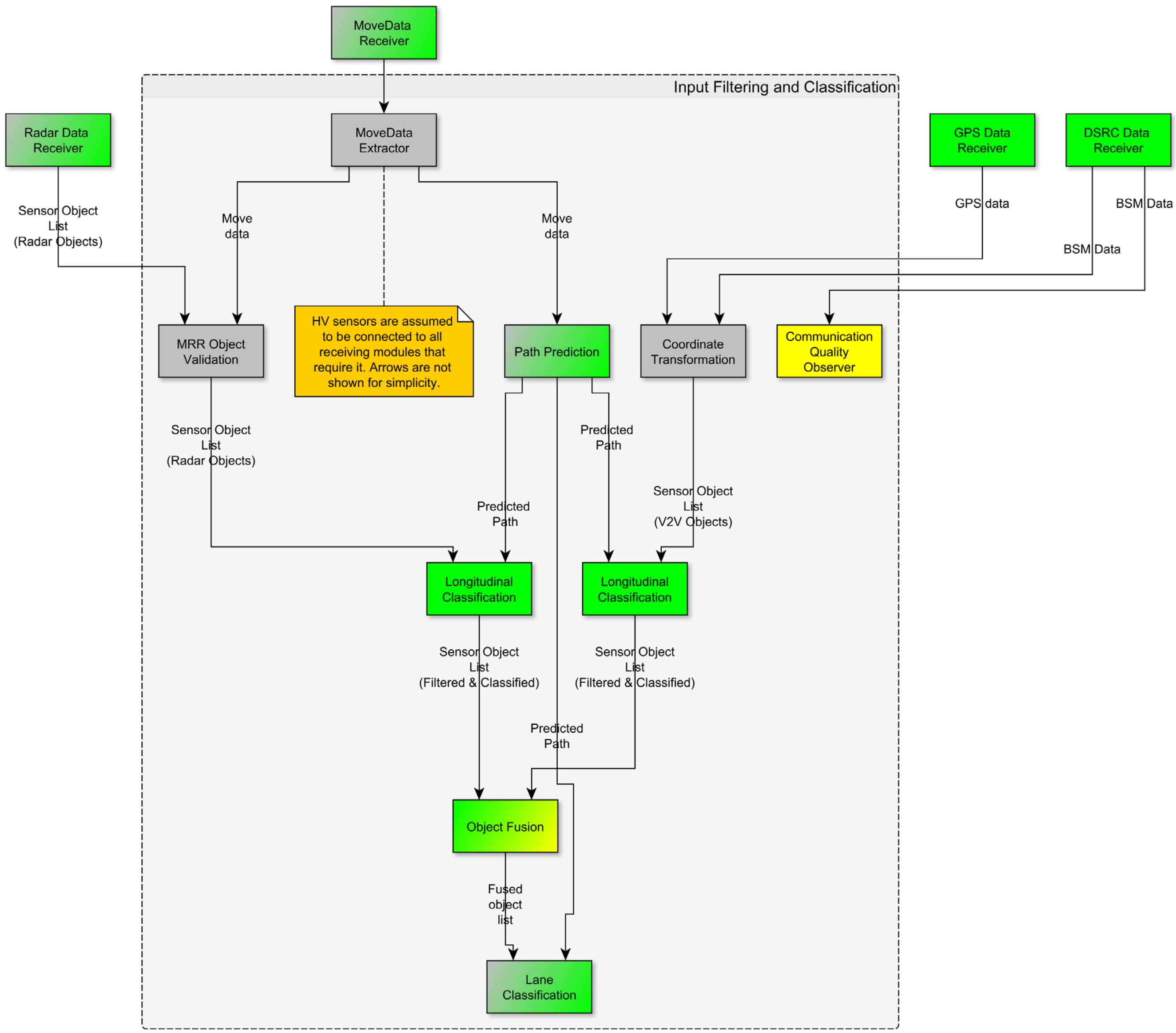
Source: CAMP V2I Consortium

APPENDIX C. Algorithm Architecture Detail



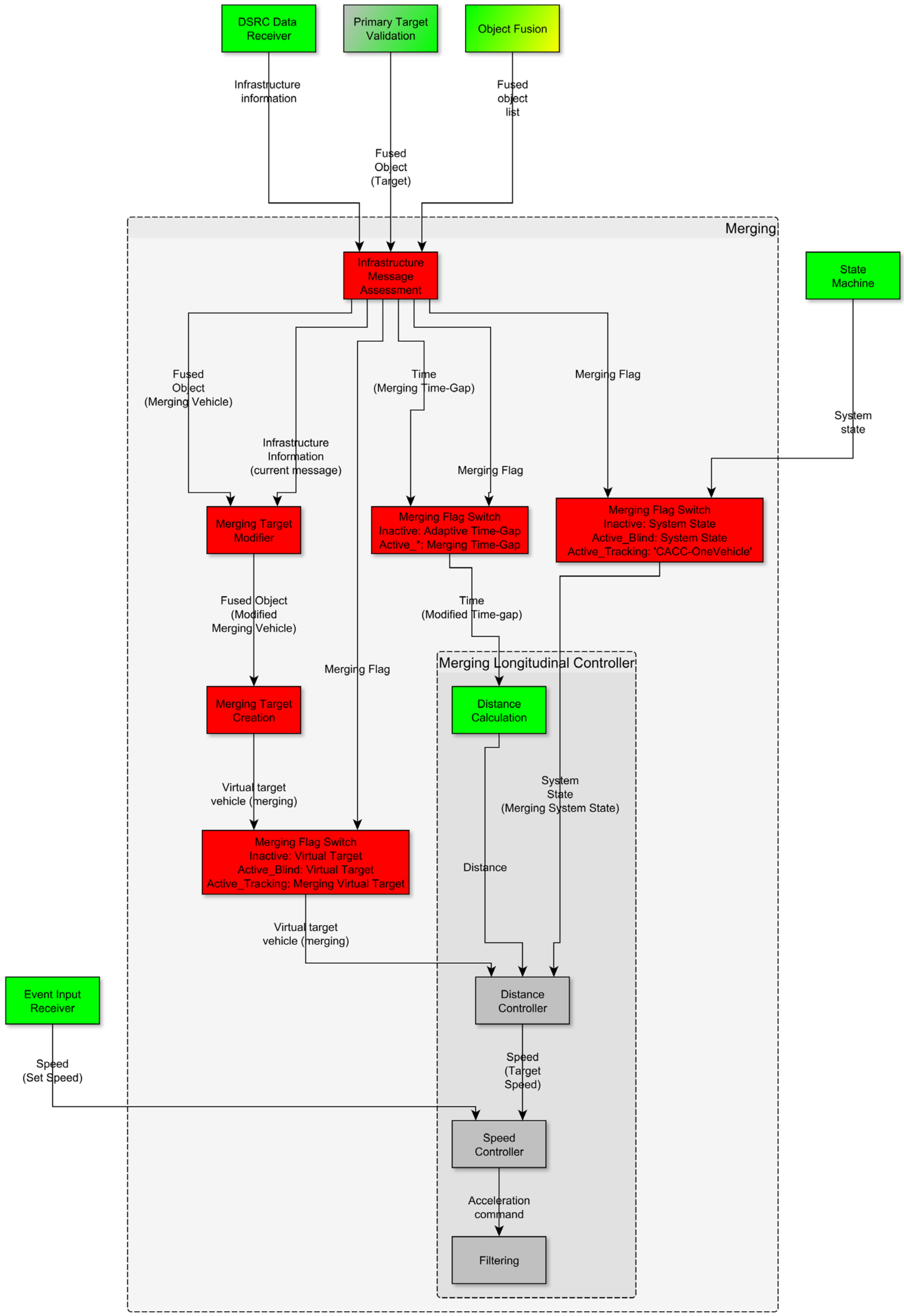
Source: CAMP V2I Consortium

Figure 104 - Software Architecture Detail – Target Selection & Vehicle Prediction



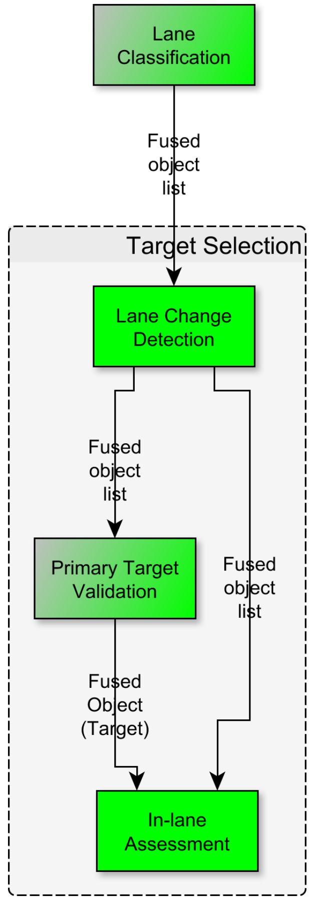
Source: CAMP V2I Consortium

Figure 105 - Software Architecture Detail – Input Filtering & Classification



Source: CAMP V2I Consortium

Figure 106 - Software Architecture Detail - Merging



Source: CAMP V2I Consortium

Figure 107 - Software Architecture Detail – Target Selection

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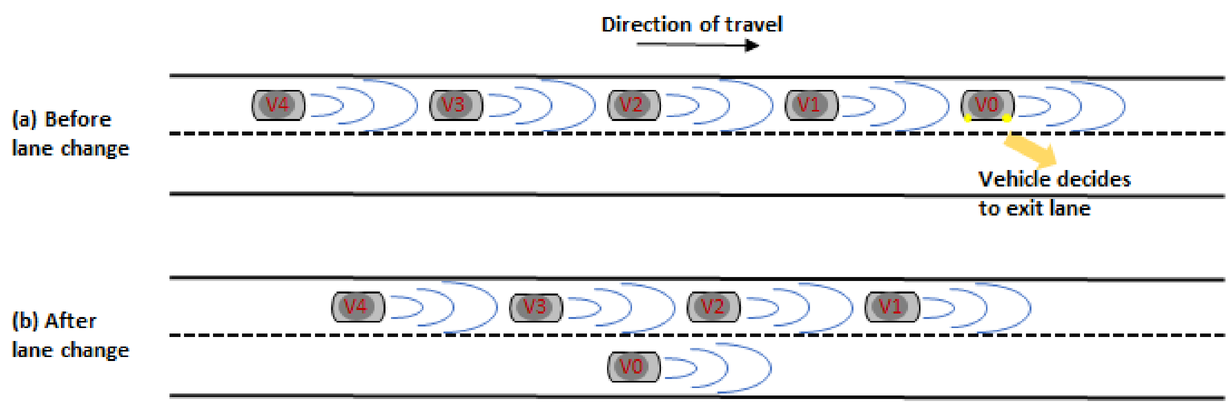
APPENDIX D. Vehicle Test Scenario Detail

T-1 Lane-Change Detection

Description	Four vehicles are driving behind each other with activated ACC systems on the left lane. The lead vehicle has a lower set speed than the other vehicles. The lead vehicle performs a lane change to the right.
Expected outcome	The system in the three rear vehicles detect the lane change and accelerate to the desired set speed of the new lead vehicle, which in this case is the second vehicle in the original ACC string. With CACC, the lane change potentially can be detected (or anticipated) earlier and the reaction can occur earlier and smoother.
Research Question	What is latency between lead vehicle activity and ACC response?
Applicable to	ACC, CACC
Questions	How much path history is needed for CACC?



Start

- V0 – V4: d = 30m (t=1.0s at 30m/s)
- Accelerate to $v_{s0}(t)$ = 20m/s (25m/s) engage ACC
- $v_{s1}(t)$ – $v_{s4}(t)$ = 30m/s => delta = 5m/s (10m/s)
- Hold for string to stabilize (TBD/10s)

Event

- V0 exits lane (start at cone 1, end at cone 2)

Response

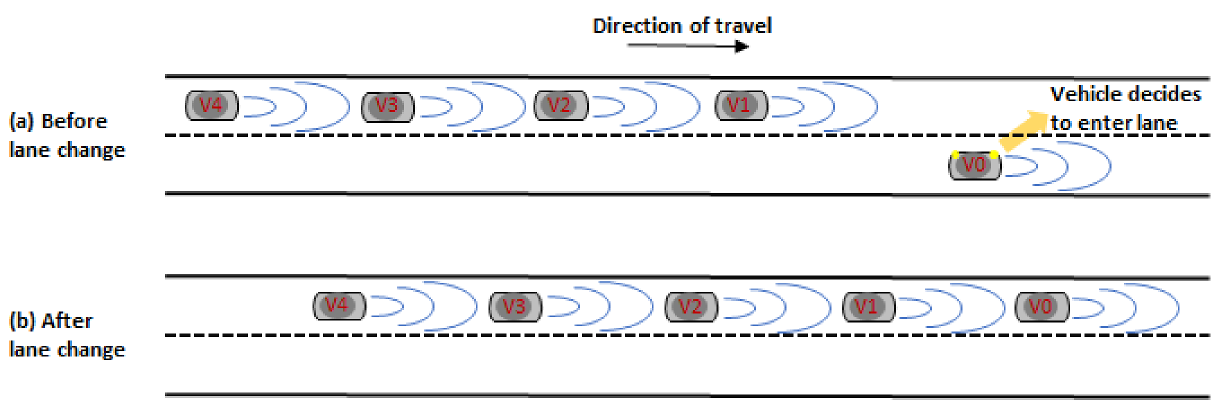
- V1 – V4 accelerate to $v_{s2}(t)$ = 30m/s

Variables

Variable	**Description**
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar.
yaw(t)	Vehicle signal: Yaw Rate
T	Steering wheel angle
RT	Right turn signal status

T-2 Lane-Change Detection 2

Description	Three (C)ACC vehicles are driving together in a string on the left lane. The string approaches another vehicle that is driving on the right lane at slower speeds. Right when the string is about to pass, the vehicle on the right lane performs a lane change into the left lane.
Expected outcome	The following vehicles detect the lane change and decelerate accordingly. With CACC, the lane change potentially can be detected (or anticipated) earlier and the reaction can occur earlier and smoother.
Applicable to	ACC, CACC



Start

- V0: d12 =100m (for ss1 = 25m/s and 10s settle)
- V1 – V4: d = 45m (t=1.0s at ss = 30m/s)
- Accelerate to set speed and engage ACC

Event

- V1 enters lane when t12 = 1s
- Based on deceleration of 3m/s^2, and immediate detection of V0 results in t12_final = ~1 sec
- If there is a 1sec delay for ACC to recognize V0, t12_final = ~0.8m => s1 < 25m/s to get back to s11.

Response

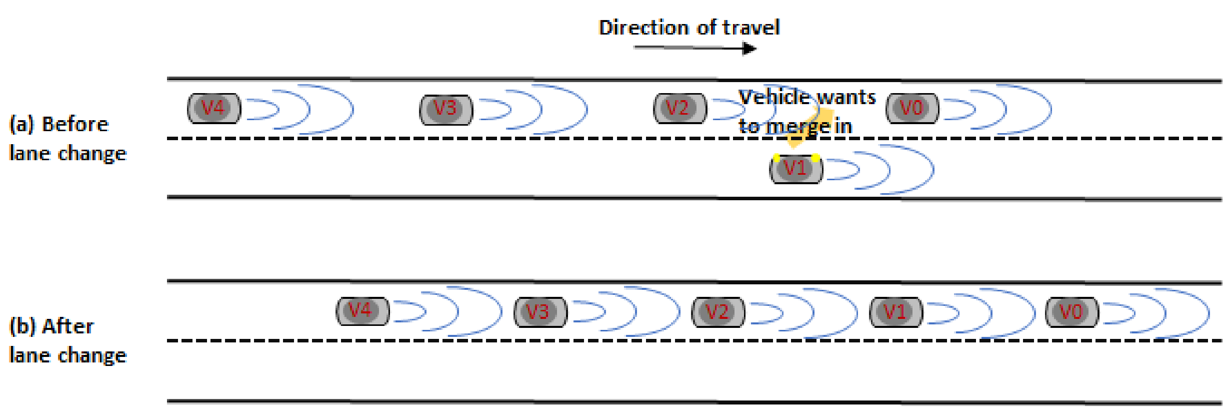
- V1 – V4 slow to $v_{s1}(t)$ = 25m/s

Variables

Variable	**Description**
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar.
yaw(t)	Vehicle signal: Yaw Rate
T	Steering wheel angle
LT	Left turn signal status
B	Brake system status

T-3 Vehicle Cut-In Maneuver

Description	Three vehicles are driving behind each other with activated ACC systems on the left lane. The set time gap between the vehicles supports a fourth vehicle to fit in between. The vehicles pass a fourth slightly slower vehicle driving on the right lane. The fourth vehicle in the right lane activates the left turn signals and performs a lane change when it is between the first and the second vehicle.
Expected outcome	The system in the second and the third vehicle detect the lane change and adapt their speed and time gap to the fourth vehicle. In case of CACC, the reaction occurs earlier and smoother (less maximum deceleration)
Applicable to	ACC, CACC



Start

- V1: d12 =100m (for $v_{s1}(t)$ = 30 m/s and 10s settle)
- V0 – V4: $v_s(t)$ = 30 m/s
- d = 60m (t=2s to allow for cut-in maneuver at 1s)
- Accel to set speed and engage ACC

Event

- V1 enters lane when V0 passes

Response

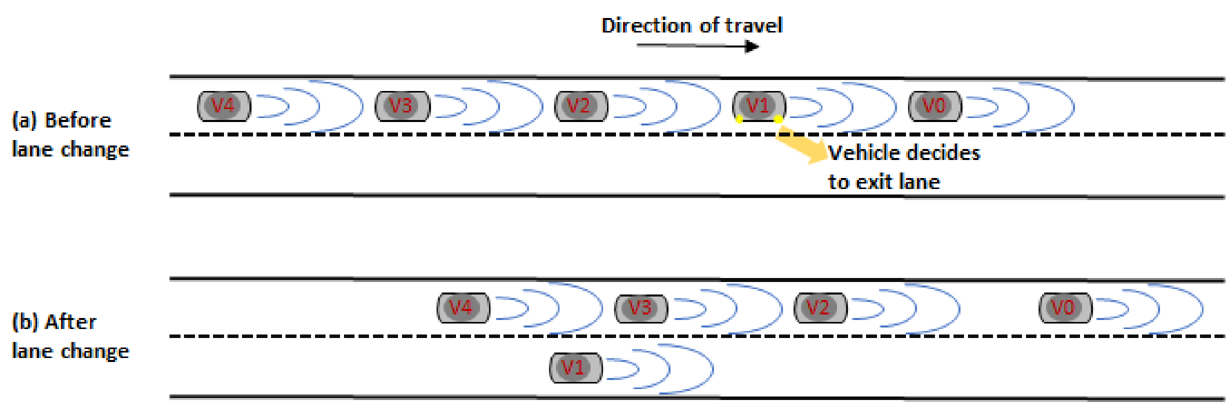
- V1 slows to get t = 2, then speeds up to match set speed = 30m/s
- V2 – V4 slow to reestablish time gap

Variables

Variable	Description
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar.
yaw(t)	Vehicle signal: Yaw Rate
T	Steering wheel angle
LT	Left turn signal status
B	Brake system status

T-4 Vehicle in the Middle Leaves String

Description	Four CACC vehicles are driving together in a string. One of the middle vehicles (2nd or 3rd vehicle) leaves the string.
Expected outcome	Following vehicles speed up to appropriate following distance of first vehicle. Following vehicles may lose signal to lead vehicle if distance gap is too large. With a CACC system, the lane change may be detected earlier, and the system can accelerate smoothly to catch up with the other vehicles in the string.
Applicable to	ACC, CACC



Start

- V0 – V4: d = 60m;
- t = 2sec at 30m/s (t = 1sec => d = 30m)
- Accel to $v_{s1}(t)$ = 30m/s engage ACC
- Hold for string to stabilize (TBD/10s)

Event

- V0 leaves string

Response

- V2 – V4 accelerate to t12 = t23 = t34 = 2s

Variables

For V2 – V4

- s(t)
- a(t)
- v(t)
- Desired acceleration
- Radar x(t), dx(t), y(t)

For V1

- Steering wheel angle
- Right turn signal status
- yaw rate

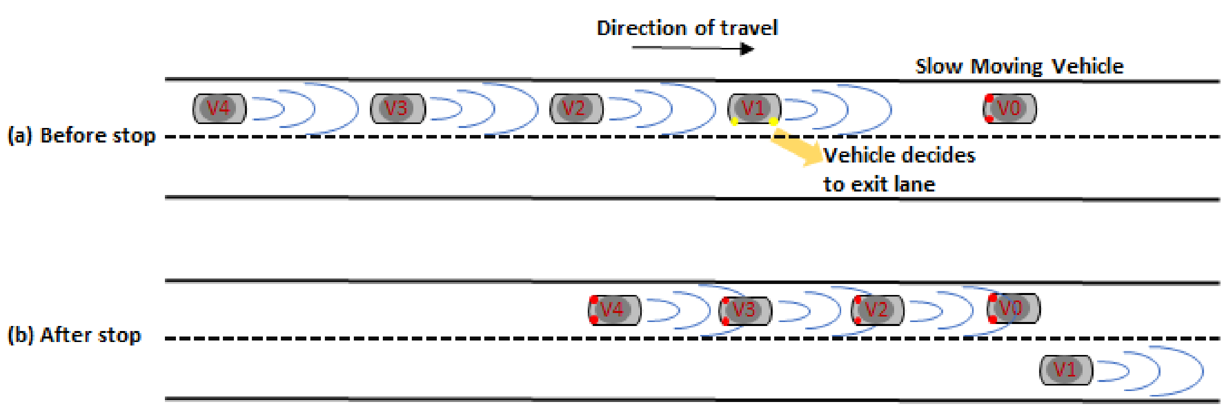
NOTE: full data set (including IMU, CAN, GPS, radar) available for all vehicles in all trials

Variable	Description
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar.

Variable	Description
yaw(t)	Vehicle signal: Yaw Rate
T	Steering wheel angle
RT	Right turn signal status

T-5 Overtaking

Description	A slow or stopped vehicle is on the road ahead. A string of vehicles approaches that vehicle from behind. The driver of the lead vehicle notices the obstacle, activates the turn signal and performs a lane change to overtake. The following vehicles stay in that lane and come to a stop behind the obstacle.
Expected outcome	It can be verified if the deceleration suppression based on the turn signal in the lead vehicle works. For the following vehicles, the obstacle is likely to be detected late (after the lead vehicle changed lanes) requiring a high deceleration value. With CACC, the obstacle can potentially be detected earlier allowing for an early deceleration and/or warning of the driver.
Applicable to	ACC, CACC



Start

- Assumption: V0 is moving very slow (above threshold of radar filter)
- V1 – V4
- d = 45m (t=1.5s at 30m/s)
- d12 = 400m (based on 10s settle time)
- Accel to $v_{s1}(t)$ = 30m/s engage ACC

Event

- V1 changes lane to pass V0 at d01 = 200m
- Set cones to indicate start, exit, and bail

Response

- V2,3,4 detect V0 and come to stop/near stop

Variables

For V1 – V4

- s(t)
- v(t)
- a(t)
- Brake status
- Desired acceleration
- Radar x(t), dx(t), y(t)

For V1 only

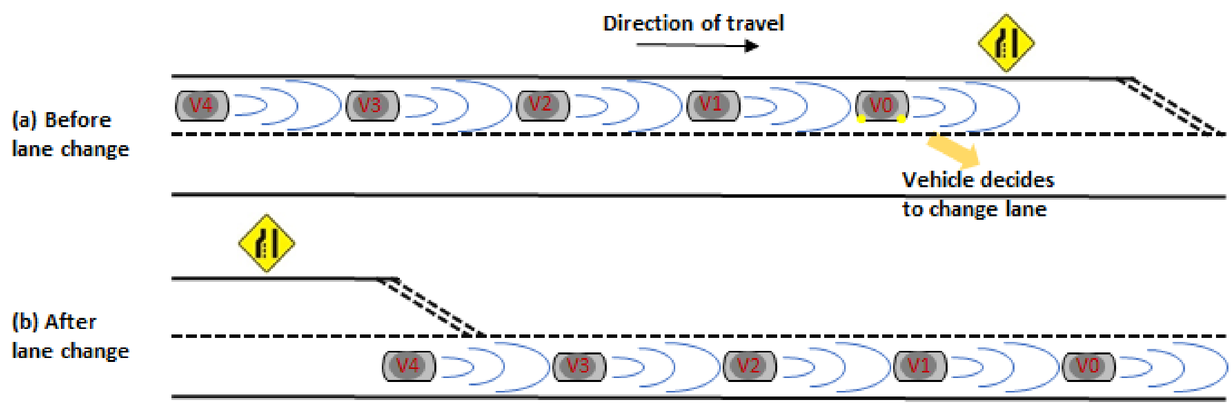
- Right turn signal
- steering wheel angle
- yaw rate

Variable	**Description**
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm

Variable	**Description**
r_{dx}	Longitudinal offset of a target measured by the Radar.
yaw(t)	Vehicle signal: Yaw Rate
T	Steering wheel angle
RT	Right turn signal status
B	Brake system status

T-6 Lane Change Following

Description	A string of vehicles is driving on the same lane. At some point, the lead vehicle performs a lane change, which can be due to road constrains such as left lane merging due to closure. Shortly after, the following vehicle performs a lane change to follow the vehicle.
Expected outcome	The following vehicles for a short period of time lose the target and then reacquire it. Best case, this happens smoothly and fast. With the CACC system, the lane closure might be detected from an infrastructure message or a map and the vehicles might avoid unnecessary acceleration. Also, in case of and implementation of target classification, the vehicles would acquire a target in an adjacent lane before performing the lane-change maneuver, thus adjusting their acceleration and speed accordingly.
Applicable to	ACC, CACC



Start

- V0 – V4: d = 45m (t=1.5s at 30m/s)
- Vary t to try to disrupt string
- Accelerate to $v_{s1}(t)$ = 30m/s engage ACC
- Hold for string to stabilize (TBD/10s)

Event

- V0 changes lane at cone (d = 90m; t = 3s)
- Place V0 in adjacent lane traveling at ss = 25m/s
- V1 – V4 change lane at cone

Response

- V1 – V4 reacquire lead vehicle to join string

Variables

For V1 – V4

- s(t)
- v(t)
- a(t) (irrelevant if set speeds equal)
- Desired acceleration
- Brake status
- Radar x(t), dx(t), y(t) (implies track/target number known)

For V0

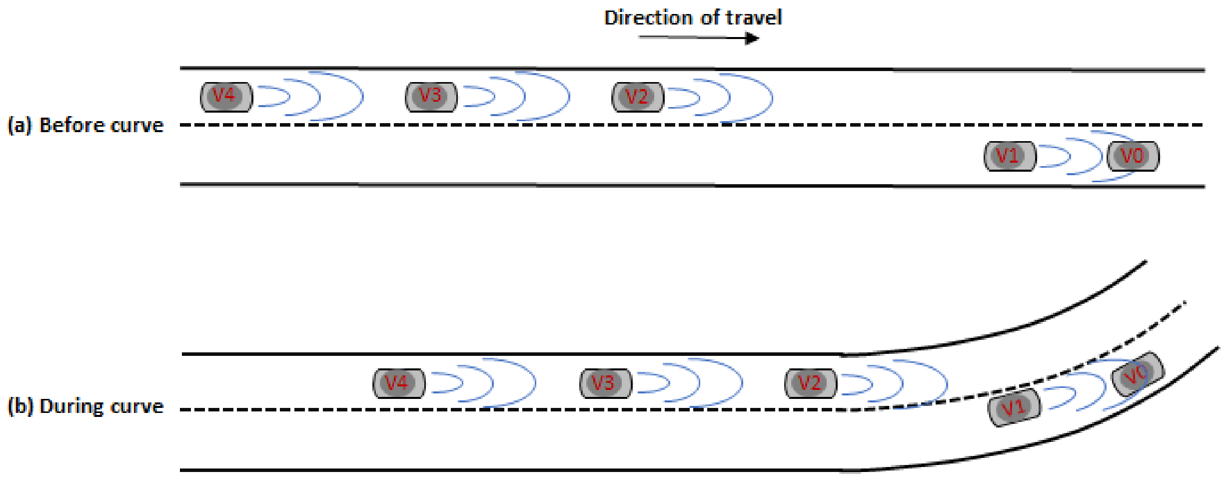
- Right turn signal status
- Yaw rate
- Steering wheel angle

Variable	**Description**
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar

Variable	**Description**
r_{dy}	Lateral offset of a target measured by the Radar
yaw(t)	Vehicle signal: Yaw Rate
T	Steering wheel angle
RT	Right turn signal status
B	Brake system status

T-7 Lane Assignment in a Curve

Description	Two vehicles follow each other on the left lane. They approach two other slower driving vehicles which are driving on the rightmost lane. Right before the faster vehicles pass the other two vehicles, the slower vehicles enter a curve. The scenario can be more challenging if the slower vehicles drive on the leftmost side of their lane.
Expected outcome	Ideally, the faster vehicles should not react on the slower vehicles and pass in between the other vehicles. Potentially there could be errors in the lane assignment that lead to reactions. It will be investigated if they can be reduced with CACC considering path history and path prediction.
Applicable to	ACC, CACC



Start

- V0 – V1 line up in lane 2 (right lane)
- d = 37m (t = 1.5s at $v_s(t)$ = 25m/s)
- V1 starts ~400m before start of curve
- V2 – V4 line up in lane 1
- d12 = 100m
- d = 60m (t = 2.0s at $v_s(t)$ = 30m/s)
- Accel to set speeds and engage ACC
- Repeat for t = 1.0s

Event

- V0 – V1 enter corner when t12 = 1.5 – 2s so they are in the FOV of V2

Response

- V2 - V4 may react to V0 & V1

Variables

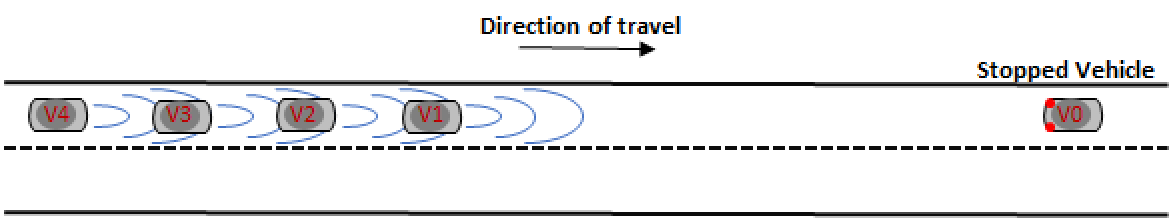
For V2 – V4

- s(t)
- a(t)
- Radar x(t), y(t), dx(t), dy(t)
- Path history & path prediction

Variable	Description
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar
r_{dy}	Lateral offset of a target measured by the Radar
P_h	Path history
P_p	Path prediction

T-8 DSRC Performance

Description	Three (C)ACC enable vehicles follow each other in the same lane at low speeds (15 mph). The order of the vehicles is Sonata, Escalade, Golf, Acura. A confederate vehicle is parked a mile ahead of the other vehicles on the same lane. The vehicles slowly approach the parked vehicle and stop behind it.
Expected outcome	DSRC communication data will be collected to determine the reliability of communication both inside the string and with regards to vehicles ahead. The Sonata acts as a reference vehicle with which the distance for reliable communication with the confederate vehicle will be determined. From the perspective of the Golf (smallest vehicle) which is blocked by the Escalade and Acura, two performance metrics can be assessed: Packet error rate and range for communication with the confederate vehicle ahead (will answer the question how far look-ahead reliably works) Packet error rate for communication with the Sonata two vehicles ahead (will answer the question how reliable two-vehicle look-ahead can be with different vehicle-sizes)
Applicable to	DSRC



Start

- V0 = VTTI supplied vehicle; $v_{s0}(t)$ = 0m/s
- V1 = Sonata; d01 = 1mi; $v_{s1}(t)$ = 5m/s;
- V2 = Acura; t12 = 2s; $v_{s2}(t)$ = 5m/s
- V3 = Escalade; t23 = 2s; $v_{s3}(t)$ = 5m/s
- V4 = VW; t34 = 2s; $v_{s4}(t)$ = 5m/s
- Look at different gaps
- Close and far (1s gap at 30m/s)
- d = 500m
- vs for 2-4 > v threshold

Event

- Transmit numbered packets at different rates

Response

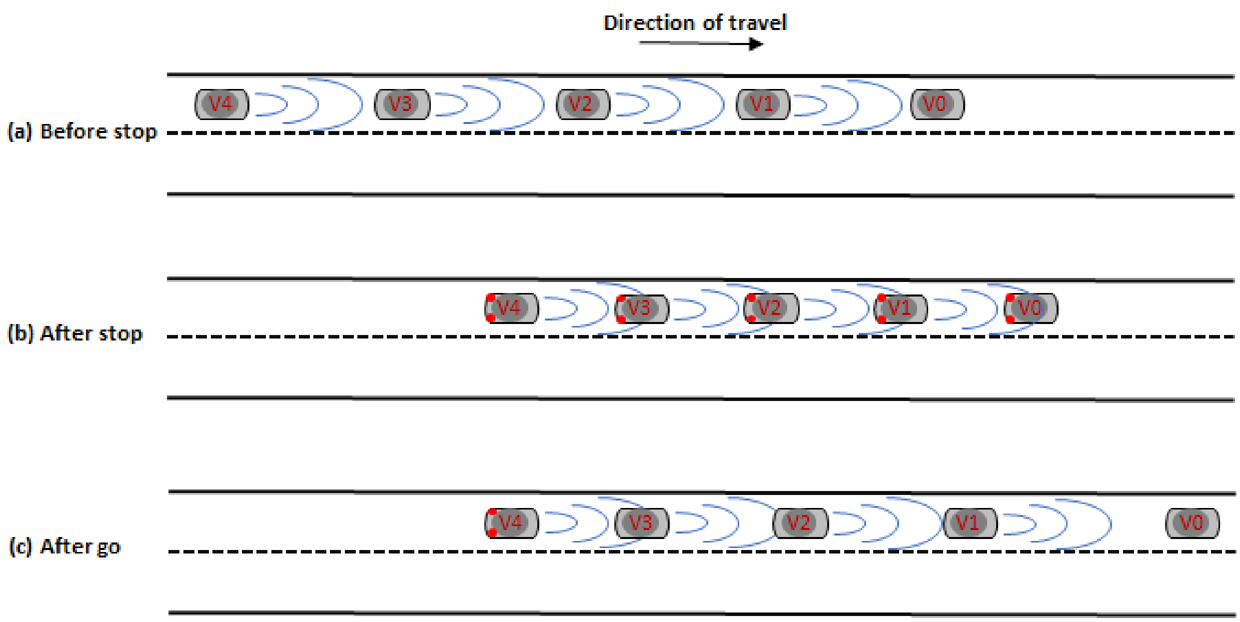
- Measure DSRC performance

Variables

- PER
- RSSI
- Inter-packet gap
- Wireless Message Handler (WMH)

T-10 Stop & Go

Description	Four (C)ACC vehicles are driving together in a string at lower speeds (e.g., maximum of 30 mph). The first vehicle repeatedly comes to a full stop and then accelerates again.
Expected outcome	The following vehicles follow the lead vehicle and come to a full stop when the lead vehicle is stopping. Through manual driver activation, the vehicles accelerate when the first vehicle accelerates. It will be investigated, if reaction times, maximum acceleration, deceleration and jerk can be reduced with CACC
Applicable to	ACC, CACC



Start

- V0 – V4
- d = 20m => t = 1.5s at 30mph (~13m/s)
- Accelerate to $v_{s1}(t)$ = 13m/s engage ACC
- Hold for string to stabilize (TBD/10s)

Event

- V0 slow to stop at $a_1(t)$ = -0.3g
- V0 accelerates to $v_{s1}(t)$ at $a_1(t)$ = 0.3g

Response

- V1 – V4 slow with V0 to stop
- V1 – V4 accelerate to ss1= 13m/s

Variables

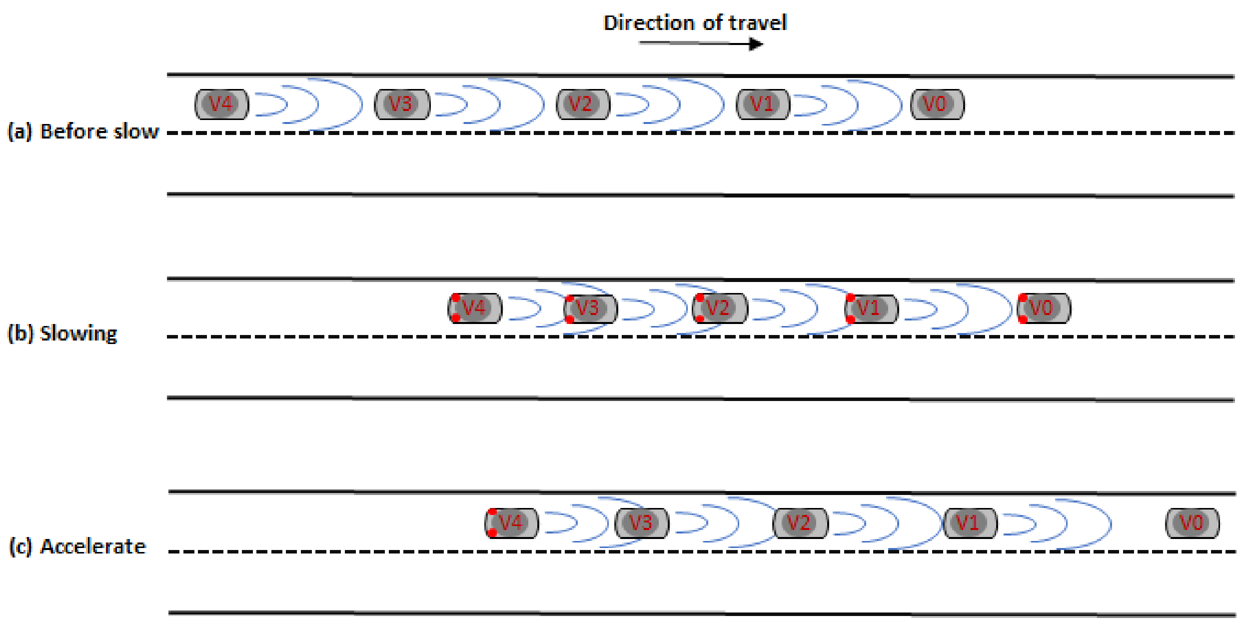
For V2 – V4

- s(t)
- v(t)
- a(t)
- Desired acceleration
- Brake status
- Radar x(t), dx(t)
- ACC state

Variable	**Description**
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar
B	Brake system status
ACC(t)	Vehicle signal: ACC engaged or not

T-11 String Stability

Description	Four (C)ACC enabled vehicles follow each other in the same lane. At some point the first vehicle starts repeated acceleration and deceleration maneuvers
Expected outcome	The following vehicles also start accelerating and decelerating repeatedly. It is likely, that an acceleration and deceleration overshoot will occur from vehicle to vehicle showing string instability. With CACC, this behavior will potentially be suppressed or improved.
Applicable to	ACC, CACC



Start

- V0 – V4
- d = 60m => t = 2s at 30m/s
- Accel to $v_{s1}(t)$ = 30m/s engage ACC
- Hold for string to stabilize (TBD/10s)
- Repeat with t = 1s

Event

- V0 slows to $v_{s2}(t)$ = 20m/s at $a_1(t)$ = -0.2g
- V0 accelerates to $v_{s1}(t)$ = 30m/s at $a_1(t)$ = 0.2g
- Repeat

Response

- V1 – V4 follow V1

Variables

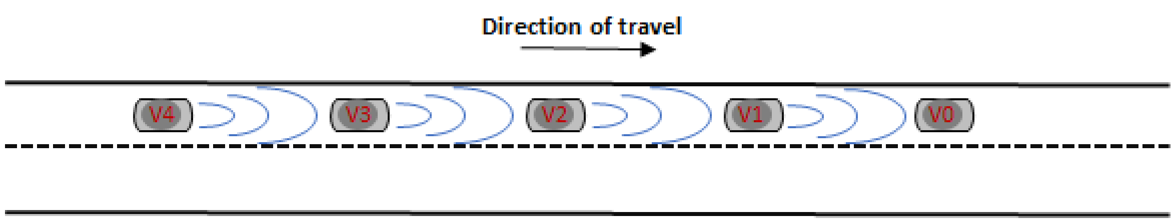
For V1 – V4

- s(t)
- v(t)
- a(t)
- Desired acceleration
- Brake status
- Radar x(t), dx(t)

Variable	**Description**
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar
B	Brake system status

T-13 Weather

Description	A string of vehicles drives on a single lane with time gaps set to maximum. The string drives through a region with heavy rain or dense fog.
Expected outcome	With ACC, the following vehicles might either lose the target (and therefore accelerate) or they could detect the fog/rain as a target and decelerate based on that. If the same scenario is repeated with CACC, the system should be able to detect the malfunction of the object detection and either continue operation for a certain amount of time using V2V only or deactivate the system early. For this scenario, it is critical to ensure that the rain/fog is challenging for the radar sensor. The options for this should be discussed with VTTI and IAV.
Applicable to	ACC, CACC
Questions	Dependent on sensitivity of radar to weather conditions that can be reproduced at VTTI.



Start

- V0 – V4
- d = 40m (t = 2s at 20m/s)
- Accelerate to $v_{s1}(t)$ = 20m/s engage ACC
- Hold for string to stabilize (TBD/10s)

Event

- Rain/fog

Response

- V1 – V4 may change speed based on false return from radar

Variables

For V1 – V4

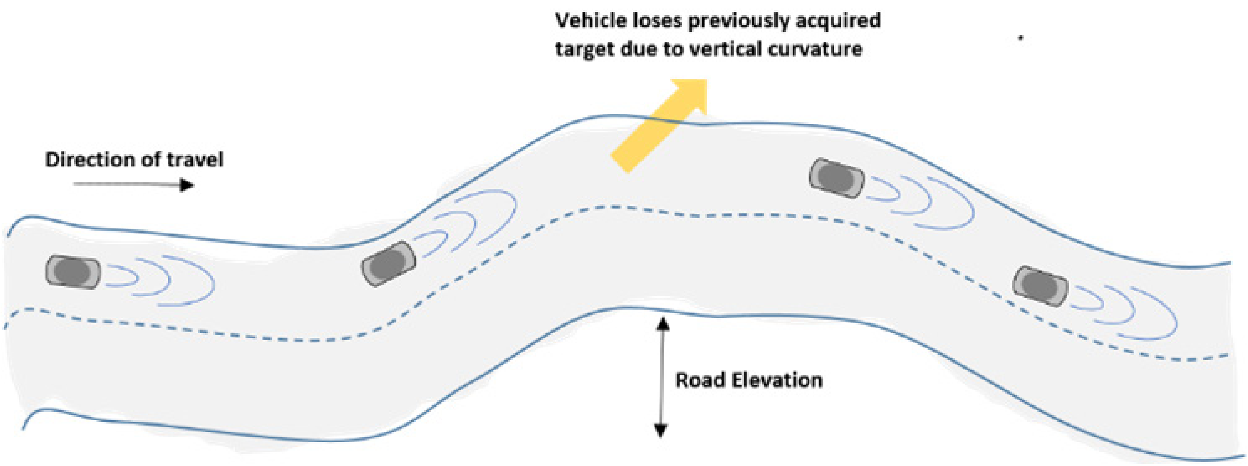
- s(t)
- v(t)
- a(t)
- Desired acceleration
- Brake status
- Radar x(t), dx(t)
- Radar confidence

Variable	**Description**
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar
B	Brake system status

Variable	**Description**
C_r	Radar Confidence

T-14 Vertical Curvature Effects

Description	A string of (C)ACC vehicles approaches a vertical curvature with a considerable grade on either side of the curve.
Expected outcome	The string may split due to loss of target. With CACC, it might be possible to keep the string formed based on V2V communication or at least improve the re-acquisition timing.
Applicable to	ACC, CACC



Start

- V1 – V4
- d = 40m => t = 2s at 20m/s
- Accel to $v_{s1}(t)$ = 20m/s engage ACC
- Hold for string to stabilize (TBD/10s)

Event

- V1 – V4 drive through rolling hill(s) or around curves with line-of-sight blocked
- Lead vehicles leave radar VFOV (or HFOV)

Response

- Following vehicles slow or speed up to set speed till lead vehicle target reacquired

Variables

For V2 – V4

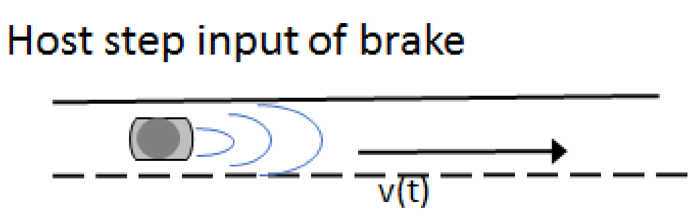
- s(t)
- v(t)
- a(t)
- Desired acceleration
- Radar x(t), dx(t), y(t)
- steering wheel angle
- yaw rate
- Path history

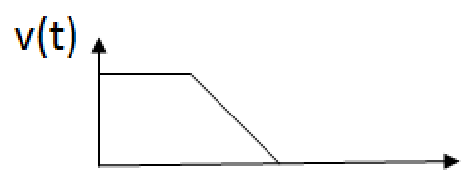
Variable	**Description**
V	Vehicle #
d	Distance
t	UTC time
s(t)	GPS position of the vehicle converted into road x/y coordinates
v(t)	Vehicle signal: speed
$v_s(t)$	ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
r_{dx}	Longitudinal offset of a target measured by the Radar
r_{dy}	Lateral offset of a target measured by the Radar

Variable	Description
T	Steering wheel angle
yaw(t)	Vehicle signal: yaw rate
P_h	Path history

T-17 Brake Pedal Step Inputs

Description	While at constant speed, a sudden large step input of braking is applied at the pedal.
Expected outcome	The vehicle will slow down to a stop.
Research Question	What are brake system response parameters?
Applicable to	Either cruise not engaged or ACC engaged (doesn't matter)
Questions	None





Note: Acceleration value could be achieved using driver expertise, cones to denote start and stop of braking, or dash-mounted accelerometer.

Roadway and Environment

- Flat roadway and dry pavement

Start

- Two trials for each of the four individual vehicles (8 trials)
- v(t) = 45 mph (26.9 m/s)
- Apply a(t) = 3.5 to 4.5 m/s/s braking until v(t) = 0

Event

- Braking applied

Response

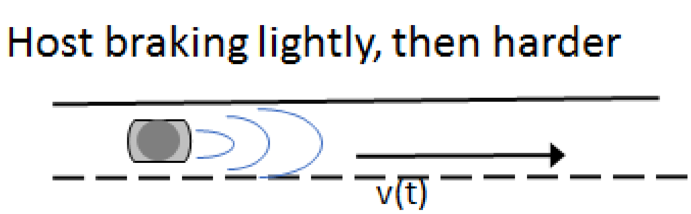
- Vehicle stops, v(t) to 0

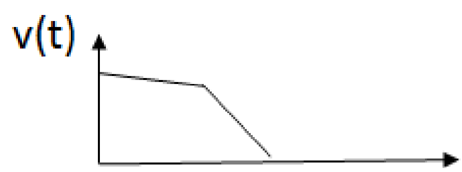
Variables

Variable	Description
$s(t)$	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
$v(t)$	Vehicle signal: speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,v}(t)$	VTTI Sensor longitudinal acceleration, if present
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm

T-18 Brake Pedal Step Input while already lightly braking

Description	While braking lightly, a sudden step input of braking is requested at the driver pedal.
Expected outcome	The vehicle will slow down to a stop.
Research Question	What are brake system response parameters, specifically are they different if the brakes are pre-filled?
Applicable to	Either cruise not engaged or ACC engaged (doesn't matter)
Questions	None





Note: Use driver expertise or a mechanical or electronic decel meter to help the driver achieve the appropriate braking level.

Roadway and Environment

- Flat roadway and dry pavement.

Start

- Two trials for each of the four individual vehicle models (8 trials)
- v(t) = 60 mph (26.8 m/s), cruise not engaged.

Event

- Apply constant a(t) = 0.7 to 1.0 m/s/s braking until v(t) = 45 mph (20.1 m/s)
- Apply step input a(t) = 2.5 to 3.5 m/s/s braking until v(t) = 0.

Response

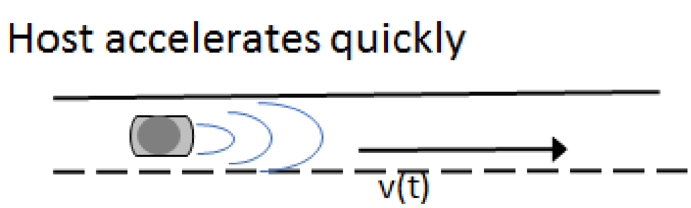
- Vehicle stops, v(t) to 0.

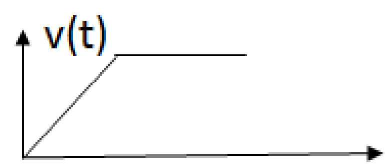
Variables

Variable	Description
$s(t)$	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
$v(t)$	Vehicle signal: speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,v}(t)$	VTTI Sensor longitudinal acceleration, if present
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm

T-19 Max Acceleration

Description	A step input of almost-maximum acceleration is applied to learn about the throttle/powertrain/tractive dynamics parameters.
Expected outcome	The vehicle will accelerate.
Research Question	A step input of almost-maximum acceleration is applied to learn about the throttle/powertrain/tractive dynamics parameters.
Applicable to	Performed without ACC or CACC.
Questions	None.





Roadway and Environment

- Flat roadway and dry pavement.

Start

- This test should be done individually for each of the four vehicle models.
- Two trials should be done for each vehicle model.
- v(t) = 0.

Event

- Apply accelerator hard, reaching 95 to 100% within 2 to 5 seconds.
- At v(t) = 70 mph (31.3 m/s), the test is over, and the vehicle should be brought to rest.

Response

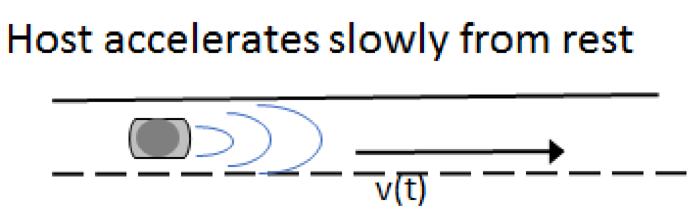
- V(t) reaches 70 mph (31.3 m/s).

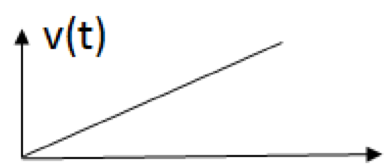
Variables

Variable	Description
s(t)	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
v(t)	Vehicle signal: speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,v}(t)$	VTTI Sensor longitudinal acceleration, if present
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
$a_p(t)$	Accelerator pedal percent from the vehicle (or throttle angle, if pedal not available)
psi(t)	GPS variable: heading angle
RPM(t)	Engine RPM from the vehicle

T-20 Transmission Gear

Description	The host vehicle slowly increases speed from rest to highway speed
Expected outcome	The engine RPM and vehicle speed provide data to know nominal shift points.
Research Question	What are nominal transmission shift parameters?
Applicable to	All, executed without cruise engaged.
Questions	None





Start

- This test should be done individually for each of the four vehicle models.
- One trial per vehicle.
- Start at rest, v(t) = 0

Event

- Apply accelerator pedal to slowly accelerate at approximately 1 mph per second to a speed of 70 mph (31.3 m/sec).

Response

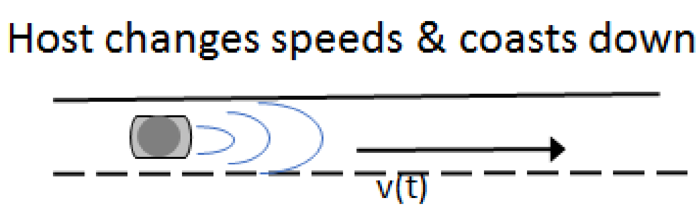
- Vehicle increases speed and the transmission shifts, appearing in the RPM(t) data.

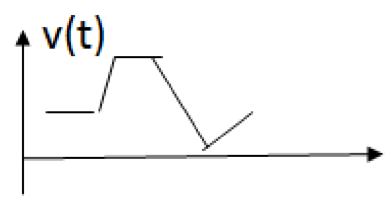
Variables

Variable	**Description**
s(t)	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
v(t)	Vehicle signal: speed
psi(t)	GPS variable: heading angle
RPM(t)	Engine RPM from the vehicle
Gear	Transmission state

T-21 Step Inputs in Set Speed and Coast Downs

Description	A sequence of step inputs of ACC set speed and disengagements and coast-downs are applied.
Expected outcome	Vehicle speed and accelerations will vary.
Research Question	What are parameters of the acceleration and coasting response of the vehicles?
Applicable to	ACC and disengaged driving, as instructed.
Questions	None





Roadway and Environment

- Flat road, wet or dry pavement

Start

- Two trials of the entire sequence below should be performed for each of the four individual vehicle models. There shall be no remote vehicles in this test.
- v(t) = 65 mph (29.1 m/s), and ACC engaged at set speed of 65 mph (29.1 m/s).

Event

- Event #1: Quickly increment ACC set speed to 78 mph (34.9 m/s) and allow 45 seconds to stabilize at the new speed.

The vehicle may be stopped, turned around, or kept moving at this point in preparation for the next steps.

- Event #2 -: Return to 65 mph in any manner, set the set speed to 65 mph and wait for at least 20 seconds for the speed to stabilize. Then quickly increment the set speed to 70 mph and allow 30 seconds for the speed to stabilize at the new set point.
- Event #3: Disengage the ACC from the 70 mph speed, and do not apply any accelerator or brake pedal controls, allowing the vehicle (still in gear) to coast down all the way to 5 mph.

The vehicle may be stopped, turned around, or kept moving at this point in preparation for the next steps.

- Event #4: Return the vehicle to 65 mph in any manner. Set the set speed at 65 mph. While traveling with ACC set speed and actual speed at 65 mph, increment the set speed quickly to 70 mph and allow 30 seconds for the speed to stabilize.
- Event #5: Disengage the ACC from the 70 mph set speed, and change the transmission gear to neutral, if possible. Do not press any accelerator or pedal controls, allowing the vehicle (now out of gear) to coast down to reach 5 mph.

Response

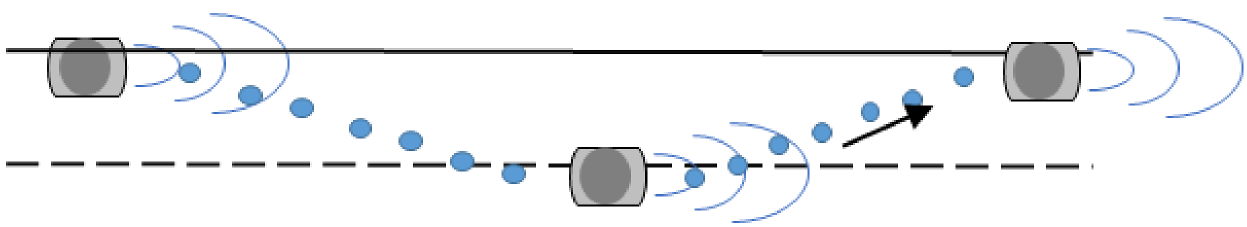
- Vehicle speed and acceleration vary.

Variables

Variable	Description
$s(t)$	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
$v(t)$	Vehicle signal: speed
$v_s(t)$	Vehicle signal: ACC set speed
$a_{lon}(t)$	Longitudinal acceleration measured by the vehicle sensor
$a_{lon,v}(t)$	VTTI Sensor longitudinal acceleration, if present
$a_{lon,d}(t)$	Desired acceleration provided by the ACC algorithm
RPM(t)	Engine RPM from the vehicle
ACC(t)	Vehicle signal: ACC engaged or not

T-22 Lane Changes

Description	The vehicle is driven to simulate lane changes of increasing aggressivity.
Expected outcome	Vehicle motion will be measured to validate vehicle-dynamics parameters and sensor values.
Research Question	What are the simulation parameters associated with the handling model and the lane-change function?
Applicable to	Manual driving or in ACC with appropriate set speed
Questions	



Host vehicle simulates lane changes to right and left, mild to moderate to aggressive.

Roadway and Environment

- Flat or constant grade roadway with constant lane width of 10.5 to 13 feet (3.2 to 4.0 m).
- Dry or slightly wet surface – no rain, flooded pavement, or large puddles

Start

- For each of four vehicle models, two trials would be executed. Each trial includes six lane changes (three to left, three to right). A total of 48 lane changes are then proposed.
- At the start, v(t) = 45 mph (20.1 m/sec).
- ACC should be engaged, i.e., ACC(t) =1.
- The left wheels of the vehicle could be on the left lane marker of a lane to provide the driver with clear cues regarding the desired starting and ending lane positions for the trials.

Event

The driver should execute several lateral motions similar to that of a lane changes, so that the left wheels move from marker “A” to lane marker “B,” which is to the right of the original lane marker. This is done as follows:

- First, execute the first simulated lane change as a “slow” lane change, requiring between 8 to 10 seconds to complete, to the right.
- Second, execute a similar “slow” lane change, to the left in order to put the left wheels back on marker “A.”
- Third, execute a “moderate” lane change, achieving the lateral movement to the “B” marker within 6 to 8 seconds, to the right.
- Fourth, execute a “moderate” lane change to the left.
- Fifth, execute an “aggressive” lane change to the right, requiring 4 to 6 seconds, to the right.
- Sixth, execute an “aggressive” lane change to the left.

Two runs are to be done for each vehicle. The vehicle can be stopped and/or turned around between any set of lane changes.

Response

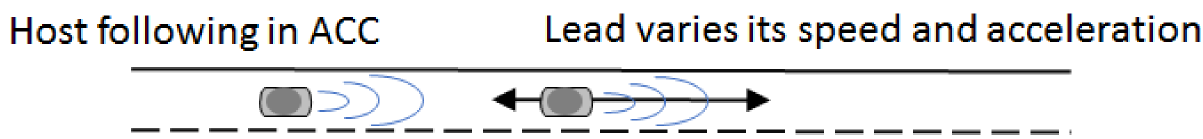
- The vehicle will move laterally to the right and left.

Variables

Variable	Description
s(t)	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
psi(t)	GPS variable: heading angle
v(t)	Vehicle signal: speed
y(t)	Vehicle or VTTI sensor, if present, lane position (useful, not critical)
$a_{lat}(t)$	Vehicle, lateral acceleration
$a_{lat,v}(t)$	VTTI sensor, if present, lateral acceleration
yaw(t)	Vehicle signal: yaw rate
$yaw_v(t)$	VTTI sensor, if present: yaw rate
Width	Lane width measurement is needed

T-23 Following a Lead Vehicle that is Changing Speed

Description	The host vehicle has ACC engaged and follows a lead vehicle which performs several speed change maneuvers.
Expected outcome	Insights into the vehicle control systems during acceleration transition will be found.
Research Question	What, if any, important vehicle control system behaviors occur during acceleration transition that are not found in simple accel/decel tests?
Applicable to	Host (test) vehicle in ACC, lead vehicle not in cruise mode
Questions	None



Roadway and Environment

- Flat surface preferred (if necessary, it is acceptable to conduct on a grade, but would be necessary to know slopes or have five passes of the route with GPS elevation traces to estimate grade).
- Wet or dry pavement or weather conditions are acceptable.

Start

This test should be done at least once individually for each of the four vehicle models.

The test vehicle follows a lead vehicle that changes its speed with different levels of acceleration and deceleration. The exact conditions below are not critical – the purpose is to stimulate the host vehicle commanded acceleration at different levels while collecting data during the entire period, to observe any unexpected dynamic system behaviors of the vehicle throttle and brake control systems during the transitions. If a precise procedure is useful, here is one:

- Host vehicle under test with ACC(t) = 1 (engaged) and set speed $v_{set}(t)$ at 75 mph (33.5 m/sec).
- ACC gap at middle setting.
- Lead vehicle speed $v_0(t)$= 55 mph (24.6 m/sec), so lead vehicle is hindering the host vehicle.

Event

- The lead vehicle should accelerate to 70 mph at a moderate pace (perhaps taking 15 seconds for the speed change), and then maintain that speed for 20 seconds to reach steady state.
- The lead vehicle should conduct a mild slow-down as follows: first, the lead vehicle should throttle down slightly, but not so much as to coast, until the speed is reduced to 60 mph. Perhaps this will take 20-30 seconds, and then speed should be held at 60 mph.
- The driver of the lead vehicle then applies brakes gently until the speed is 50 mph (perhaps 0.1 g), and then hold that speed. (Perhaps 5 seconds of braking.)

- The lead vehicle should then quickly accelerate up to 60 mph and hold that speed for just a few seconds before throttling off (coasting in gear). The vehicle should slow down to 45 mph and hold that speed.
- The lead vehicle should then slow down, as if approaching a stop sign, to about 25 mph, and then increase back up to 55 mph.

Response

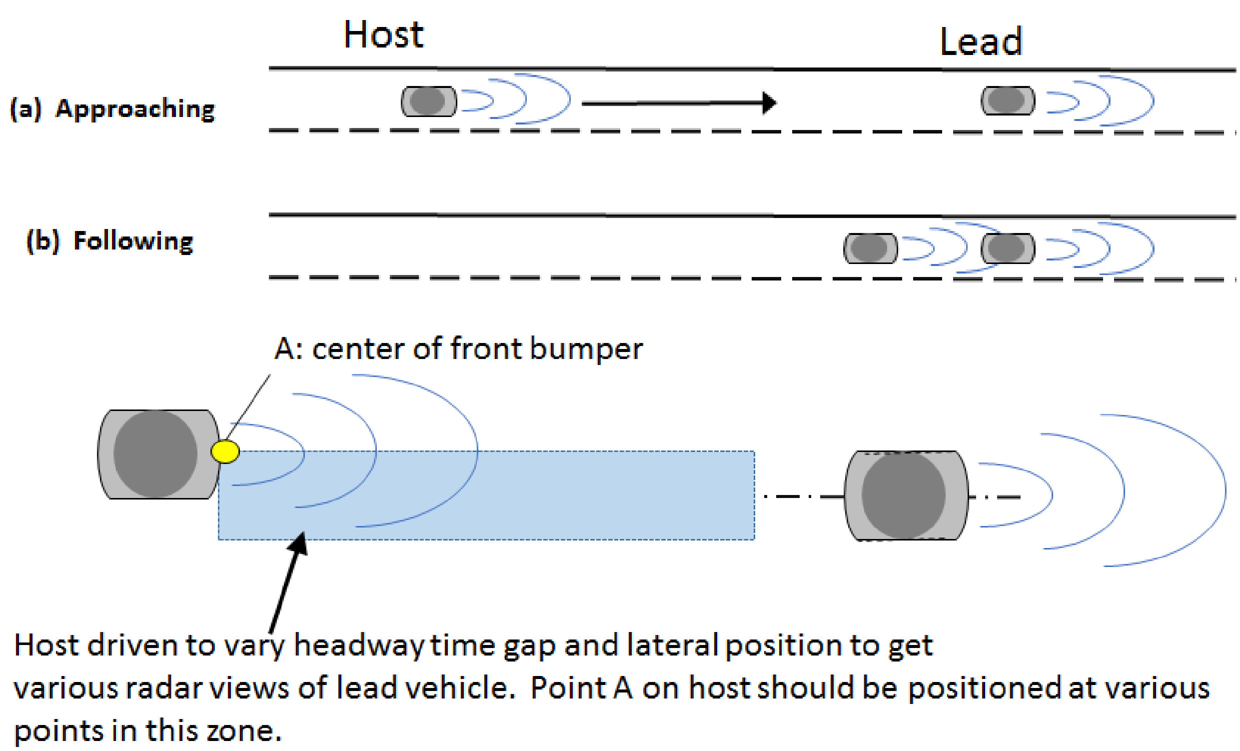
- This host vehicle will respond to the lead vehicle's changing speed by modifying its speed and time gap accordingly.

Variables

For V0 (lead vehicle):	
s(t)	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
For V1 (host vehicle under test)	
s(t)	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
v(t)	Vehicle signal: speed
$v_s(t)$	Vehicle signal: ACC set speed
$a_{lon}(t)$	Vehicle signal: longitudinal acceleration
$a_{lon,v}(t)$	VTTI sensor, if present: longitudinal acceleration
$a_{lon,d}(t)$	Vehicle signal: commanded acceleration
ACC(t)	Vehicle signal: ACC engaged or not

T-24 Radar - Approach and Follow

Description	An ACC vehicle performs approaches to a lead vehicle, as well as following activities to inform radar models.
Expected outcome	Data to set parameter values for simulation radar models.
Research Question	What are the primary target acquisition ranges? What is the jitter in the location of radar tracks along the rear end of a lead vehicle?
Applicable to	ACC or CACC
Questions	None



Roadway and Environment

- Straight road with constant grade sections (no sag or crest). No rain allowed, but wet pavement is acceptable.

Start

- Only one test vehicle is needed, but two lead vehicles are suggested: the 2016 Golf hatchback and the Escalade SUV, representing the extremes of expected target track movement on the rear ends.
- One trial of each of three events or activities needed for each lead vehicle.
- Event #1: begins with the lead vehicle speed at v0(t) = 10 mph (4.5 m/sec), and the host vehicle at a long range (150 m or more) approaching with ACC engaged (ACC(t)=1) and a set speed of vset(t) = 30 mph (13.4 m/sec).
- The host vehicle ACC gap setting should be the smallest gap possible.

Event

Event #1:

- The host vehicle approaches the slower vehicle described above, and reaches a steady state following distance in ACC. The drivers should attempt to drive straight with the longitudinal centerlines of the vehicles aligned as much as possible.
- The host vehicle should then disengage ACC but maintain approximately 10 mph.
- The lead vehicle should accelerate away quickly in order to create data wherein the target track disappears.

Event #2:

- The same sequence should be repeated with the lead vehicle at v0(t) = 20 mph (8.9 m/sec) and the host vehicle approaching with set speed at 60 mph (26.8 m/sec).

Event #3:

- On a different pass of the road/track, the lead vehicle should be in cruise control at 30 mph (13.4 m/sec) and remain driving in the lane center.
- The host vehicle should follow the lead vehicle with ACC disengaged (ACC(t) = 0). The host should maneuver closer and farther from the rear of the lead vehicle, and should also move side to side such that the center of the front bumper of the host vehicle covers points within a rectangle as shown in the figure, with
- closest point of 0.5s (6.7 m) from the rear of the lead vehicle, and farthest away of 4.5s or 60.3 m,
- with host vehicle centerline alignment varying half a vehicle width from left to right of the center of the lead vehicle, as in the figure.

Response

- The radar tracks from the host vehicle will be recorded.

Variables

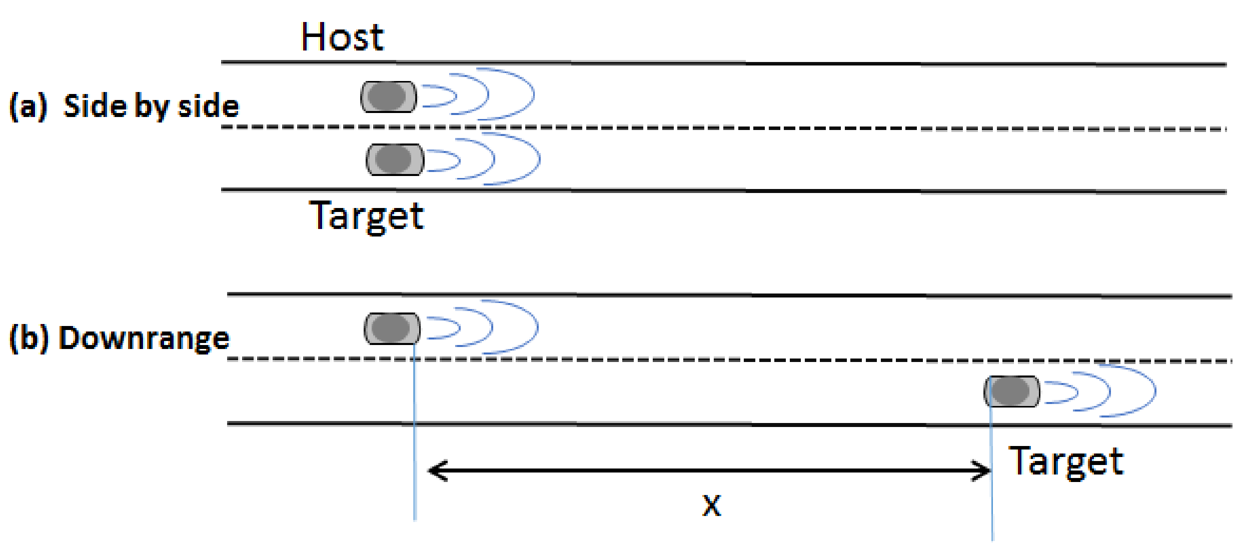
GPS	GPS location, speed, and heading for the lead vehicle
GPS	GPS location, speed, and heading for the lead vehicle
Tracks	All radar tracks from the host vehicle

Variable	**Description**
s(t)	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
psi(t)	GPS variable: heading angle
r_{dx}	Longitudinal offset of a target measured by the Radar
r_{dy}	Lateral offset of a target measured by the Radar

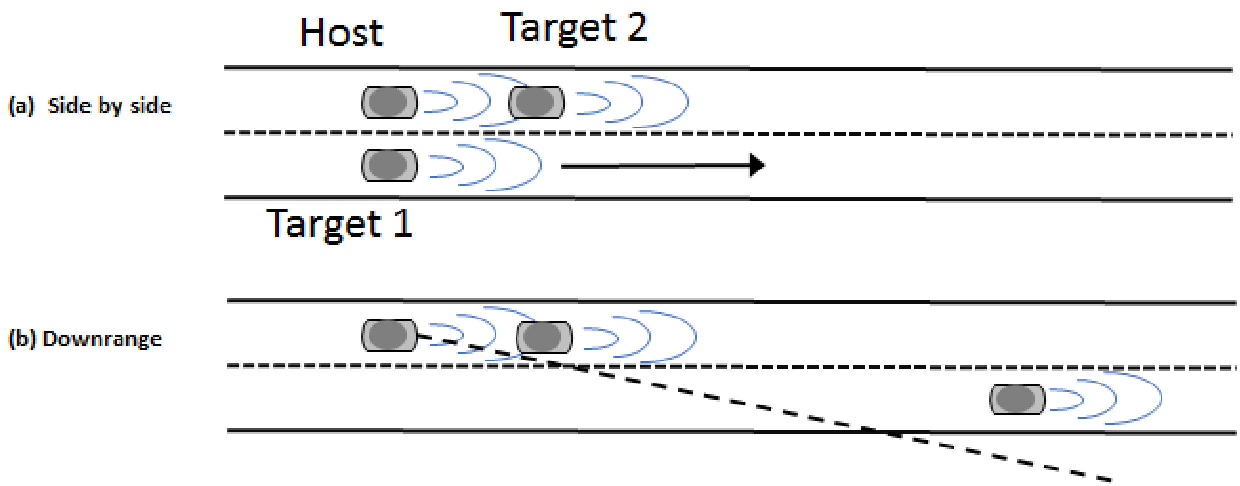
T-25 Radar - Vehicle in Adjacent Lane and Ahead

Description	The radar track data is collected for scenarios in which target vehicles enter or exit the field of view of the radar due to azimuth location or obscuration.
Expected outcome	Data to set parameter values for simulation radar models.
Research Question	What is track behavior like for adjacent lane traffic? What is a good model of how a target vehicle disappears from view due to another lead vehicle blocking the line of sight?
Applicable to	ACC or CACC
Questions	None

Event #1



Event #2



Roadway and Environment

- Straight road with constant grade sections (no sag or crest). No rain allowed, but wet pavement is acceptable.

Start

- Only one test vehicle is needed, but two lead vehicles are suggested for the adjacent lane: the 2016 Golf Hatchback and the Escalade SUV, representing the extremes of expected target track movement on the rear ends.
- Two trials of each of two events or activities needed for each lead vehicle.
- Event #1: begins with the host vehicle and the target vehicle in the figure both at a speed of v(t) = 30 mph (13.4 m/sec), and driving beside each other, as shown in the figure.

Event

Event #1

- The target vehicle then accelerates to approximately 40 mph (17.9 m/sec) within its lane (the adjacent lane) until it is far ahead (100 m).
- The target vehicle then slowly decelerates until it is alongside the host again.

Event #2

- As shown in the figure (b), this activity is identical to the first, except there is a target vehicle at the same original speed of 30 mph (13.4 m/sec) in front of the host vehicle. The host is following using ACC engaged at the nominal gap setting, and the ACC set speed set high enough so that the host vehicle remains hindered by the Target 2 vehicle.
- The target vehicle Target 1 then accelerates to approximately 40 mph (17.9 m/sec) within its lane (the adjacent lane) until it is far ahead (100 m).
- The target vehicle then slowly decelerates until it is alongside the host again.

Response

- The target track lists are collected to allow data analysis to inform simulation models.

Variables

GPS	GPS location, speed, and heading for the lead vehicle
GPS	GPS location, speed, and heading for the lead vehicle
Tracks	All radar tracks from the host vehicle

Variable	Description
s(t)	GPS position of the vehicle converted into road x/y coordinates
$v_{GPS}(t)$	GPS variable: speed
psi(t)	GPS variable: heading angle
r_{dx}	Longitudinal offset of a target measured by the Radar
r_{dy}	Lateral offset of a target measured by the Radar

APPENDIX E. Regional BSM Extension ASN.1

The private regional extension of the BasicSafetyMessage containing longitudinal control information is specified as follows. It is described as a list of necessary changes to be applied on top of the message set in SAE J2735 2016.3.

In the ASN.1 module REGION in SAE J2735, add the following value assignment:

```
    longitudinalControlTestingRegion DSRC.RegionId ::= 129
```

and replace the current definition of Reg-BasicSafetyMessage with the following:

```
    Reg-BasicSafetyMessage DSRC.REG-EXT-ID-AND-TYPE ::= {
        { LONGITUDINAL-CONTROL-TESTING-REGION.BasicSafetyMessage-regExt
IDENTIFIED BY longitudinalControlTestingRegion} ,
        ...
     }
```

Add the following ASN.1 module:

```
  LONGITUDINAL-CONTROL-TESTING-REGION DEFINITIONS AUTOMATIC TAGS ::= BEGIN

    IMPORTS Acceleration, TemporaryID FROM DSRC;

    BasicSafetyMessage-regExt ::= LongitudinalControlExtension

    LongitudinalControlExtension ::= SEQUENCE {
      state            LongitudinalControlState,
      targetID         TemporaryID     OPTIONAL,
      accelForecast    Acceleration    OPTIONAL,
      tau              TimeConstant    OPTIONAL,
      ...
    }

    LongitudinalControlState ::= ENUMERATED {
      manual,
      cc,
      acc,
      cacc-one,
      cacc-multi,
      sensor-auto,
      fused-auto,
      manual-over,
      ...
    }

    TimeConstant ::= INTEGER (0..63) -- Unit is 0.1s

    END
```

APPENDIX F. References

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[4] Mani Amoozadeh et al. Platoon Management with Cooperative Adaptive Cruise Control

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