Traffic Optimization for Signalized Corridors (TOSCo) Phase I Project

Cooperative Adaptive Cruise Control (CACC) Vehicle Build and Testing Report

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16. Abstract

This report documents the work completed in Task 8 of the Traffic Optimization for Signalized Corridors (TOSCo) Project. This project was conducted by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium. The Participants in this project are Ford, General Motors, Hyundai-Kia, Honda, Mazda, Subaru, Volvo Technology of America, and Volkswagen Group of America. This project was sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH6114H00002 and was conducted from July 2017 to March 2019.

The key technical objectives that the project team focused their efforts on in this task of the project were:

- Integrating a Cooperative Adaptive Cruise Control (CACC) system into four test vehicles
- The testing to verify the performance of CACC relative to Adaptive Cruise Control (ACC)
- Detailed comparative data analysis of the vehicle test scenarios

Previous research was conducted in the Cooperative Adaptive Cruise Control – Small Scale Test (CACC-SST) Phase 1 Project (Meier, et al., 2018), wherein, the algorithm used in the CACC implementation was created along with respective simulations investigating the benefits of the CACC algorithm.

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1 Introduction and Background

This report documents the work completed in Task 8 of the Traffic Optimization for Signalized Corridors (TOSCo) Project. Task 8 is comprised of both integrating a Cooperative Adaptive Cruise Control (CACC) system into four test vehicles as well as the corresponding testing to verify the performance of CACC relative to Adaptive Cruise Control (ACC). This project was conducted by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium. The Participants in this project are Ford, General Motors, Hyundai-Kia, Honda, Mazda, Subaru, Volvo Technology of America, and Volkswagen Group of America. This project was sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH6114H00002 and was conducted from July 2017 to March 2019.

Previous research was conducted in the Cooperative Adaptive Cruise Control – Small Scale Test (CACC-SST) Phase 1 Project (Meier, et al., 2018). In the CACC-SST Project, the algorithm used in the CACC implementation was created along with respective simulations investigating the benefits of the CACC algorithm.

1.1 Vehicle Build

Four prototype ACC vehicles that were built as part of the CACC-SST Phase 1 Project were re-purposed for this project (see Table 1 below). These vehicles were chosen to span the typical range of light vehicle size and 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 experimental CACC or ACC (CACC) system.

Table 1: Vehicle Selection

Vehicle	Function	Type	Length	Width	Height	Weight
0	DSRC Only	Full-size sedan	5.0 m	1.86 m	1.46 m	1500 kg
1	CACC	Hatchback	4.2 m	1.76 m	1.45 m	1350 kg
2	CACC	Large SUV	5.7 m	2.05 m	1.88 m	3300 kg
3	CACC	Mid-size sedan	4.8 m	1.87 m	1.47 m	1600 kg
4	CACC	Full-size sedan	5.0 m	1.89 m	1.46 m	1800 kg

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

1.2 Vehicle Architecture

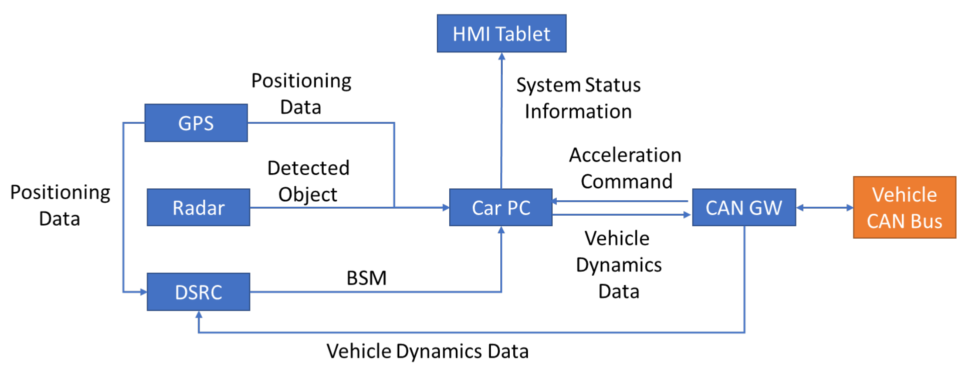
The reference CACC architecture implemented is shown at a high level in the CACC Phase 1 Final Report (Meier, et al., 2018). Both the detailed hardware architecture and the list of hardware components are contained in Appendix B of the CACC Final Report (Meier, et al., 2018). This reference architecture was upgraded to provide the functionality required for this project.

The new hardware architecture contains a RADAR sensor connected to Mini-PC (referred in the vehicle architecture as CarPC). This unit hosts the object validation and target selection algorithms.

The CarPC is also connected to a Dedicated Short Range Communication (DSRC) unit, with an inbuilt Global Navigation Satellite System (GNSS) receiver to provide time, position updates and also function as a Network Time Protocol (NTP) server for time synchronization. The DSRC unit was upgraded to transmit and receive Basic Safety Messages (BSMs) with the CACC extension (Section 1.3) as defined in the CACC-SST Phase 1 Final Report (Meier, et al., 2018)**.** The BSMs are also forwarded to the CarPC for object fusion.

A new Human Machine Interface (HMI) to visualize the CACC system status information was developed and is described in Section 1.4.

Sensor object information is then 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 Original Equipment Manufacturer (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 experimental platform into all prototype vehicles.



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

Figure 1. High-level Hardware Architecture for CACC

1.3 DSRC Radio Integration

The CACC-SST Phase 1 Project identified data elements that enhance the performance of CACC and defined a CACC extension to be included with the BSM transmission. During this project the DSRC unit was upgraded to transmit and receive BSMs with the CACC extension. The CarPC – DSRC CAN interface which earlier provided the current vehicle status information (required to populate Host Vehicle (HV) BSMs) was enhanced to also provide the BSM extension content required for CACC. A new CAN message was implemented as shown in Table 2.

Table 2: Signal Information

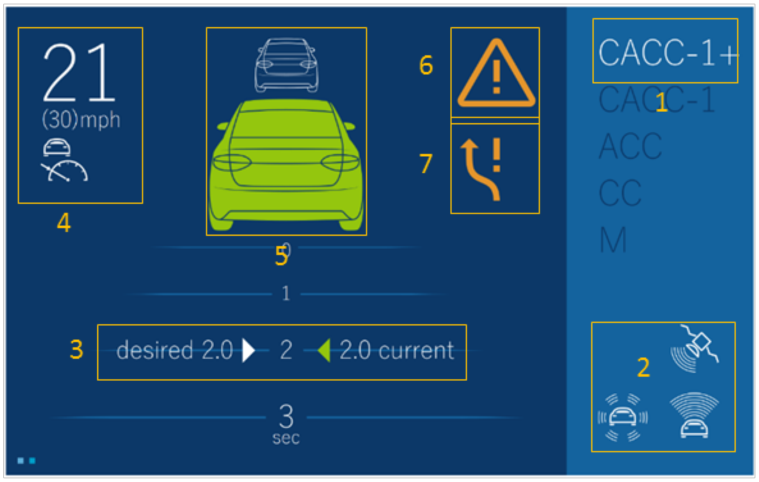
Signal	Start Byte	Start Bit	Length	Data Type	Range	Conversion	Notes
validTargetID	7	7	1	Boolean	0,1	0 not valid / undefined 1 valid	indicates whether the targetID is defined/valid or undefined/not valid
tauTimeConst	4	7	8	unsigned	0 to 6.3 (max 25.4) s	E = N * 0.1	Resolution 0.1 s Value 255 = signal *undefined*
targetID	0	7	32	unsigned	0 to 2^{32}-1 (4294967295)	E = N * 1	validity through additional flag *validTargetID*
LonCtrlState	6	3	4	Enum (unsigned)	0 to 15	E = N * 1 0: manual 1: cc 2: acc 3: cacc-one 4: cacc-multi 5: sensor-auto 6: used-auto 7: manual-over 15: undefined	Value 15 = signal *undefined*
accelForecast	5	7	12	unsigned	-20.00 to 20.00 m/s^2	E = N * 0.01 - 20.00	resolution 0.01 m/s^2 E value 20.01 = signal undefined (int N = 4001)

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

1.4 HMI Integration

A new HMI to visualize the CACC system state was developed for research use only. The information displayed on the HMI (as shown below in Figure 2) includes the HV sensor status (GPS, CAN, and radar), CACC system state, set speed and current HV speed, set time gap and instantaneous time gap and vehicle detection status.

CACC Vehicle HMI



1. HV is in Multi-Vehicle Look-Ahead mode
2. HV sensor status is good (GPs, Radar, V2V)
3. ACC time-gap setting is set to 2s, and HV is maintaining the 2s time gap
4. HV's cruse is set to 30mph, but its current speed is 21mph to maintain the time gap with target vehicle
5. Icon showing multiple vehicles ahead (consistent with 1.)
6. HV detected a hard braking from vehicle ahead
7. HV detected a lane change maneuver from vehicle ahead

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

Figure 2: In-vehicle Tablet HMI

1.5 GNSS and Time Synchronization

The CarPC performs real-time computations using time sensitive information from the DSRC unit. Hence, it is very important that internal clocks in the two units are synchronized to a reference time. The DSRC radio uses its inbuilt GNSS receiver, and synchronizes its clock to UTC time. This was also configured as an NTP server for the CarPC to synchronize its internal time.

2 Test Description

2.1 Scenario Description

In the CACC-SST Project, different potential test scenarios were defined in order to evaluate an experimental ACC system. A subset of these scenarios was identified to evaluate the performance of ACC and CACC algorithms in simulation environment. During this project, the team chose a set of simulation scenarios to comprehensively represent the majority of the previously defined test scenarios. The scenarios were chosen to better understand the string stability and response time differences between the ACC and the CACC systems and are defined in further detail in Section 4 and Sections 7.3 to 7.6. Setup and Location.

After clearly defining the test setup, a list of assumptions and requirements for a potential testing location was compiled. The test area was divided into 3 sections as described below.

1. Setup/Staging area, where the vehicles are stationed for the test. The length of the setup/staging area was calculated to be approximately 200m with the following considerations in mind:

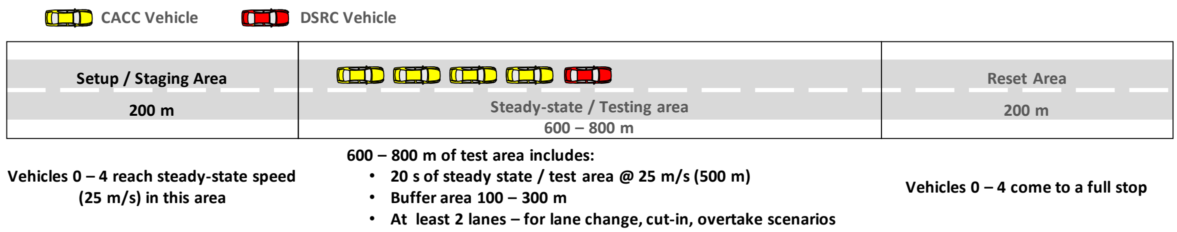
    - Steady state vehicle speed: 25m/s (average speed of the lead vehicle in most scenarios)
    - Initial spacing between vehicles: 25m (equivalent to 1s time gap)
    - Setup area length: up to 200m

2. Steady state testing area, where the vehicle maneuvers (lane changes, braking etc.) are conducted and the system performance is evaluated. The length of the steady state test area was calculated to be 600m – 800m, with the following assumptions:

    - Average steady state test duration: 20s
    - Buffer time for test: 10s (approximate)
    - Average vehicle speed: 25m/s
    - Average spacing between vehicles: 25m (equivalent to 1s time gap)
    - Total steady state space – 600 to 800m

3. Rest area, for vehicles to stop after completing the test scenario. The length of an average rest area was assumed to be the same as the setup/staging area (200m).

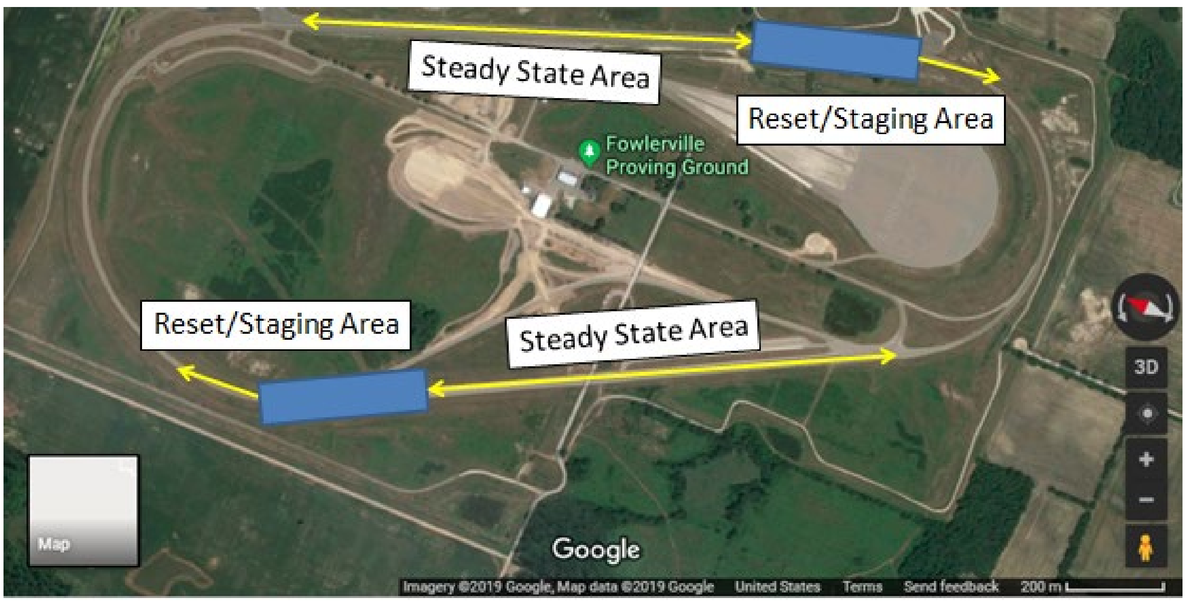
Using these assumptions, the total test track space required was estimated to be 1000m to 1200m. Figure 3 below summarizes the testing area requirements.



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

Figure 3: Testing Setup Area Requirements

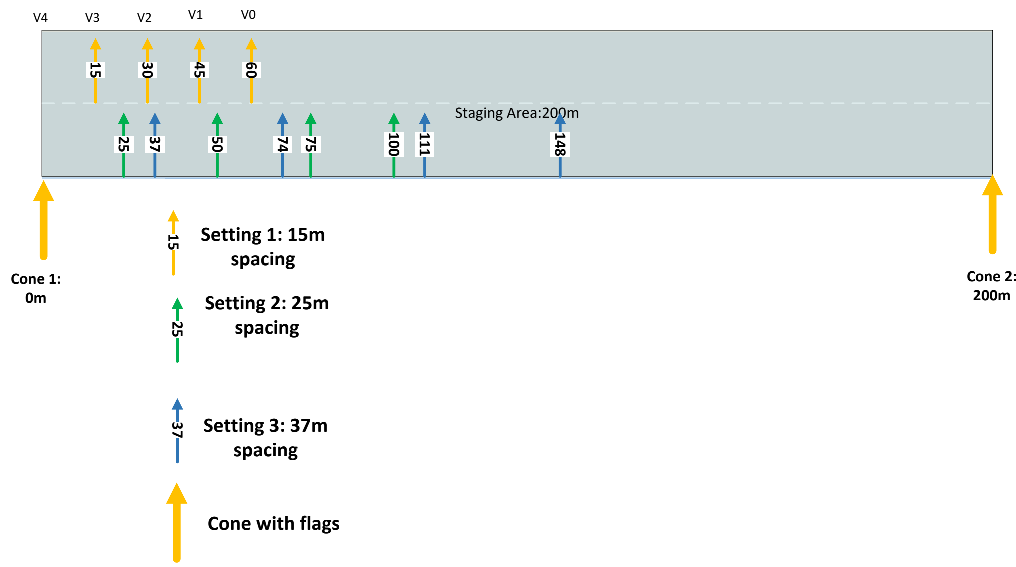
To conduct the test, the FT Techno of America Fowlerville Proving Ground (FTTA) was used. Below (Figure 4) is a map of FTTA's Road D course overlaid with the testing setup diagram. The curves in the road course were used to get the vehicles into a steady state in order to test each scenario on the straightaway.



Source: Imagery ©2019 Google, Map data ©2019 Google

Figure 4: FTTA Proving Ground with Testing Setup

Within the Staging Area, vehicles were positioned at intervals corresponding to the time gap setting of the test performed. The time gaps were either 1.5 seconds, 1 second, or 0.6 seconds, which respectively correspond to Setting 3, Setting 2, and Setting 1 in the Figure 5 below. In this testing, CACC and ACC were both compared at a 1 second time gap, as larger time gaps fail to address the issues that the CACC function with the BSM extension attempts to resolve.



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

Figure 5: Vehicle Spacing for Various Time Gap Settings

2.2 Data Collection and Post-Processing

Throughout each verification scenario, data is logged in a proprietary format using the CarPC. Post processing steps included the conversion of the raw data to a standardized .json format, followed by the use of proprietary software to generate and analyze plots (see Chapter 2.4.1). The raw data was also exported in the form of a .csv file, as requested by FHWA.

2.3 Testing Conditions

2.3.1 Weather Conditions

The weather conditions for the conducted tests are tabulated below.

Table 3: Testing Conditions

Test Date	Weather Condition	Temperature (^{o}F)	Wind (mph)	Wind Direction
1/30/2018	Cloudy	18	5	NNW
1/31/2018	Cloudy	30	16	SSE
2/20/2018	Rain	57	10	SSW
2/21/2018	Cloudy	42	10	WNW
10/9/2018	Cloudy	76	6	SSE
10/10/2018	Cloudy with Periodic Rain	70	7	SSE

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

2.4 OEM Specific Commanded Acceleration

It was observed throughout vehicle build, testing, and demonstrations that the fourth CACC-enabled vehicle had OEM specific commanded acceleration limitations. This resulted in the fourth vehicle being unable to catch up with the other vehicles in the string during acceleration to the initial speed after the deceleration maneuver and is reflected in the resultant data analysis.

2.4.1 Object Fusion and Time Synchronization Issues[1]

The following observations were made throughout testing:

- Object Fusion: It was observed that the current specification of the object fusion system had challenges with fusing incoming BSM data with onboard radar information about the preceding vehicle on significant curves. This is the result of the parameterization of the fusion algorithm and needs to be revisited in future work. It should be noted that this observation did not affect the test results listed in Chapter 2.4.1 as these tests were conducted on straight road segments.
- Time Synchronization: It was observed that, particularly, after restarting the system, time synchronizing the various components in the testing described in Chapter 2 resulted in time overhead. This is due to the utilized time synchronization protocol known as NTP, which has not been designed for automotive applications. Future work has to assess different time synchronization methods on the hardware level, e.g., PTP.

[1] The effects of the object fusion and time synchronization issues are a result of the implementation of the system and are addressed in relevant time series plots located in Section 7.2

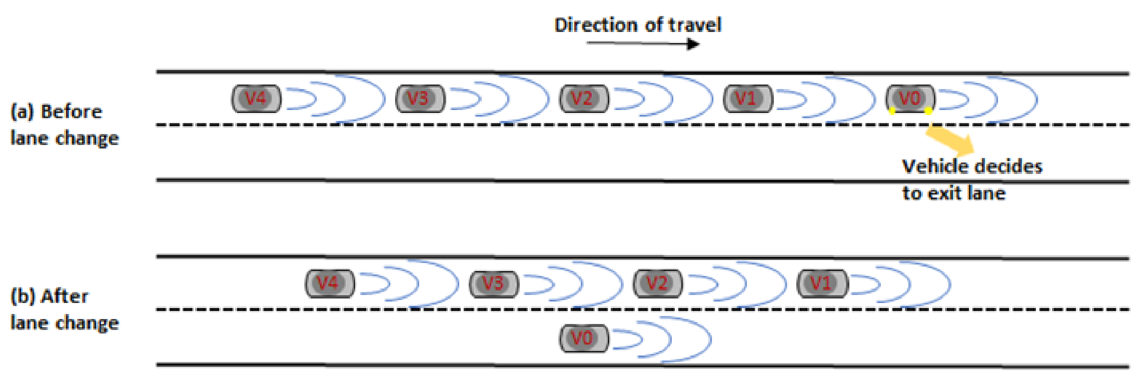
3 Verifying CACC Implementation

In order to verify the in-vehicle performance of the CACC system versus the experimental ACC system, the following scenarios were examined. These scenarios focus on verifying the implementation of the CACC system with specific edge cases throughout the development of the system. To compare the performance of the CACC system versus the experimental ACC system, the stabilization time was examined. This is defined by the time elapsed between the time of the beginning of the maneuver and the time at which the velocity value of each vehicle reaches its respective target final speed value without significant fluctuation (+/- 5% of the range between the initial and final target velocities) was observed.

3.1 Lane Change Detection- Cut Out

3.1.1 Scenario Description

In this scenario (as shown in Figure 6), the lead vehicle in a string of five vehicles with CACC activated has a lower set speed than the following vehicles. The lead vehicle then changes lanes, and the behavior of the remaining string of four vehicles is observed.

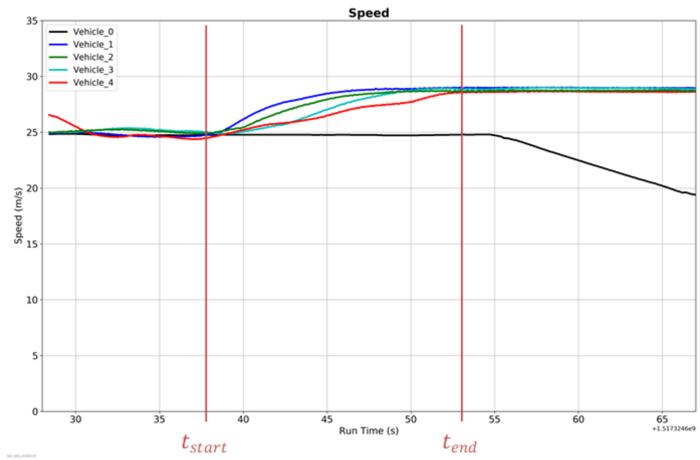


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 6: Lane Change Detection—Cut Out

3.1.2 Analysis

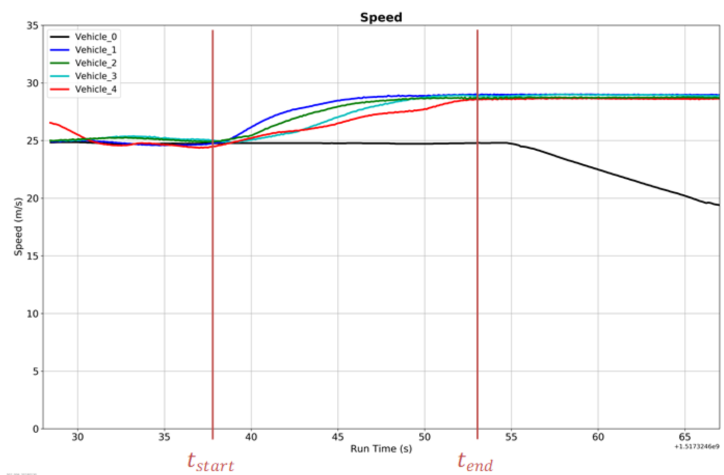
Figure 7 shows a string of vehicles in ACC with Vehicle 0, depicted in black, as a lead vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 47 seconds, Vehicle 0 cuts out of the lane, Vehicles 1-4 speed up to 29 m/s, and Vehicles 1-3 stabilize after 11 seconds, with Vehicle 4 stabilizing after 20 seconds. Vehicle 4's behavior is attributed to the maximum commanded acceleration discussed in Section 2.4.



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

Figure 7: Lane Change Detection- Cut Out, ACC

Figure 8 shows a string of vehicles in CACC with Vehicle 0, depicted in black, as a lead vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 38 seconds, Vehicle 0 cuts out of the lane, Vehicles 1-4 speed up to 29 m/s, Vehicles 1-3 stabilize after 10 seconds, and Vehicle 4 stabilizes after 15 seconds.



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

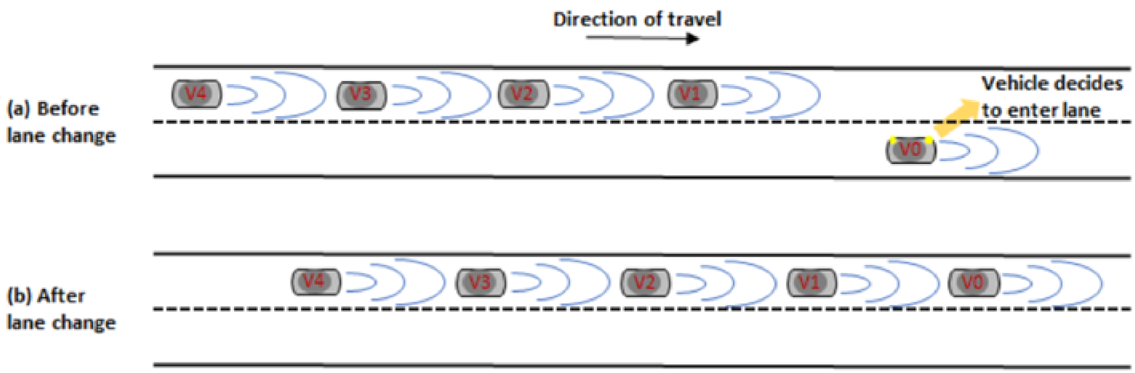
Figure 8: Lane Change Detection- Cut Out, CACC

In CACC mode, the vehicle string with Vehicle 4 stabilizes approximately 15 seconds after the lead vehicle conducts a lane change. On the other hand, in ACC mode, the vehicle string stabilizes approximately 20 seconds after the lead vehicle's lane change. Although Vehicles 1-3 stabilize in relatively similar timeframes, Vehicle 4 starts accelerating at the same time as the rest of the vehicles in the string and is thus able to reach the final target speed more quickly.

3.2 Lane Change Detection- Cut In

3.2.1 Scenario Description

In this scenario (as shown in Figure 9), a string of four vehicles with CACC activated travels in a lane adjacent to a slower moving vehicle. Right before the string passes the slower moving vehicle, the vehicle cuts in front of the string, and the behavior of the four vehicle string is observed.

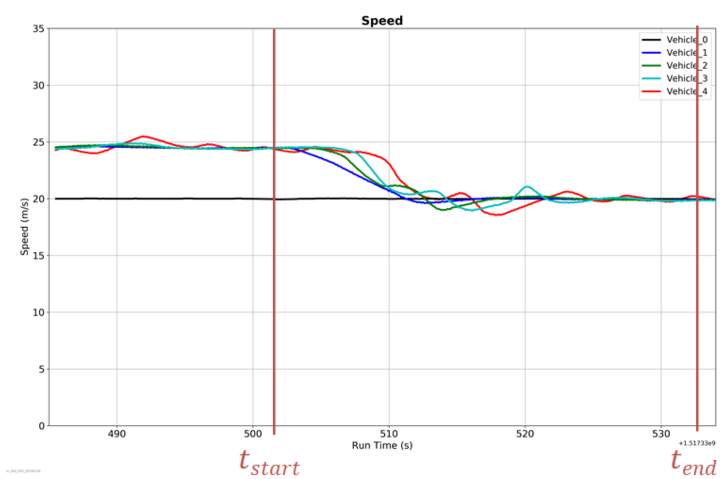


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 9: Lane Change Detection—Cut In

3.2.2 Analysis

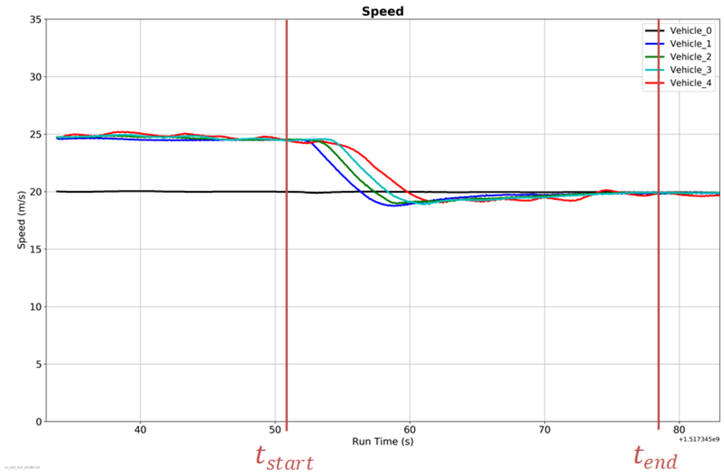
Figure 10 shows a string of vehicles in ACC with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All ACC-enabled vehicles are travelling at 25 m/s, and Vehicle 0 is travelling at 20 m/s. At approximately 504 seconds, Vehicle 0 cuts in front of the string, and Vehicles 1-4 slow down to 20 m/s. The string stabilizes after 23 seconds.



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

Figure 10: Lane Change Detection- Cut In, ACC

Figure 11 shows a string of vehicles in CACC with Vehicle 0, depicted in black, as vehicle with only DSRC communication. All CACC-enabled vehicles are travelling at 25 m/s, and Vehicle 0 is travelling at 20 m/s. At approximately 53 seconds, Vehicle 0 cuts in front of the string, and Vehicles 1-4 slow down to 20 m/s. The string stabilizes after 20 seconds.



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

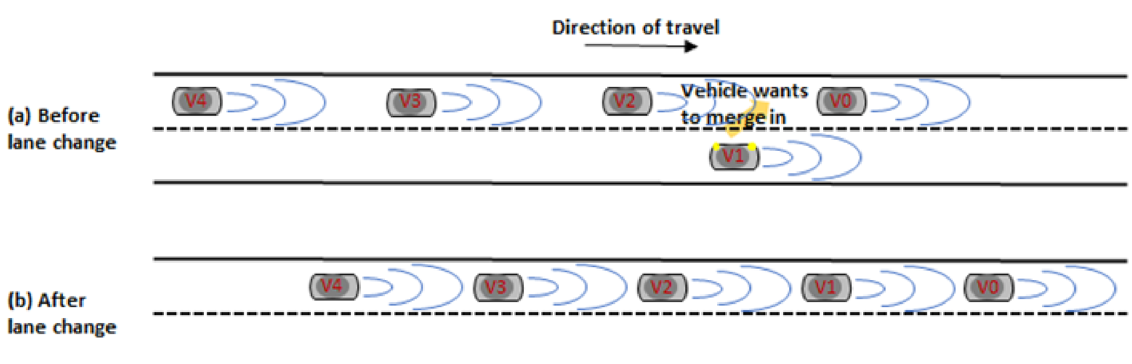
Figure 11: Lane Change Detection- Cut In, CACC

Similar to Section 3.1, the vehicles correctly detect another vehicle cutting in front and slow down accordingly. In both ACC and CACC mode, the string stabilizes approximately 20 and 23 seconds after the cut in, respectively.

3.3 Cut-In Maneuver

3.3.1 Scenario Description

In this scenario (as shown in Figure 12), a string of 4 vehicles with CACC activated travels in a lane adjacent to another vehicle. The second vehicle in the string has a larger time gap set than the other vehicles, and a vehicle adjacent to the string cuts in between vehicles 0 and 2 of the string. The behavior of the last 3 vehicles in the string is observed.

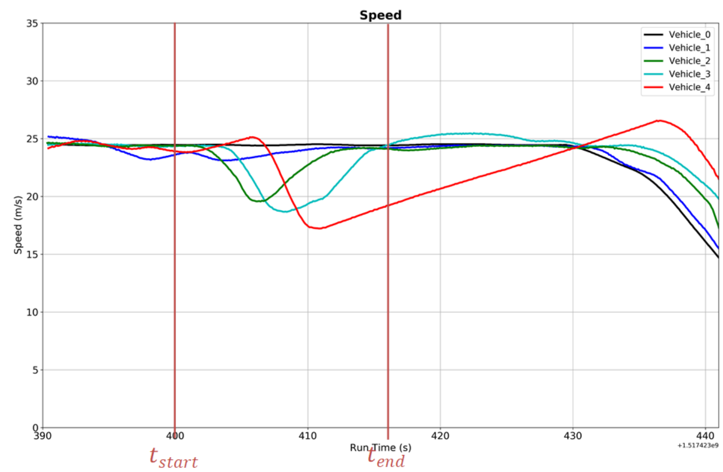


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 12: Cut-In Maneuver

3.3.2 Analysis

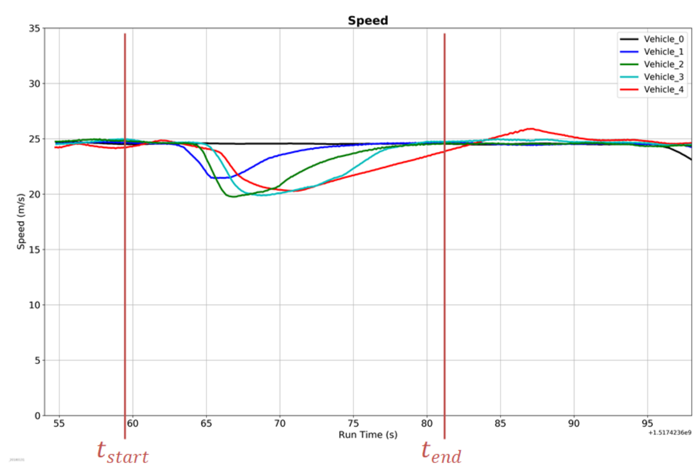
Figure 13 shows a string of vehicles in ACC with Vehicle 0, depicted in black, as a lead vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 402 seconds, Vehicle 1 cuts into the string between vehicles 0 and 2, and Vehicles 2-4 slow down to accommodate the vehicle cutting in, with each vehicle progressively slowing down further. At approximately 415 seconds, all vehicles except Vehicle 4 stabilize. Vehicle 4's inability to properly stabilize before the end of the run is attributed to the maximum commanded acceleration issue discussed in Section 2.4.



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

Figure 13: Cut-In Maneuver, ACC

Figure 14 shows a string of vehicles in CACC with Vehicle 0, depicted in black, as a lead vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 63 seconds, Vehicle 1 cuts into the string between vehicles 0 and 2, and Vehicles 2-4 slow down to accommodate the vehicle cutting in, with each of these vehicles decelerating to 20 m/s. At approximately 80 seconds, all vehicles except Vehicle 4 stabilize. Vehicle 4 stabilizes at approximately 92 seconds.



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

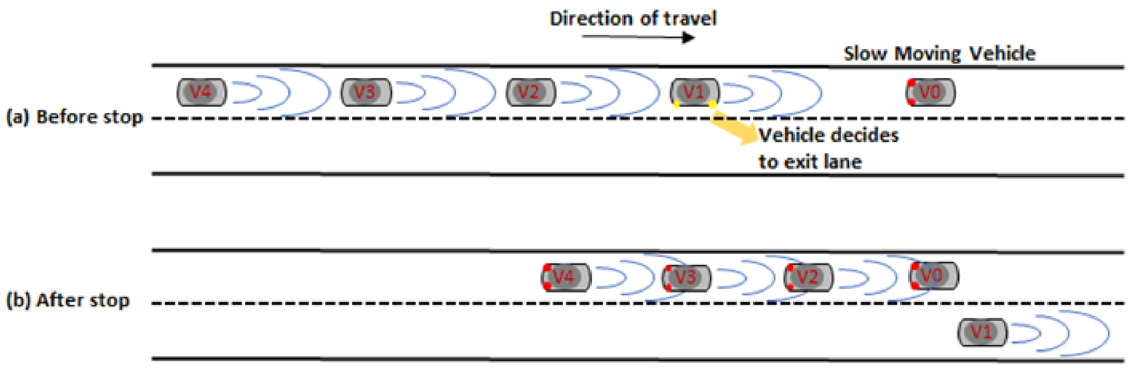
Figure 14: Cut-In Maneuver, CACC

In the Cut-In Maneuver Scenario, the three vehicles behind the cut-in maneuver correctly identify the vehicle cutting into the string and slow down accordingly. The string in CACC mode was able to stabilize in 17 seconds while the string in ACC mode was able to stabilize in 13 seconds. However, the ACC vehicles needed to decelerate to progressively slower velocities down the string.

3.4 Overtaking

3.4.1 Scenario Description

In this scenario (as shown in Figure 15), a string of four vehicles with CACC activated travel towards a vehicle in the same lane with a lower speed. The lead vehicle in the string makes a lane change to avoid the obstacle. The behavior of the remaining string of three vehicles is observed.

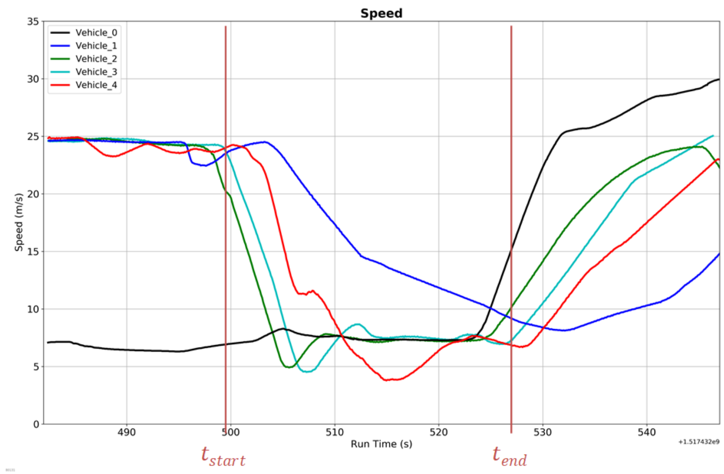


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 15: Overtaking

3.4.2 Analysis

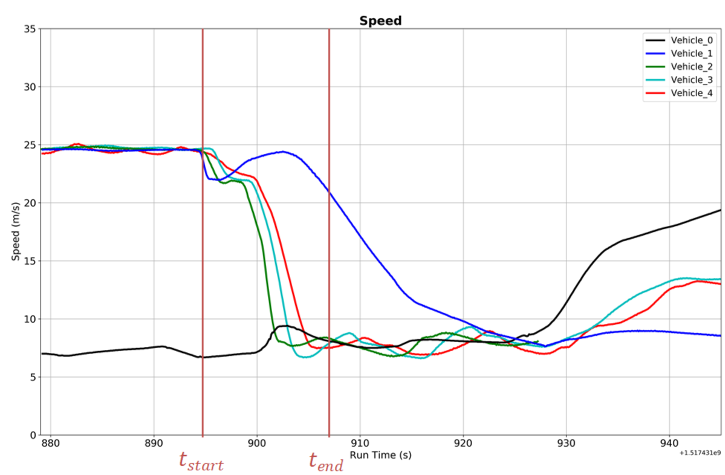
Figure 16 shows a string of vehicles in ACC with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s with Vehicle 0 travelling at 7 m/s. At approximately 496 seconds, Vehicle 1 changes lanes to overtake the slow-moving Vehicle 0, and Vehicles 2-4 slow down to approximately 5 m/s. After approximately 27 seconds, the string stabilizes.



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

Figure 16: **Overtaking, ACC**

Figure 17 shows a string of vehicles in CACC with a leading Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s with Vehicle 0 travelling at 7 m/s. At approximately 895 seconds, Vehicle 1 changes lanes to overtake the slow-moving Vehicle 0, and Vehicles 2-4 slow down to 7 m/s. After approximately 13 seconds, the string stabilizes.



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

Figure 17: Overtaking, CACC

In the Overtaking Scenario, Vehicle 1 makes a lane change to overtake the obstacle, Vehicle 0. Vehicles 2-4 correctly decelerate after detecting Vehicle 0 moving at a much slower speed. In ACC, vehicles took approximately 27 seconds to all stabilize after Vehicle 1 made the overtaking maneuver as compared to 13 seconds in CACC mode.

4 Comparative Data Analysis

4.1 Analysis Metrics

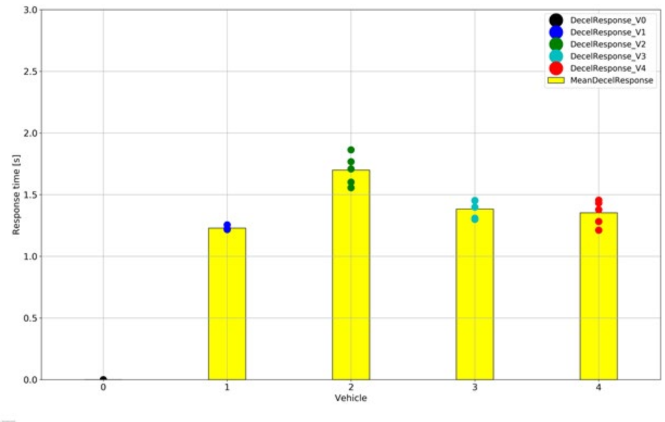
After reviewing the Volpe Center's platooning concept (Tim A. Tiernan, 2017) and CAMP's CACC documentation, both CAMP and FHWA agreed upon a set of scenarios that examine string stability for automated longitudinal control as this most directly describes the benefits of the use of DSRC to complement ACC. These are the String Stability previously outlined in the CACC Phase 1 Final Report (Meier, et al., 2018), as well as a variation of the String Stability Scenario, with accelerations and decelerations between 45 and 60 mph. Testing for these scenarios was conducted again at FTTA using a testing setup similar to those outlined in Section 2.

In this section, several Key Performance Indicators (KPIs) are defined. These KPIs require the string of vehicles to have been previously travelling in a steady CACC state, as described in Section 2. Data analyses for these KPIs are described in Sections 4.2, 4.3, and 4.4, a summary of the KPI results is tabulated in Section 7.1, and time series plots for these KPIs are contained in Section 7.2.

4.1.1 Deceleration Response Delay

As the name suggests, deceleration response delay is the time taken by the host vehicle CACC system to respond to a deceleration maneuver performed by the vehicle ahead. In this analysis, a vehicle is considered to be decelerating when the vehicle's acceleration reaches -1.2 m/s^2. For each CACC-enabled vehicle in a string over the duration of the decelerating maneuver, the time difference between the time instance when the magnitude of each host vehicle's acceleration reaches -1.2 m/s^2 and the time instance when the magnitude of the acceleration of its respective preceding vehicle reaches -1.2 m/s^2 is calculated in order to gauge the delay in deceleration response. These time differences are calculated for the first deceleration maneuver. Ideal performance for this indicator is characterized by a smaller average value.

Figure 18 shows a sample deceleration response delay chart. The chart uses colored circles to summarize the deceleration response for each vehicle, for each repetition of the test scenario. The average deceleration response delay of all the runs is represented by the yellow bars.



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

Figure 18: Sample Deceleration Response Delay Chart

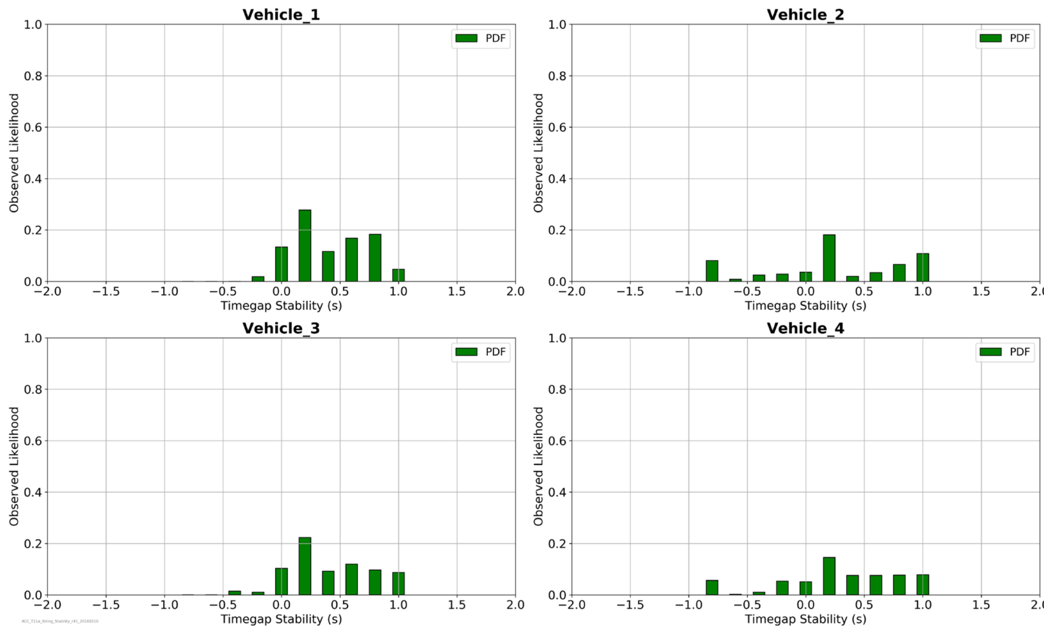
4.1.2 Minimum Speed Value

For each CACC-enabled vehicle in a string over the duration that the CACC function is active, the average change in the minimum speed value that each vehicle attains with respect to its respective preceding vehicle's minimum speed value is calculated. The minimum speed value is examined because vehicles with better performance in string stability scenarios do not need to slow down as much as a result of the stimulus to the string. Ideal performance for this indicator is characterized by minimizing the average difference between the preceding vehicle's minimum speed value and the HV's minimum speed value. Performance is therefore indicated by the larger average value.

The following KPIs are computed from a Probability Density Function resulting from an aggregation of all sample points for each scenario and from every vehicle position:

4.1.3 Time Gap Stability

For each CACC-enabled vehicle in a string over the duration that the CACC function is active, the difference between the vehicle set time gap and the actual measured time gap from the preceding vehicle is calculated. A negative value of time gap difference indicates that actual measured time gap is less than user set time gap, and a positive value of time gap difference indicates that the measured time gap is greater than the user set time gap . A Probability Density Function of the observed differences is computed in order to gauge the mean and variance of the deviation of each vehicle from their respective set time gap. Ideal performance for this indicator is characterized by a mean near zero and a small standard deviation; an exemplary plot is depicted in Figure 19.

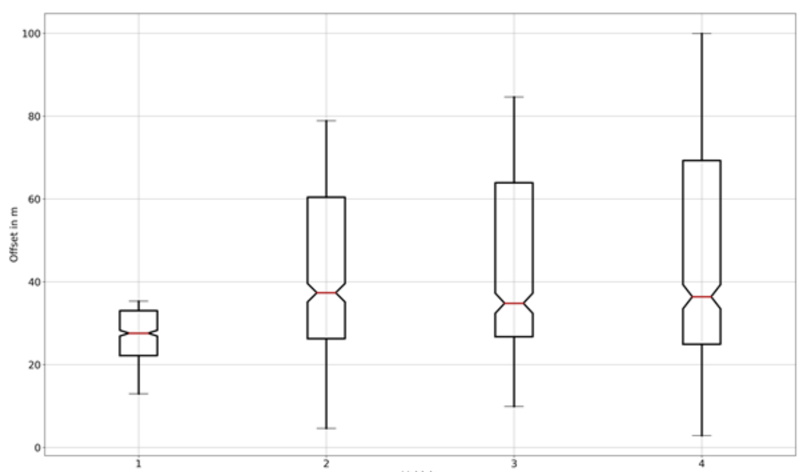


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 19: Sample Time Gap Stability Chart

4.1.4 Relative Longitudinal Offset

For each CACC-enabled vehicle in a string over the duration that the CACC function is active, a Probability Density Function of all measured distances to each vehicle's respective preceding vehicle is constructed in order to gauge the variance of the distance of each vehicle to its respective target. Ideal performance for this indicator is characterized by a small standard deviation. In Figure 20, a box plot is shown to best visualize the spread of the data; the demarcations in the midsection denote the 25th, 50th, and 75th percentile values for the Relative Longitudinal Offset.



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

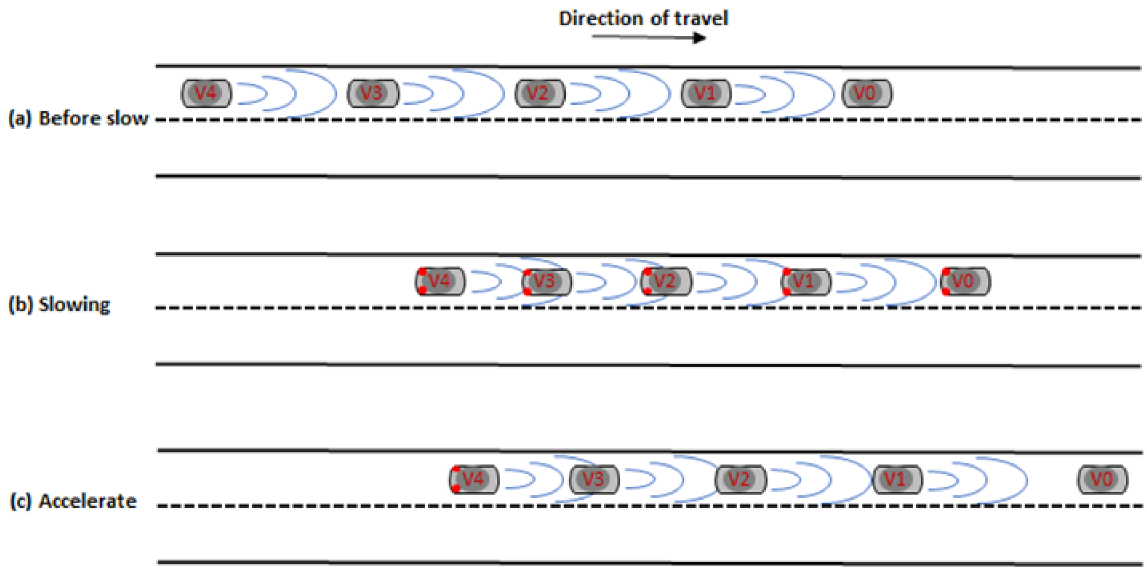
Figure 20: Sample Relative Longitudinal Offset

4.2 String Stability Scenario, 55 mph to 30 mph, Harsh Deceleration (-3.5 m/s^2)[2]

4.2.1 Scenario Description

4.2.1.1 String Stability Scenario: 55 mph to 30 mph with Harsh Deceleration

In this scenario (as shown in Figure 21), a string of vehicles with CACC activated travels along a straightaway at 55 mph. The lead vehicle slows down to 30 mph at a deceleration of -3.5 m/s^2 and then accelerates to its original speed. This process is repeated once, and the behavior of the string is observed.

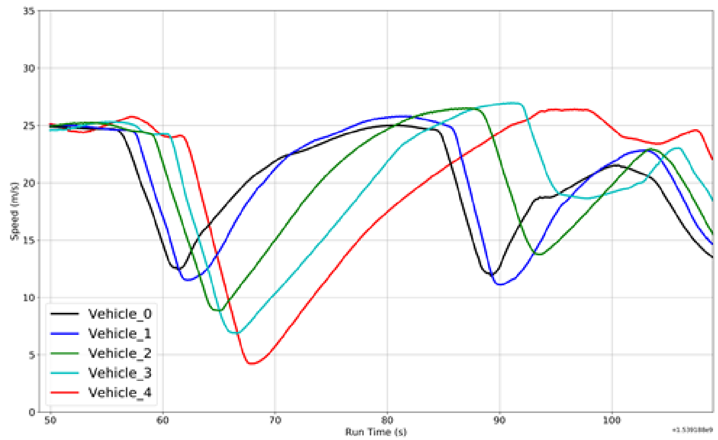


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 21: String Stability Scenario: 55 mph to 30 mph with Harsh Deceleration

Figure 22 depicts a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 57 seconds, Vehicle 0 decelerates to 12.4 m/s at a rate of -3.5 m/s^2, followed by an acceleration back to 25 m/s. Vehicles 1-4 decelerate to speeds of 11.5, 8.8, 6.8, and 4.3 m/s, respectively. Vehicles in ACC decelerate to slower speeds down the string since they each have a progressively shorter amount of time to respond to the deceleration of each vehicles' respective preceding vehicle.

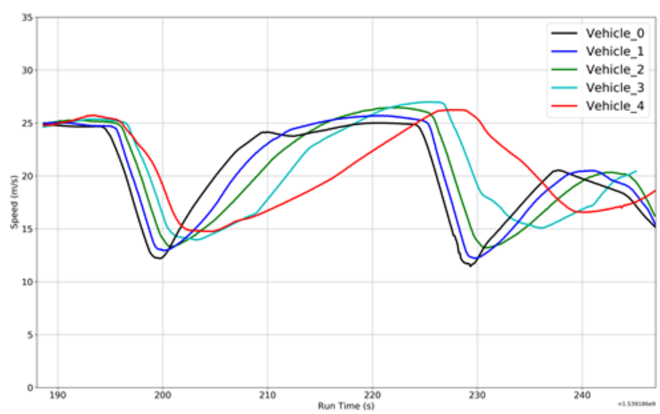
[2] For all time series plots, only the first deceleration maneuver was examined, as the time between deceleration maneuvers was insufficient to create a stable string before the start of the second maneuver.



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

Figure 22: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, ACC Time Series Plot for Speed

Figure 23 depicts a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 195 seconds, Vehicle 0 decelerates to 12.2 m/s at a rate of -3.5 m/s^2, followed by an acceleration back to 25 m/s. Vehicles 1-4 decelerate to speeds of 12.9, 13.2, 13.9, and 14.1 m/s, respectively. Due to the information received from the BSM, vehicles in CACC do not need to decelerate to significantly slower speeds since they each have a progressively longer amount of time to respond to the deceleration of each vehicles' respective preceding vehicle.

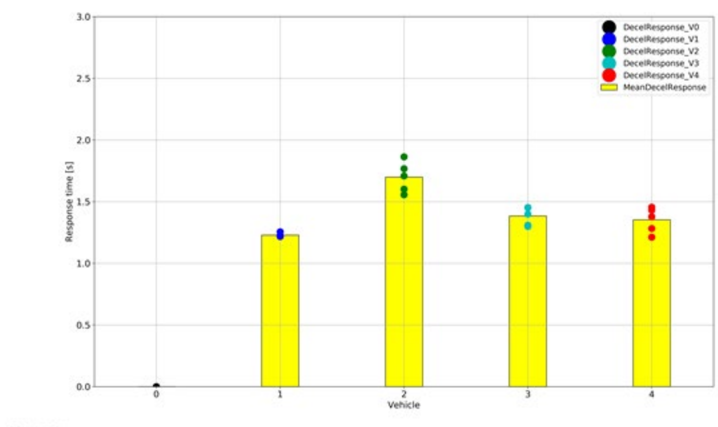


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 23: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Speed

4.2.2 Deceleration Response Delay[3]

Figure 24 depicts the difference, for a string of ACC vehicles, in time between the time where each HV reaches a deceleration of -1.2 m/s^2 and where its respective preceding vehicle reaches a deceleration of -1.2 m/s^2. For each vehicle, the average value over all runs is shown in the bar graph. The average values for Vehicles 1-4 are 1.19, 1.68, 1.38, and 1.39 m/s^2, respectively.

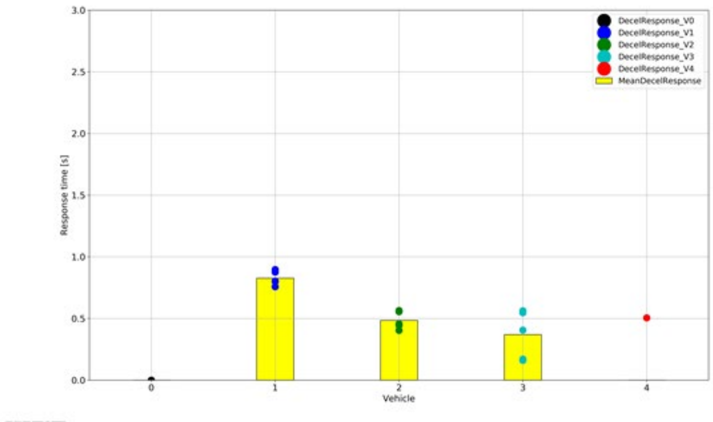


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 24: String Stability Scenario, 55 mph to 30 mph, Harsh Deceleration: ACC Deceleration Response Time

Figure 25 depicts the difference, for a string of CACC vehicles, in time between the time where each HV reaches a deceleration of -1.2 m/s^2 and where its respective preceding vehicle reaches a deceleration of -1.2 m/s^2. For each vehicle, the average value over all runs is shown in the bar graph. The average values for Vehicles 1-4 are 0.83, 0.46, 0.39, and 0.27 m/s^2, respectively. Vehicles in CACC have a much lower response time than ACC due to the information communicated in the BSM, and the response time decreases down the string, as each vehicle has progressively more time to respond.

[3] All bar graphs for Deceleration Response Time depict the average response time of each respective vehicle over all the test runs used for analysis. The data points for each vehicle are the individual response times for each test run.

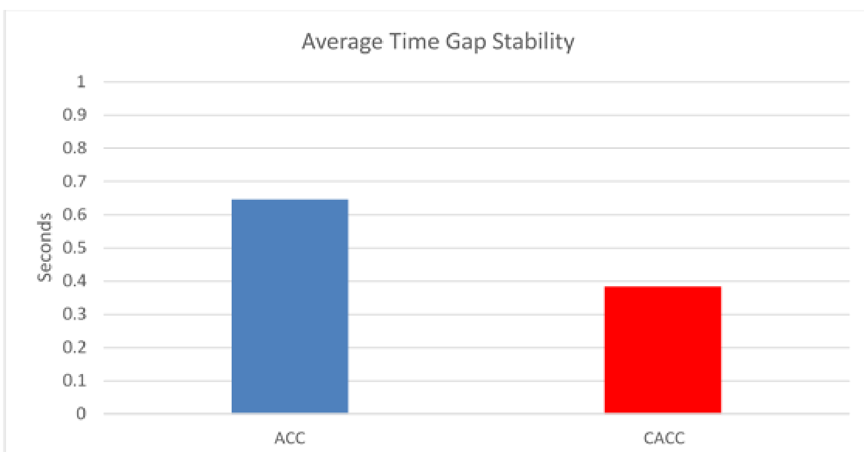


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 25: String Stability Scenario, 55 mph to 30 mph, Harsh Deceleration: CACC Deceleration Response Time

4.2.3 Time Gap Stability

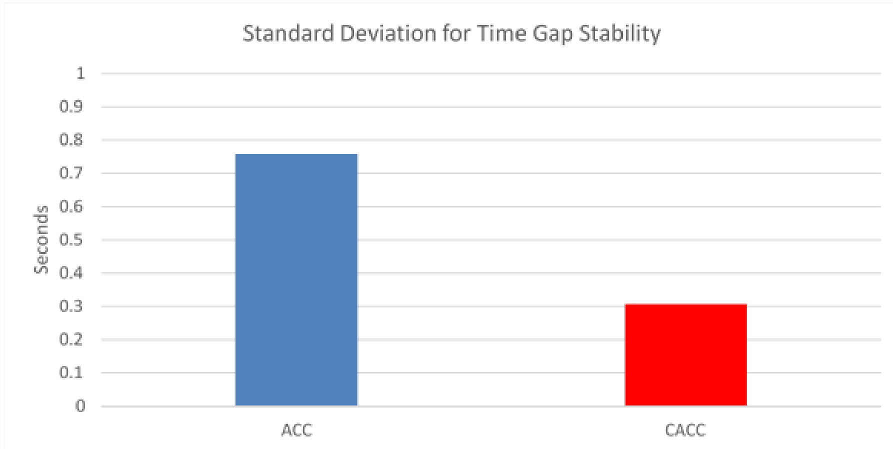
Figure 26 depicts the average value of the aggregated values for the difference in each HV's actual and set time gap of 1 second. ACC has an average time gap deviation of 0.65 seconds, compared to CACC having an average time gap deviation of 0.38 seconds. CACC performs better with a lower average deviation from the set time gap due to the information from the BSM.



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

Figure 26: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, Average Time Gap Stability between ACC and CACC

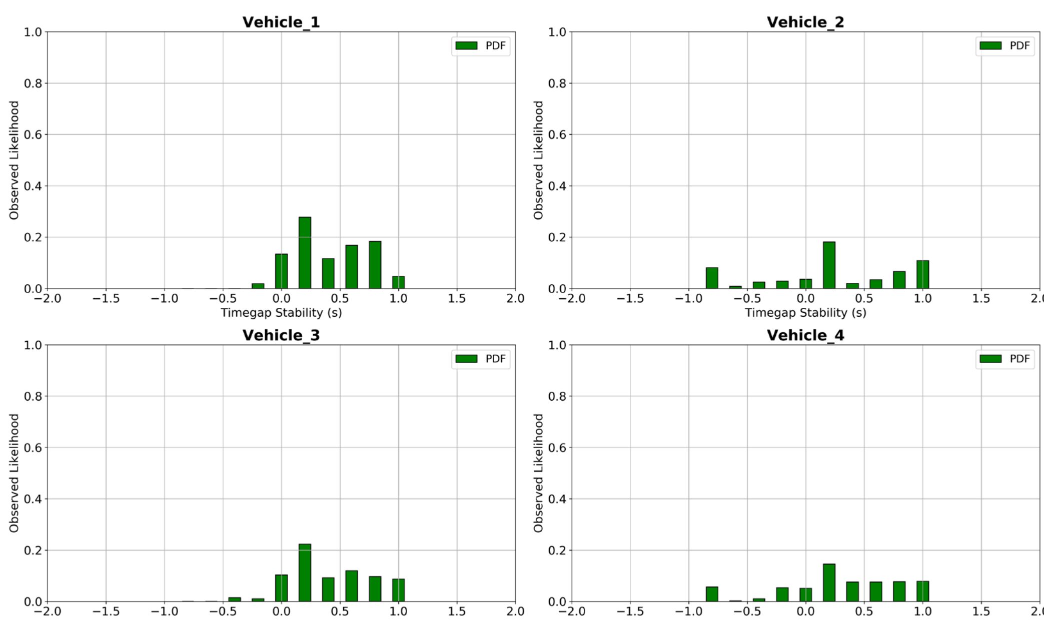
Figure 27 depicts the standard deviation of the aggregated values for the difference in each HV's actual and set time gaps. The standard deviation of the ACC vehicles' time gap deviation was 0.76 seconds, compared to CACC having a standard deviation of 0.31 seconds. CACC performs better with a lower standard deviation due to the information from the BSM.



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

Figure 27: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, Standard Deviation of Time Gap Stability between ACC and CACC

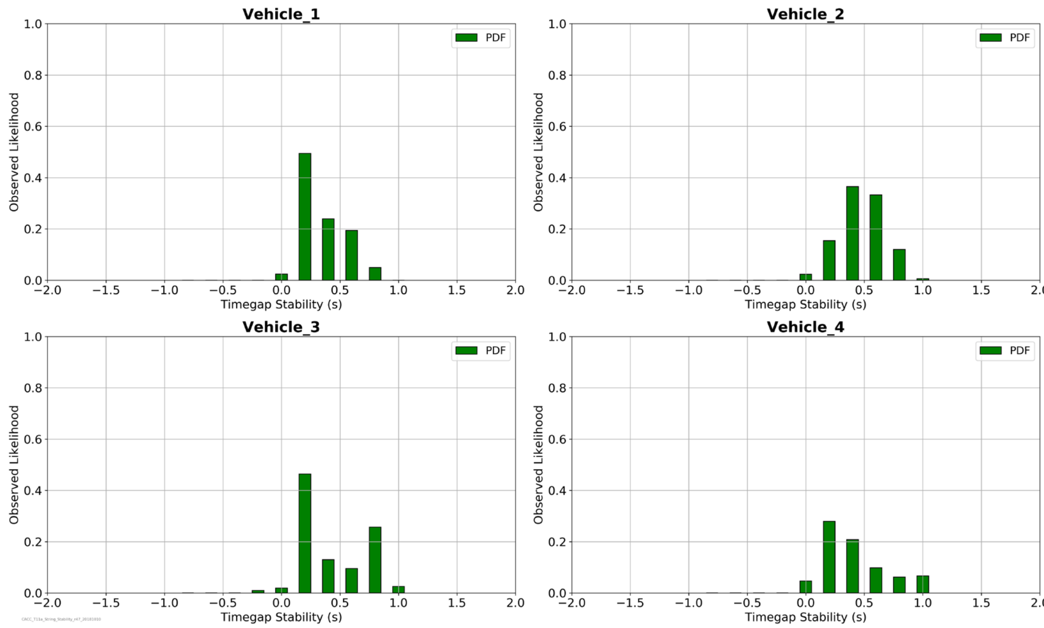
Figure 28 shows a Probability Density Function (PDF) for the aggregated values for the difference in each HV's actual and set time gaps, separated for each ACC vehicle in the string. The mean values for each PDF are 0.35, 0.75, 0.62, and 0.86 seconds difference for Vehicles 1-4, respectively, showing that in ACC the vehicles deviate progressively more from the set time gap down the string. The standard deviations for each PDF are 0.36, 0.92, 0.67, and 1.07 seconds for Vehicles 1-4, respectively, showing that in ACC the stability for each vehicles' time gaps progressively decreases down the string.



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

Figure 28: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, ACC Time Gap Stability

Figure 29 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each CACC vehicle in the string. The mean values for each PDF are 0.23, 0.38, 0.32, and 0.58 seconds difference for Vehicles 1-4, respectively, showing that in CACC the vehicles deviate progressively more from the set time gap down the string, but significantly less so than the same scenario in ACC. The standard deviations for each PDF are 0.19, 0.18, 0.28, and 0.56 seconds for Vehicles 1-4, respectively, showing that in CACC the stability for each vehicles' time gaps progressively decreases down the string, but again, significantly less so than ACC.

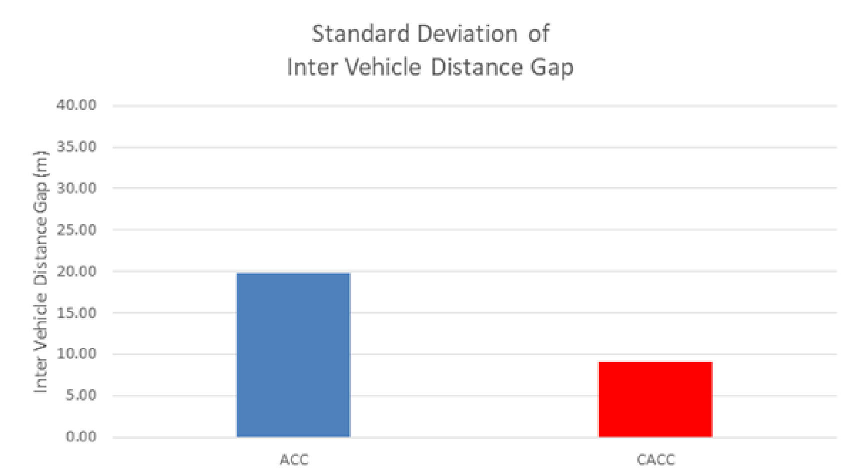


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 29: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Gap Stability

4.2.4 Relative Longitudinal Offset

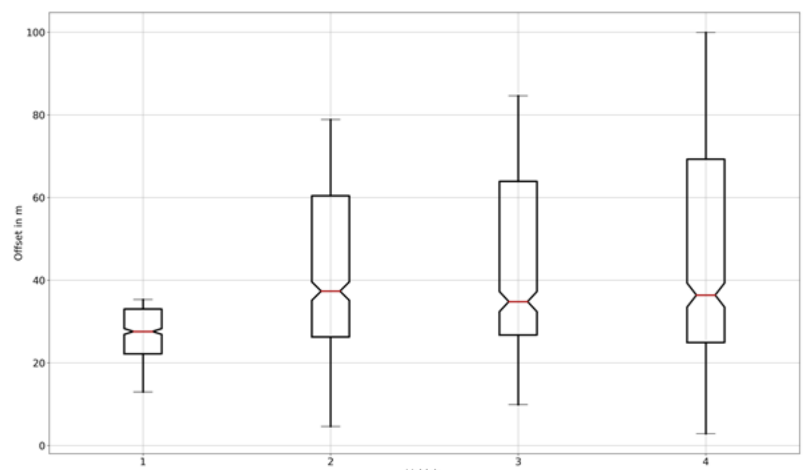
Figure 30 depicts the standard deviation of the aggregated values for the difference in each HV's actual and set time gaps. The standard deviation of the ACC vehicles' time gap deviation was 19.77 meters as compared to CACC having a standard deviation of 9.02 meters. CACC performs better with a lower standard deviation due to the information from the BSM.



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

Figure 30: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, Average Time Gap Stability between ACC and CACC

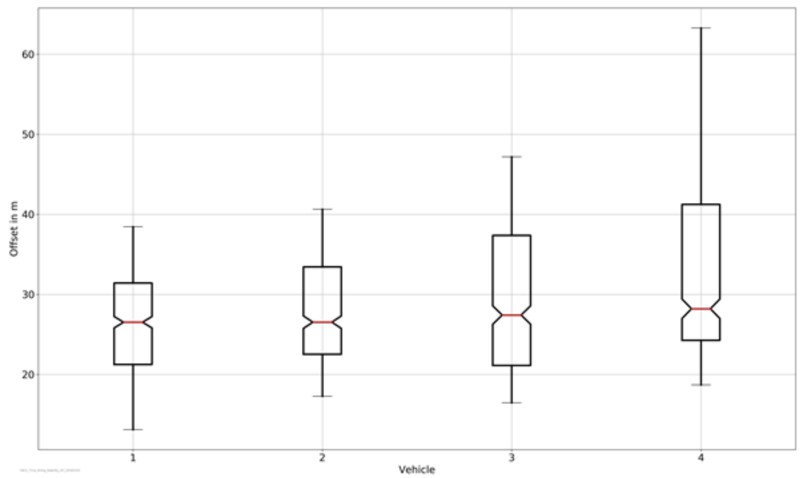
Figure 31 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each ACC vehicle in the string. The inter-quartile ranges for each box plot are 10.48, 34.16, 37.18, and 44.36 meters for Vehicles 1-4, respectively, showing that in ACC the stability for each vehicles' time gaps progressively decreases down the string.



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

Figure 31: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, ACC Relative Longitudinal Offset

Figure 32 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each CACC vehicle in the string. The inter-quartile ranges for each box plot are 10.18, 10.92, 27.41, and 29.20 meters for Vehicles 1-4, respectively, showing that in CACC the stability for each vehicles' time gaps progressively decreases down the string, but again, significantly less so than ACC.



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

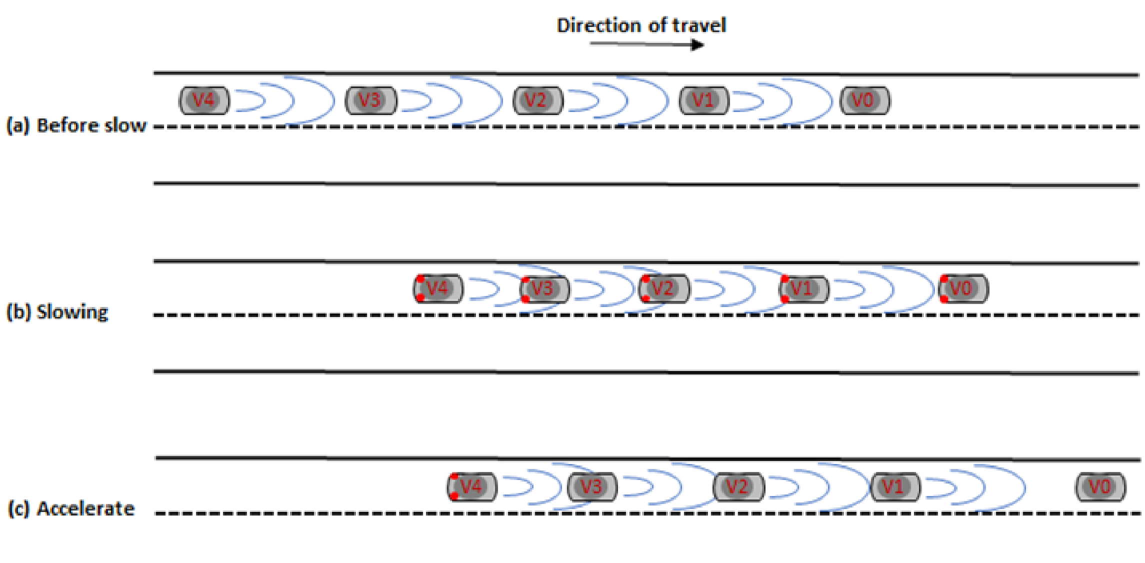
Figure 32: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Relative Longitudinal Offset

4.3 String Stability Scenario, 55 mph to Rolling Stop

4.3.1 Scenario Description

4.3.1.1 String Stability Scenario, 55 mph to Rolling Stop

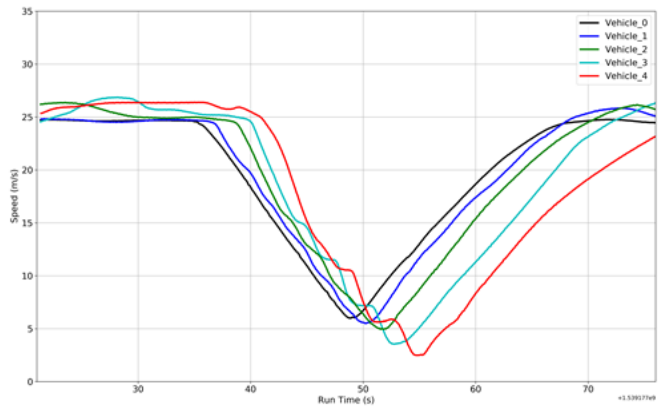
In this scenario (as shown in Figure 33), a string of vehicles with CACC activated travels along a straightaway. The lead vehicle slows down to a rolling stop from 55 mph at a deceleration of -2.5 m/s^2 and then speeds up to its original speed. This process is repeated once, and the behavior of the string is observed.



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

Figure 33: String Stability Scenario, 55 mph to Rolling Stop

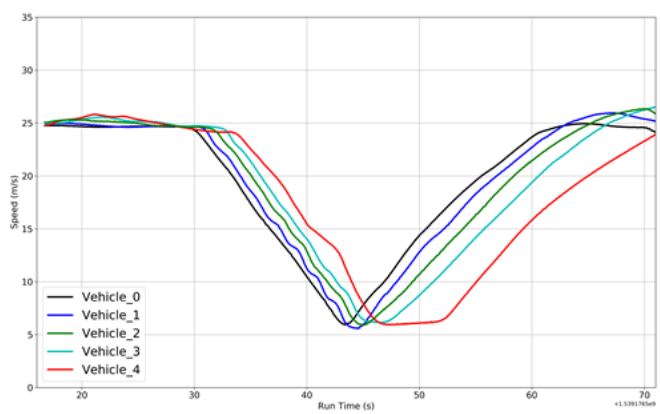
Figure 34 depicts a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 36 seconds, Vehicle 0 decelerates to 6 m/s at a rate of -2.5 m/s², followed by an acceleration back to 25 m/s. Vehicles 1-4 decelerate to speeds of 5.4, 4.9, 3.5, and 2.4 m/s, respectively. Vehicles in ACC decelerate to slower speeds down the string since they each have a progressively shorter amount of time to respond to the deceleration of each vehicles' respective preceding vehicle.



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

Figure 34: String Stability Scenario, 55 mph to Rolling Stop: ACC Time Series Plot for Speed

Figure 35 depicts a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 30 seconds, Vehicle 0 decelerates to 5.9 m/s at a rate of -2.5 m/s², followed by an acceleration back to 25 m/s. Vehicles 1-4 decelerate to speeds of 5.6, 5.6, 6.2, and 5.9 m/s, respectively. Due to the information received from the BSM, vehicles in CACC do not need to decelerate to significantly slower speeds since they each have a progressively longer amount of time to respond to the deceleration of each vehicles' respective preceding vehicle.

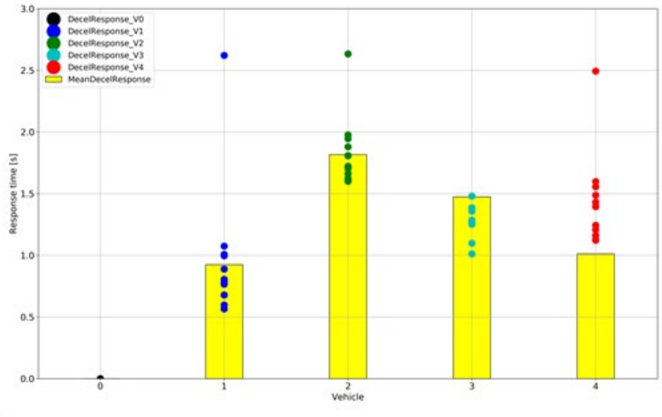


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 35: String Stability Scenario, 55 mph to Rolling Stop: CACC Time Series Plot for Speed

4.3.2 Deceleration Response Delay

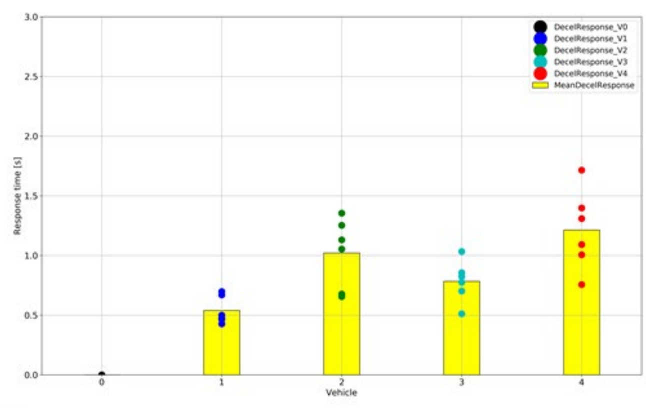
Figure 36 depicts the difference, for a string of ACC vehicles, in time between the time where each HV reaches a deceleration of -1.2 m/s^2 and where its respective preceding vehicle reaches a deceleration of -1.2 m/s^2. For each vehicle, the average value over all runs is shown in the bar graph. The average values for Vehicles 1-4 are 0.92, 1.81, 1.47, and 1.01 m/s^2, respectively.



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

Figure 36: String Stability Scenario, 55 mph to Rolling Stop: ACC Deceleration Response Time

Figure 37 depicts the difference, for a string of CACC vehicles, in time between the time where each HV reaches a deceleration of -1.2 m/s^2 and where its respective preceding vehicle reaches a deceleration of -1.2 m/s^2. For each vehicle, the average value over all runs is shown in the bar graph. The average values for Vehicles 1-4 are 0.54, 1.02, 0.78, and 1.21 m/s^2, respectively. Vehicles in CACC have a much lower response time than ACC due to the information communicated in the BSM, and the response time decreases down the string as each vehicle has progressively more time to respond.

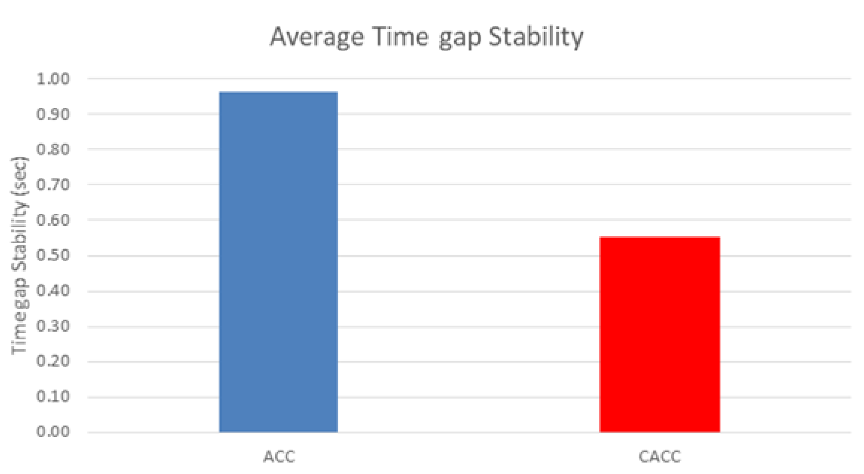


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 37: String Stability Scenario, 55 mph to Rolling Stop: CACC Deceleration Response Time

4.3.3 Time Gap Stability

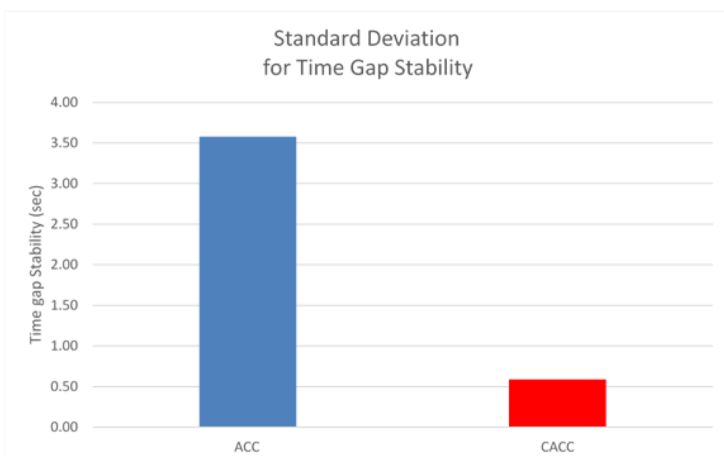
Figure 38 depicts the average value of the aggregated values for the difference in each HV's actual and set time gaps. ACC has an average time gap deviation of 0.96 seconds, compared to CACC having an average time gap deviation of 0.55 seconds. CACC performs better with a lower average deviation from the set time gap due to the information from the BSM.



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

Figure 38: String Stability Scenario, 55 mph to Rolling Stop: Average Time Gap Stability between ACC and CACC

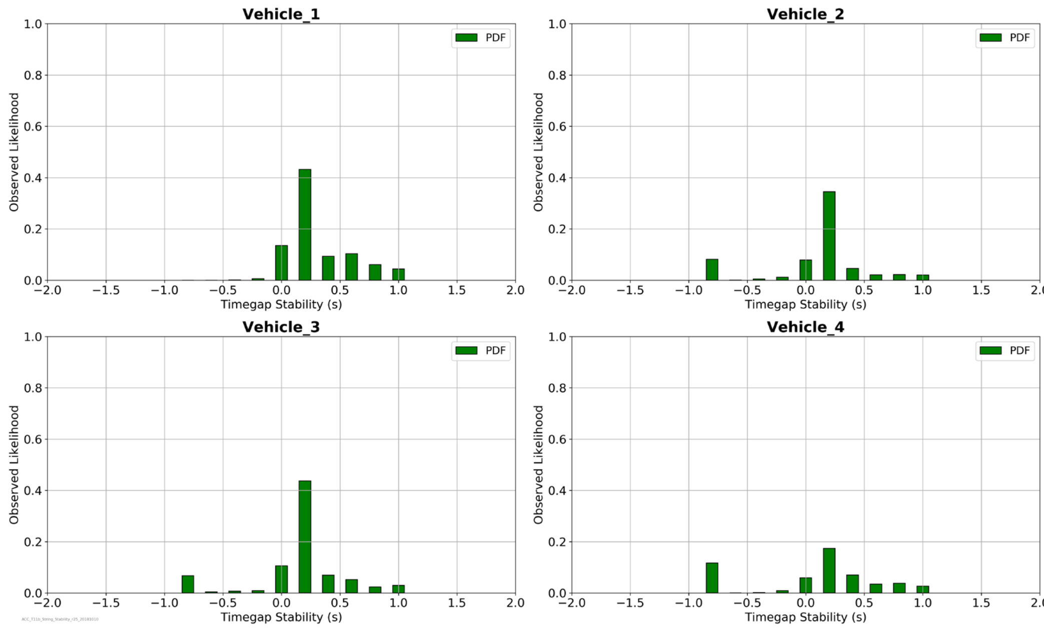
Figure 39 depicts the standard deviation of the aggregated values for the difference in each HV's actual and set time gaps. The standard deviation of the ACC vehicles' time gap deviation was 3.58 seconds, compared to CACC having a standard deviation of 0.59 seconds. CACC performs better with a lower standard deviation due to the information from the BSM.



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

Figure 39: String Stability Scenario, 55 mph to Rolling Stop: Standard Deviation of Time Gap Stability between ACC and CACC

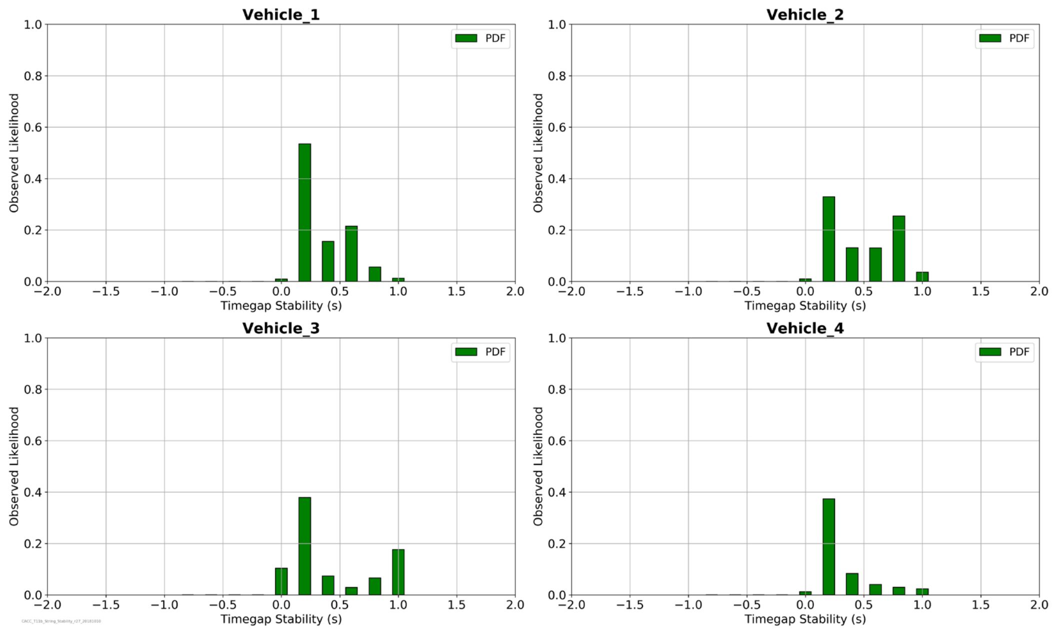
Figure 40 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each ACC vehicle in the string. The mean values for each PDF are 0.47, 1.16, 0.91, and 1.32 seconds difference for Vehicles 1-4, respectively, showing that in ACC, the vehicles deviate progressively more from the set time gap down the string. The standard deviations for each PDF are 2.55, 5.37, 3.47, and 2.92 seconds for Vehicles 1-4, respectively, showing that in ACC, the stability for each vehicles' time gaps progressively decreases down the string.



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

Figure 40: String Stability Scenario, 55 mph to Rolling Stop: ACC Time Gap Stability

Figure 41 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each CACC vehicle in the string. The mean values for each PDF are 0.27, 0.54, 0.50, and 0.89 seconds difference for Vehicles 1-4, respectively, showing that in CACC, the vehicles deviate progressively more from the set time gap down the string, but significantly less so than the same scenario in ACC. The standard deviations for each PDF are 0.44, 0.53, 0.56, and 0.82 seconds for Vehicles 1-4, respectively, showing that in CACC, the stability for each vehicles' time gaps progressively decreases down the string, but again, significantly less so than ACC.

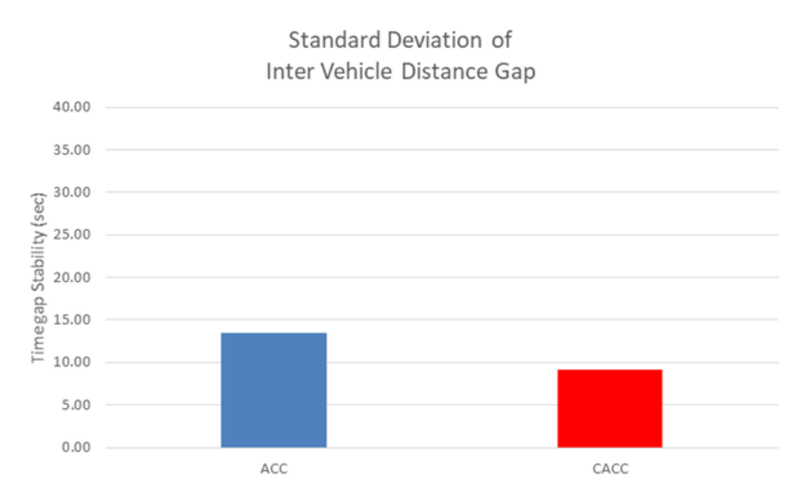


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 41: String Stability Scenario, 55 mph to Rolling Stop: CACC Time Gap Stability

4.3.4 Relative Longitudinal Offset

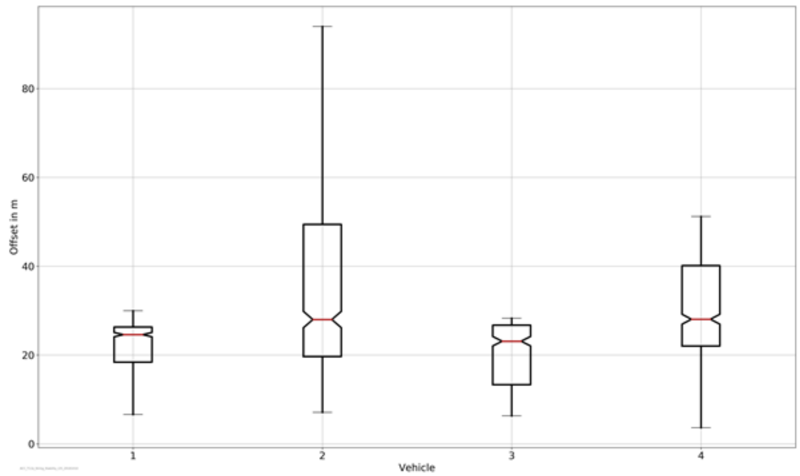
Figure 42 depicts the standard deviation of the aggregated values for the difference in each HV's actual and set time gaps. The standard deviation of the ACC vehicles' time gap deviation was 13.51 meters as compared to CACC having a standard deviation of 9.16 meters. CACC performs better with a lower standard deviation due to the information from the BSM.



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

Figure 42: String Stability Scenario, 55 mph to Rolling Stop: Average Time Gap Stability between ACC and CACC

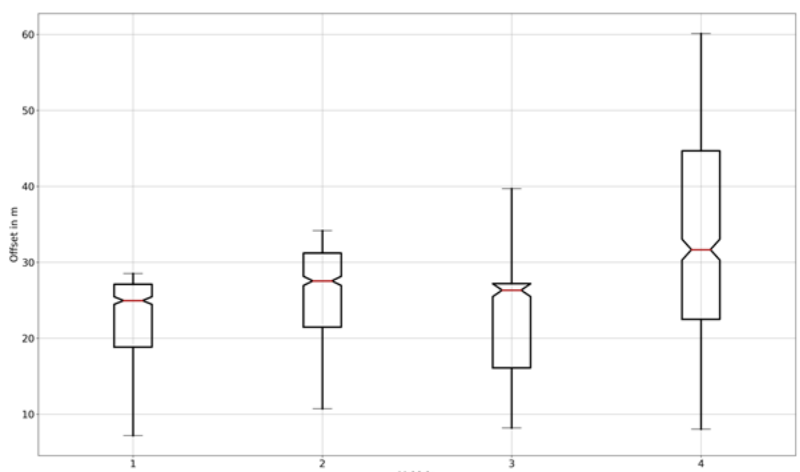
Figure 43 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each ACC vehicle in the string. The inter-quartile ranges for each box plot are 7.91, 29.76, 13.41, and 18.11 meters for Vehicles 1-4, respectively, showing that in ACC, the stability for each vehicles' time gaps progressively decreases down the string.



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

Figure 43: String Stability Scenario, 55 mph to Rolling Stop: ACC Relative Longitudinal Offset

Figure 44 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each CACC vehicle in the string. The inter-quartile ranges for each box plot are 8.27, 9.75, 11.09, and 22.18 meters for Vehicles 1-4, respectively, showing that in CACC, the stability for each vehicles' time gaps progressively decreases down the string, but again, significantly less so than ACC.



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

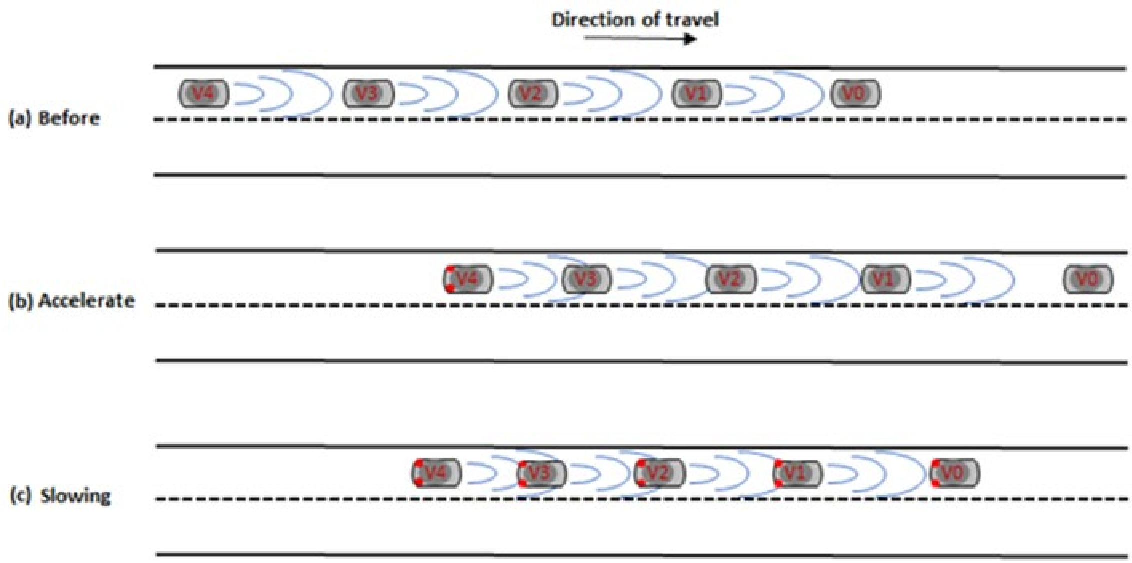
Figure 44: String Stability Scenario, 55 mph to Rolling Stop: CACC Relative Longitudinal Offset

4.4 String Stability Scenario, 45 mph to 60 mph[4]

4.4.1 Scenario Description

4.4.1.1 String Stability Scenario, 45 mph to 60 mph

In this scenario (as shown in Figure 45), a string of vehicles with either ACC/CACC activated travels along a straightaway at 45 mph. The lead vehicle speeds up to 60 mph at an acceleration of 2.5 m/s^2 and then decelerates to its original speed. This process is repeated once, and the behavior of the string is observed.



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

Figure 45: String Stability Scenario, 45 mph to 60 mph

4.4.2 Time Gap Stability

Figure 46 depicts the average value of the aggregated values for the difference in each HV's actual and set time gaps. ACC has an average time gap deviation of 0.17 seconds as compared to CACC having an average time gap deviation of 0.12 seconds. CACC performs better with a lower average deviation from the set time gap due to the information from the BSM.

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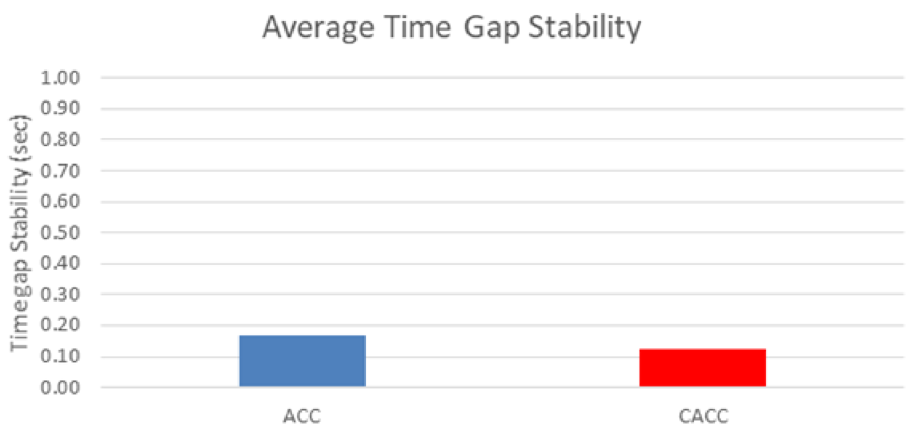
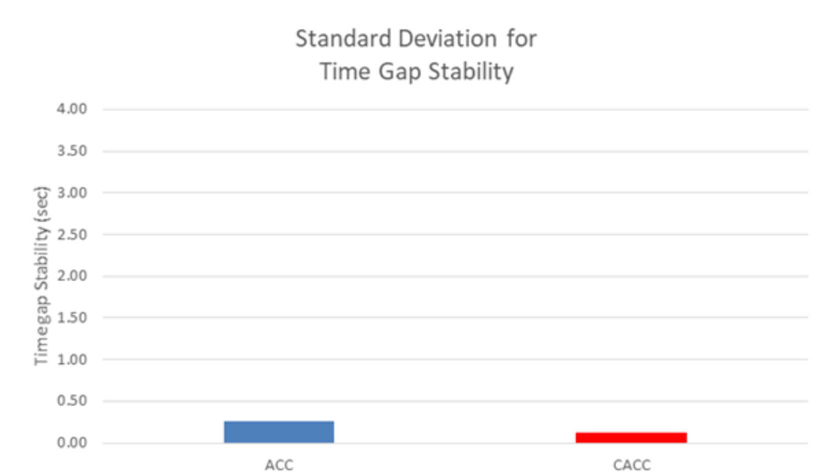
[4] Due to the smaller differences in minimum and maximum speed values in the maneuvers, the differences between ACC and CACC are less pronounced as those of the other String Stability Scenarios. Additionally, as the setup of the 45 mph to 60 mph String Stability Scenario uses an initial accelerative rather than a decelerative maneuver, the Deceleration Response Delay and Minimum Velocity Value KPIs were not examined.



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

Figure 46: String Stability Scenario, 45 mph to 60 mph: Average Time Gap Stability between ACC and CACC

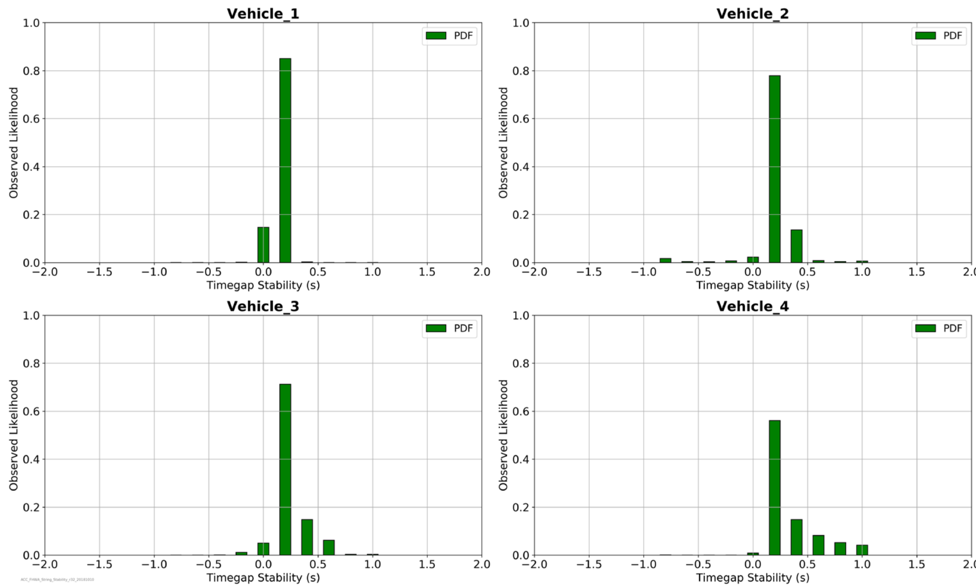
Figure 47 depicts the standard deviation of the aggregated values for the difference in each HV's actual and set time gaps. The standard deviation of the ACC vehicles' time gap deviation was 0.26 seconds as compared to CACC having a standard deviation of 0.12 seconds. CACC performs better with a lower standard deviation due to the information from the BSM.



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

Figure 47: String Stability Scenario, 45 mph to 60 mph: Standard Deviation of Time Gap Stability between ACC and CACC

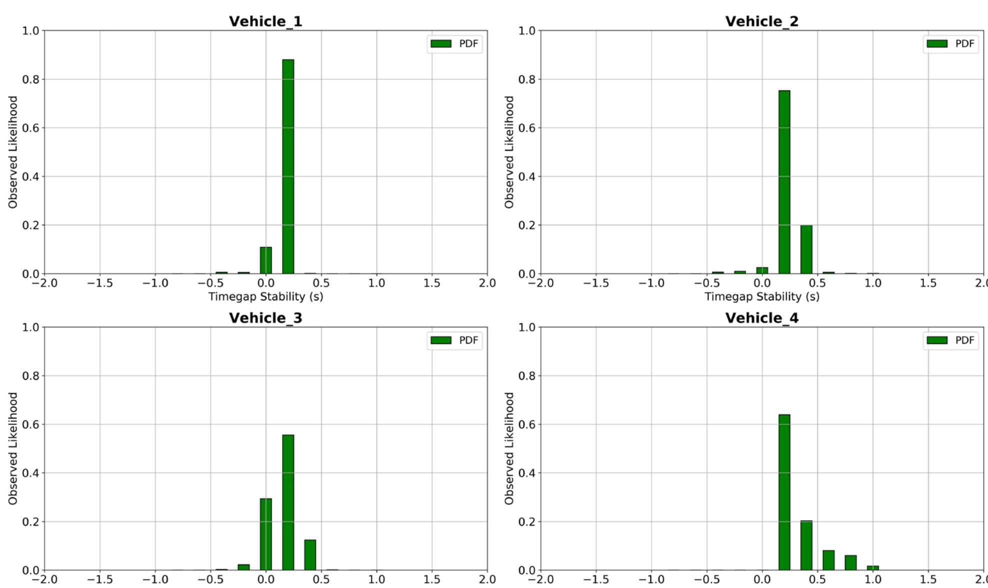
Figure 48 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each ACC vehicle in the string. The mean values for each PDF are 0.03, 0.12, 0.14, and 0.37 seconds difference for Vehicles 1-4, respectively, showing that in ACC the vehicles deviate progressively more from the set time gap down the string. The standard deviations for each PDF are 0.04, 0.28, 0.23, and 0.49 seconds for Vehicles 1-4, respectively, showing that in ACC the stability for each vehicles' time gaps progressively decreases down the string.



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

Figure 48: String Stability Scenario, 45 mph to 60 mph: ACC Time Gap Stability

Figure 49 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each CACC vehicle in the string. The mean values for each PDF are 0.04, 0.16, 0.04, and 0.24 seconds difference for Vehicles 1-4, respectively, showing that in CACC the vehicles deviate progressively more from the set time gap down the string but significantly less so than the same scenario in ACC. The standard deviations for each PDF are 0.07, 0.10, 0.11, and 0.18 seconds for Vehicles 1-4, respectively, showing that in CACC the stability for each vehicles' time gaps progressively decreases down the string, but again, significantly less so than ACC.

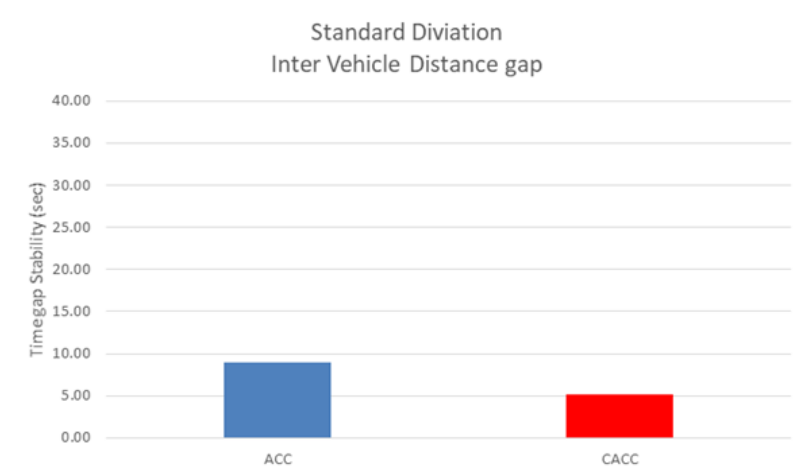


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 49: String Stability Scenario, 45 mph to 60 mph: CACC Time Gap Stability

4.4.3 Relative Longitudinal Offset

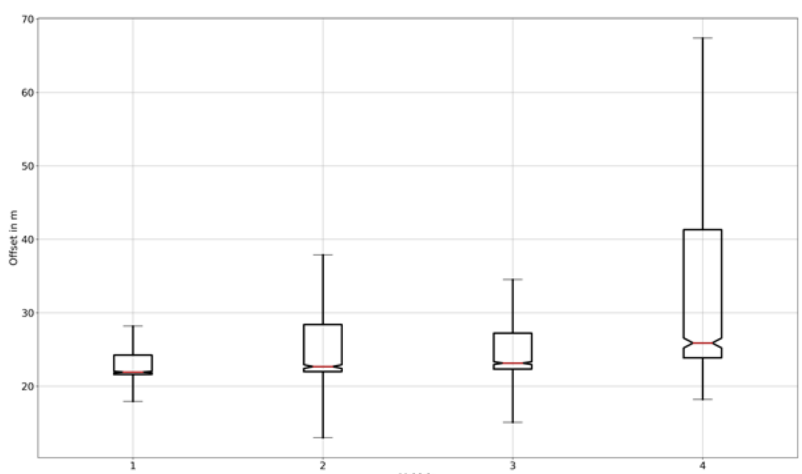
Figure 50 depicts the standard deviation of the aggregated values for the difference in each HV's actual and set time gaps. The standard deviation of the ACC vehicles' time gap deviation was 8.99 meters as compared to CACC having a standard deviation of 5.11 meters. CACC performs better with a lower standard deviation due to the information from the BSM.



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

Figure 50: String Stability Scenario, 45 mph to 60 mph: Average Time Gap Stability between ACC and CACC

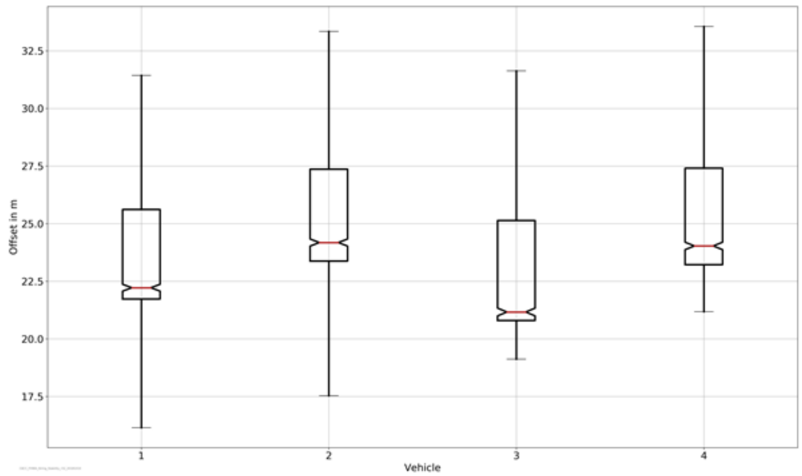
Figure 51 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each ACC vehicle in the string. The inter-quartile ranges for each box plot are 2.63, 6.41, 4.89, and 17.44 meters for Vehicles 1-4, respectively, showing that in ACC the stability for each vehicles' time gaps progressively decreases down the string.



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

Figure 51: String Stability Scenario, 45 mph to 60 mph: ACC Relative Longitudinal Offset

Figure 52 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each CACC vehicle in the string. The inter-quartile ranges for each box plot are 3.89, 3.99, 4.34, and 4.19 meters for Vehicles 1-4, respectively, showing that in CACC the stability for each vehicles' time gaps progressively decreases down the string, but again, significantly less so than ACC.



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

Figure 52: String Stability Scenario, 45 mph to 60 mph: CACC Relative Longitudinal Offset

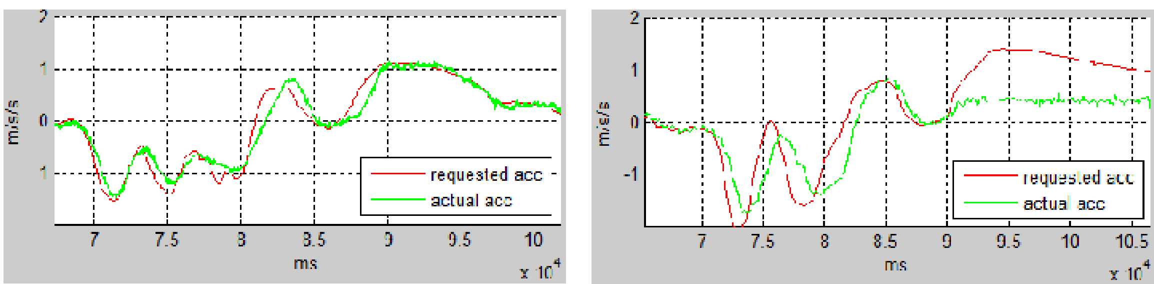
5 Stakeholder Demonstration

In order to exhibit the differences between ACC and CACC functionality to various stakeholders, both the experimental CACC systems were demonstrated using the Slow Down and String Stability Scenario, 55 mph to Rolling Stop requirements. This demonstration took place at FTTA’s Road D with the lead vehicle switching to the rearmost position in the string after each lap around the test course (2 sets of maneuvers) in order for each vehicle to perform maneuvers in each position in the CACC string.

6 Conclusions

6.1 Minimum Performance Requirements

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 CACC system but due to limitations in the interface that was being used to control the vehicles. This is illustrated in Figure 53 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: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 53: Vehicle Response to Acceleration Command

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 thereby 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. This project did not explicitly focus on deriving minimum performance requirements for acceleration. But based on the response of all four CACC vehicles in this project, it was observed that the vehicles with a minimum acceleration/deceleration capability of +1.0 m/s^2 to -3.5 m/s^2 were able to maintain the string.

6.2 Outlook

The algorithms developed, as well as its respective system architecture, are adapted by the TOSCo architecture and aims at integrating traffic light information with the longitudinal controller to compute optimized approach strategies.

7 Appendices

7.1 Final KPI Tables

Table 4: Deceleration Response and Minimum Speed Value Results

					ACC		CACC	
KPI	**Unit**	**Metric**	**Scenario**	**Acceleration**	**µ**	**σ**	**µ**	**σ**
Relative Longitudinal Offset	m	Standard Deviation	55 to 30 mph	-2.5		8.961		8.556
			55 to 30 mph	-3.5		19.77		9.021
			60 to 25 mph	-2.5		34.483		18.509
			55 mph to Rolling Stop	-2.5		13.514		9.156
			45 to 60 mph	-2.5		8.994		5.112
Time Gap Stability	s	Mean and Standard Deviation	55 to 30 mph	-2.5	0.471	0.486	0.343	0.278
			55 to 30 mph	-3.5	0.646	0.759	0.383	0.307
			60 to 25 mph	-2.5	0.718	1.812	0.53	0.498
			55 mph to Rolling Stop	-2.5	0.964	3.58	0.554	0.59
			45 to 60 mph	-2.5	0.17	0.265	0.122	0.117

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

Table 5: Relative Longitudinal Offset and Time Gap Stability Results[5]

KPI	Unit	Metric	Scenario	Acceleration	ACC	CACC
Acceleration Response Delay	s	Time Difference	55 to 30 mph	-2.5	1.35	0.925
			55 to 30 mph	-3.5	1.475	0.475
			60 to 25 mph	-2.5	1.667	0.825
			55 mph to Rolling Stop	-2.5	1.25	0.95
			45 to 60 mph	-2.5	1.35	0.3
Minimum Velocity Value	s	Average Value	55 to 30 mph	-2.5	-1.35	0.25
			55 to 30 mph	-3.5	-2.025	0.625
			60 to 25 mph	-2.5	-1.125	0.4
			55 mph to Rolling Stop	-2.5	-0.9	0.013
			45 to 60 mph	-2.5		

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

[5] As the setup of the 45 mph to 60 mph String Stability Scenario uses an initial accelerative rather than a decelerative maneuver, the Deceleration Response Delay and Minimum Velocity Value KPIs were not examined.

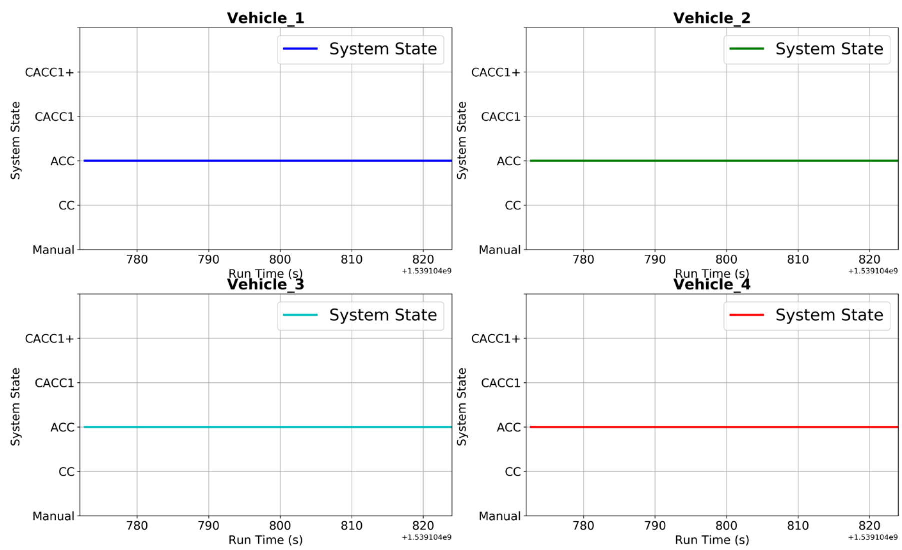
7.2 Time Series Plots[6]

7.2.1 String Stability Scenario, 55 mph to 30 mph

7.2.1.1 Moderate Deceleration (-2.5 m/s²)

7.2.1.1.1 ACC

Figure 54 depicts the system state that each ACC vehicle was in for the duration of the test and that each vehicle was completely in ACC mode for the duration of the test.

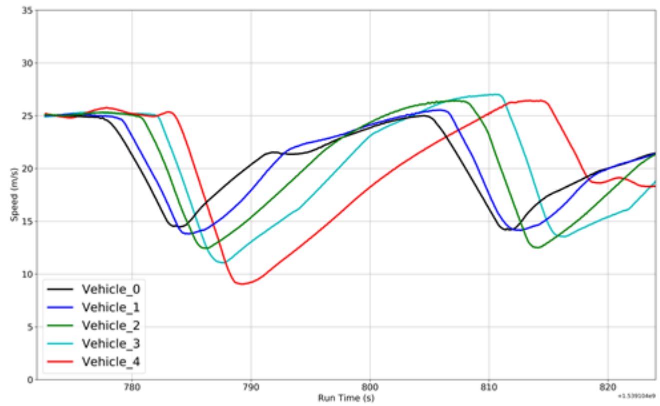


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 54: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: ACC Time Series Plot for System State

Figure 55 depicts the speed plot for a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 777 seconds, Vehicle 0 decelerates to 14.4 m/s, followed by an acceleration back to 25 m/s. Vehicles 1-4 decelerate to 13.7, 12.4, 10.9, and 9.0 m/s, respectively. These vehicles decelerate to slower speeds down the string since they each have a progressively shorter amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.

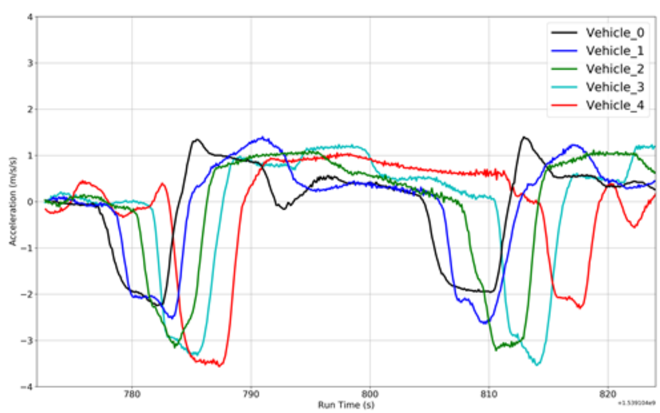
[6] Speed time series plots for String Stability Scenario, 55 mph to 30 mph, with a deceleration of -3.5 m/s² and String Stability Scenario, 55 mph to Rolling Stop are used in Section 4.



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

Figure 55: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: ACC Time Series Plot for Speed

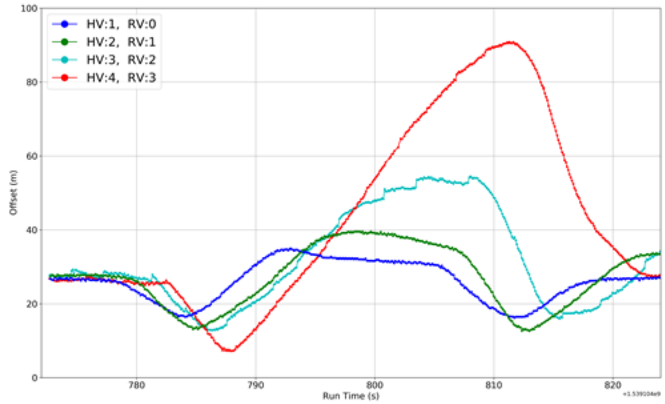
Figure 56 depicts the acceleration plot for a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 777 seconds, Vehicle 0 decelerates, followed by acceleration back to 25 m/s. The maximum decelerations down the string of ACC vehicles became progressively harsher since they each have a progressively shorter amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 56: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: ACC Time Series Plot for Acceleration

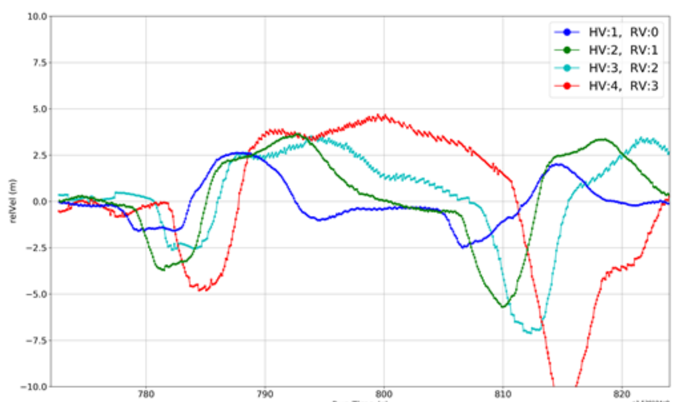
Figure 57 depicts the relative longitudinal offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 777 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each ACC vehicle relative to its preceding vehicle decreased down the string, due to increasingly longer response times.



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

Figure 57: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: ACC Time Series Plot for Relative Longitudinal Offset

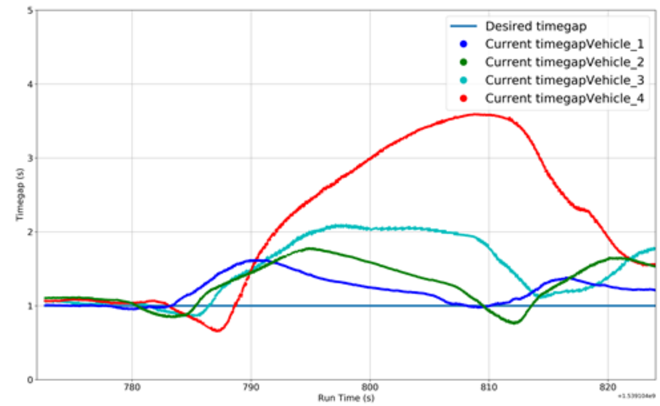
Figure 58 depicts the relative speed offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 777 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each ACC vehicle relative to its preceding vehicle decreased down the string in the deceleration maneuver, due to increasingly longer response times.



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

Figure 58: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: ACC Time Series Plot for Relative Speed

Figure 59 depicts the time gap plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 777 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each ACC vehicle's time gap decreased below the desired time gap and then corrected accordingly to return to its set time gap of 1 second.

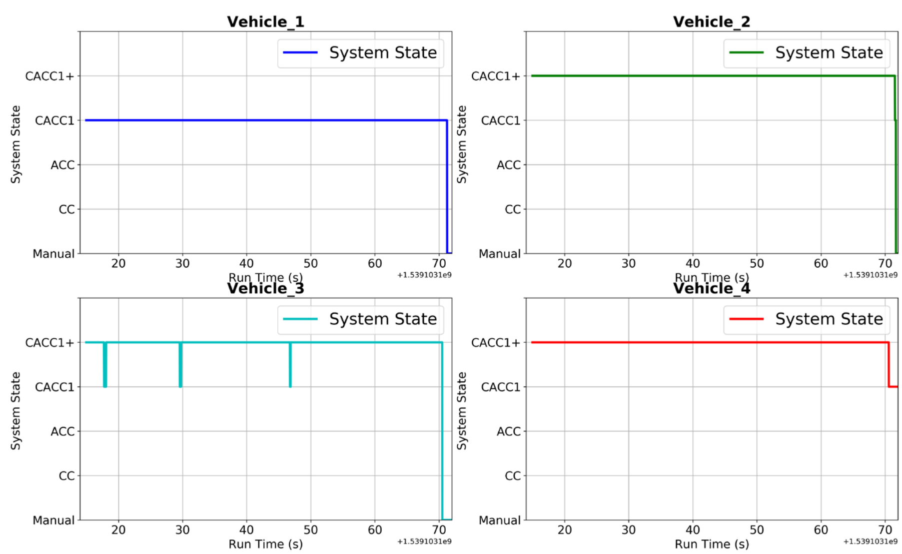


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 59: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: ACC Time Series Plot for Time Gap

7.2.1.1.2 CACC

Figure 60 depicts the system state that each CACC vehicle was in for the duration of the test. This shows that each vehicle was completely in CACC mode for the duration of the test, with small changes in Vehicle 3 due to minor time synchronization issues.

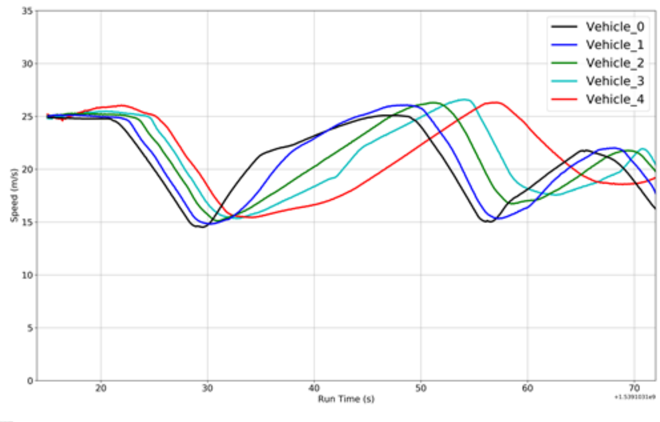


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 60: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: CACC Time Series Plot for System State

Figure 61 depicts the speed plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 21 seconds, Vehicle 0 decelerates to 14.5 m/s, followed by an acceleration back to

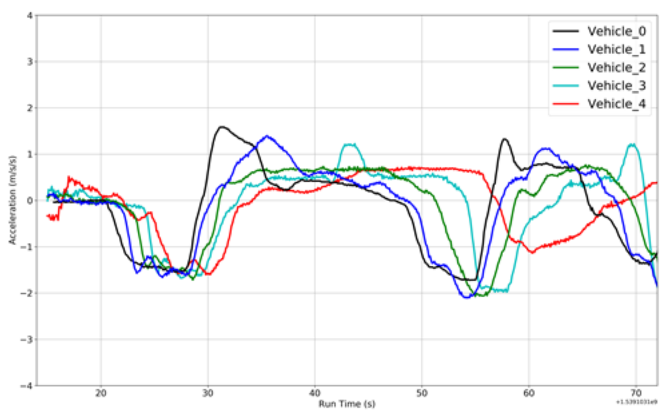
25 m/s. Vehicles 1-4 decelerate to 14.8, 15.1, 15.4, and 15.5 m/s, respectively. These vehicles decelerate to higher speeds down the string since they each have a progressively longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 61: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: CACC Time Series Plot for Speed

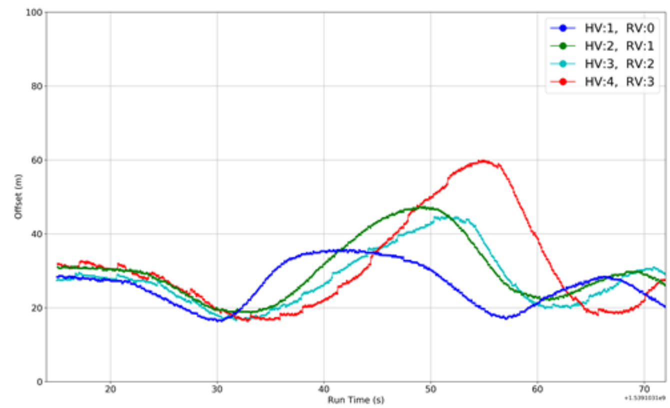
Figure 62 depicts the acceleration plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 21 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of CACC vehicles remained relatively consistent since they each have a longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle compared to ACC.



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

Figure 62 : String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: CACC Time Series Plot for Acceleration

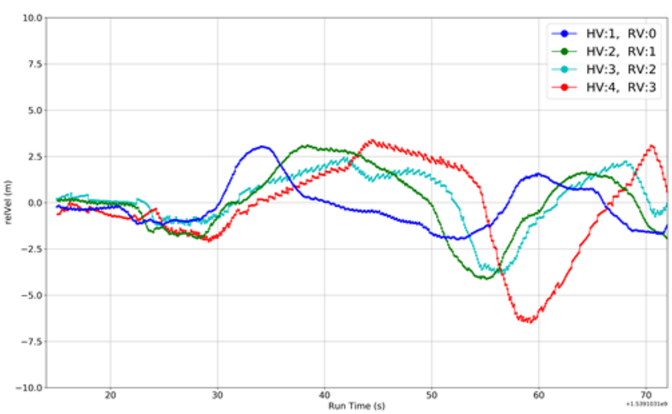
Figure 63 depicts the relative longitudinal offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 21 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each CACC vehicle relative to its preceding vehicle remained constant down the string due to the increasingly longer times to respond.



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

Figure 63: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: CACC Time Series Plot for Relative Longitudinal Offset

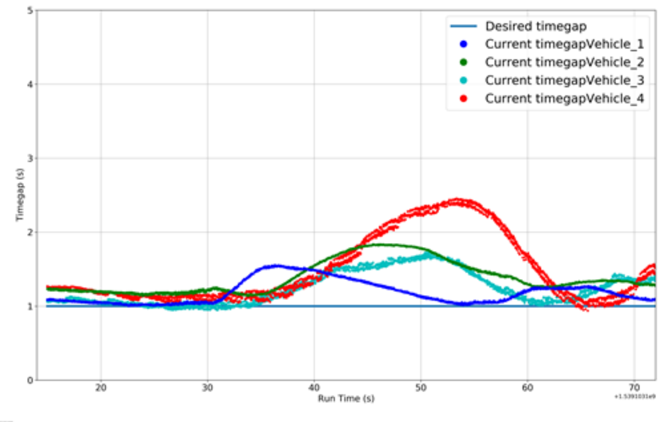
Figure 64 depicts the relative speed offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 21 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each CACC vehicle relative to its preceding vehicle remained constant down the string in the deceleration maneuver due to the increasingly longer times to respond.



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

Figure 64: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: CACC Time Series Plot for Relative Speed

Figure 65 depicts the time gap plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 21 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each CACC vehicle's time gap remained at or above the desired time gap.

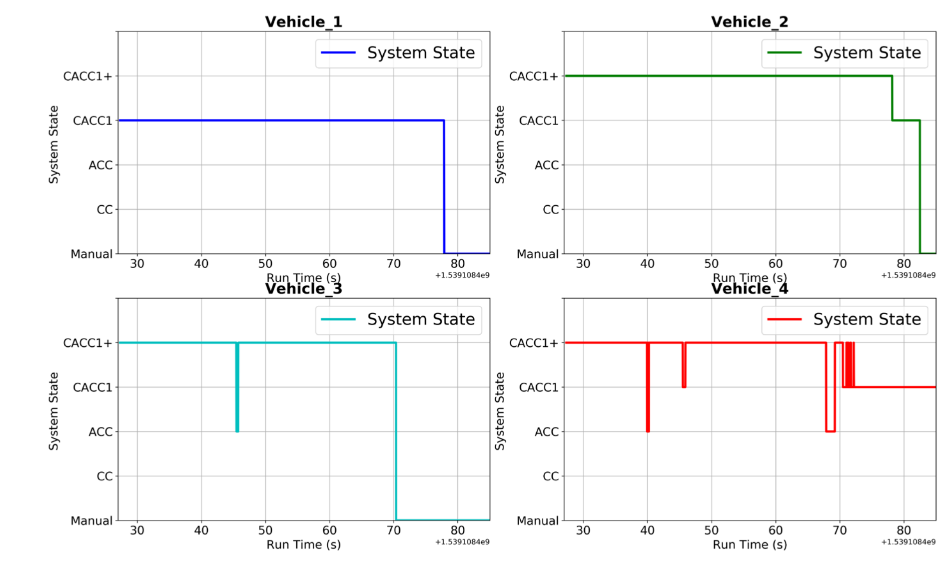


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 65: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration: CACC Time Series Plot for Time Gap

7.2.1.1.3 CACC with 0.6 Second Time Gap

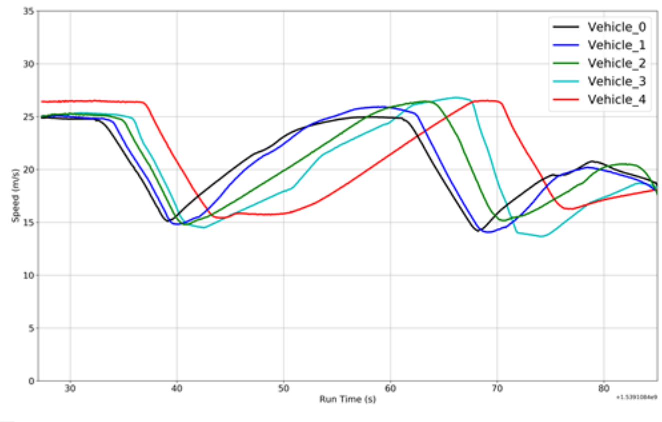
Figure 66 depicts the system state that each CACC vehicle was in for the duration of the test. This shows that each vehicle was completely in CACC mode for the duration of the maneuver with small changes in Vehicles 3 and 4 due to object fusion issues and manual braking by all vehicles at the end of the test run. Vehicle 4 continued to follow in CACC mode without braking at the end of the test run.



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

Figure 66: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Time Series Plot for System State, 0.6 Second Time Gap

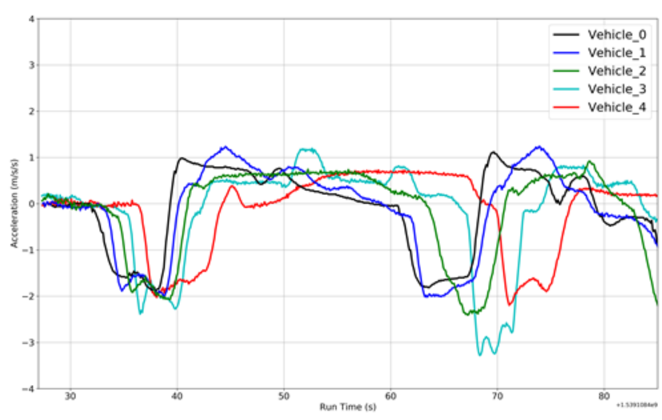
Figure 67 depicts the speed plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 33 seconds, Vehicle 0 decelerates to 15.1 m/s, followed by an acceleration back to 25 m/s. Vehicles 1-4 decelerate to 14.75, 14.7, 14.4, and 15.45 m/s, respectively. These vehicles decelerate to relatively consistent or higher speeds down the string since they each have a progressively longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 67: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Time Series Plot for Speed, 0.6 Second Time Gap

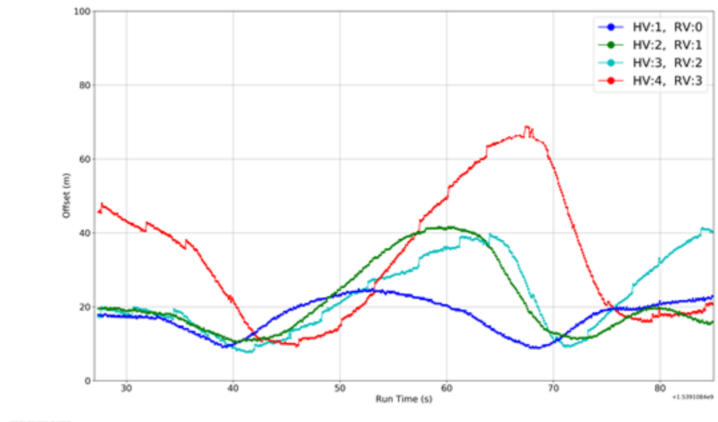
Figure 68 depicts the acceleration plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 33 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of CACC vehicles remained relatively consistent since they each have a longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle compared to ACC.



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

Figure 68: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Time Series Plot for Acceleration, 0.6 Second Time Gap

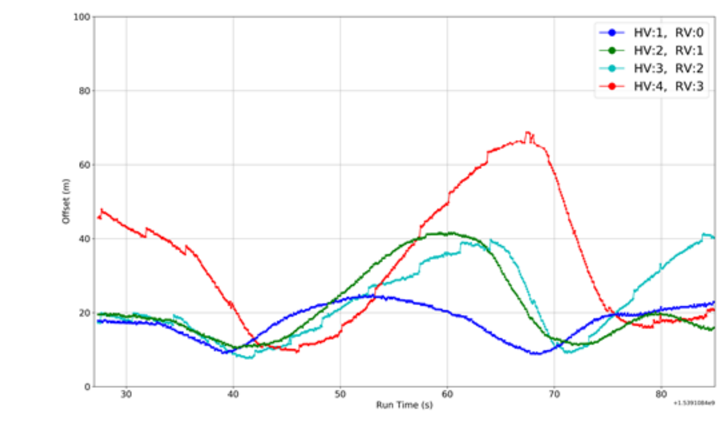
Figure 69 depicts the relative longitudinal offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 33 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each CACC vehicle relative to its preceding vehicle remained relatively consistent down the string due to the increasingly longer times to respond.



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

Figure 69: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Time Series Plot for Relative Longitudinal Offset, 0.6 Second Time Gap

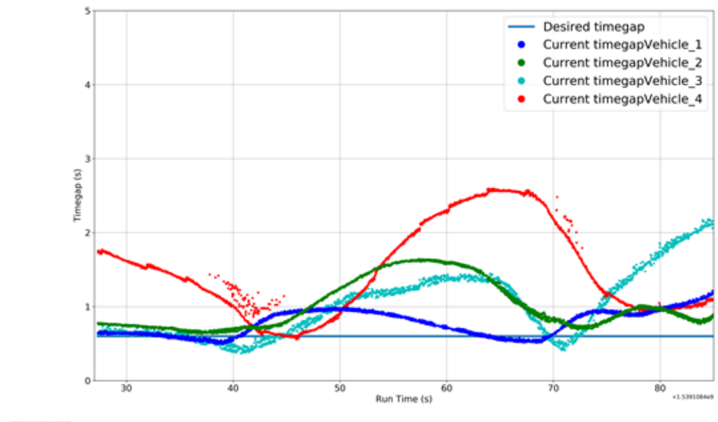
Figure 70 depicts the relative speed offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 33 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each CACC vehicle relative to its preceding vehicle remained constant, with the exception of Vehicle 4 (see Section 2.4) down the string in the deceleration maneuver due to the increasingly longer times to respond.



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

Figure 70: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Time Series Plot for Relative Speed, 0.6 Second Time Gap

Figure 71 depicts the time gap plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 33 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each CACC vehicle's time gap remained relatively close to the desired time gap.



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

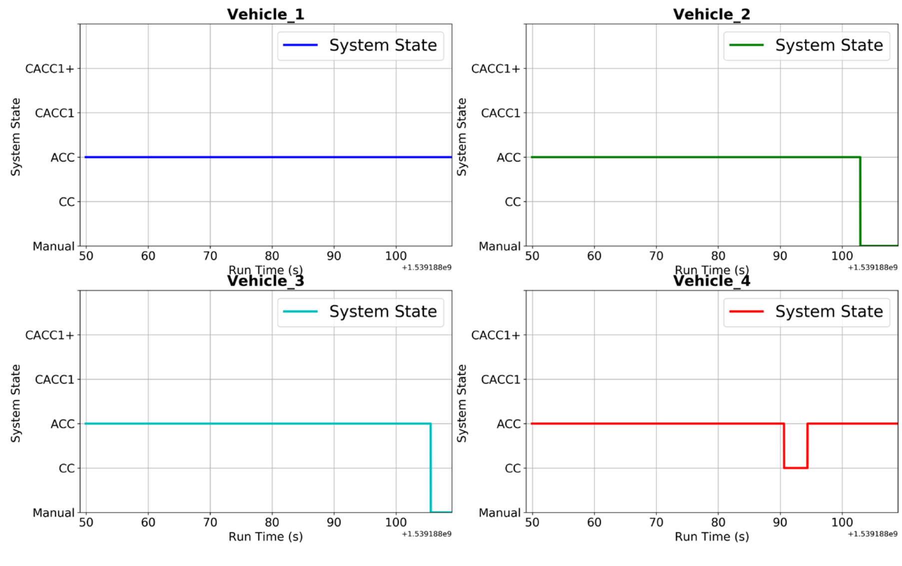
Figure 71: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Time Series Plot for Time Gap, 0.6 Second Time Gap

7.2.1.2 Harsh Deceleration (-3.5 m/s²)[7]

7.2.1.2.1 ACC

Figure 72 depicts the system state that each ACC vehicle was in for the duration of the test. This shows that each vehicle was completely in ACC mode for the duration of the test, with the exception of Vehicle 4 which had a limited maximum commanded acceleration and lost its radar target (see Section 2.4).

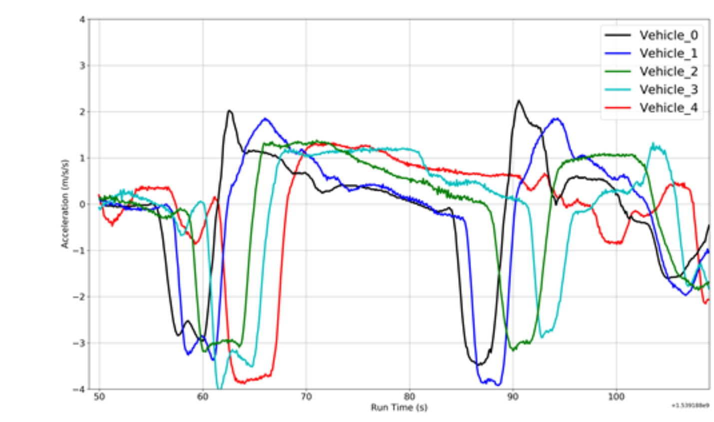
[7] Time Series Plots for Speed are used in Chapter 4.2.



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

Figure 72: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, ACC Time Series Plot for System State

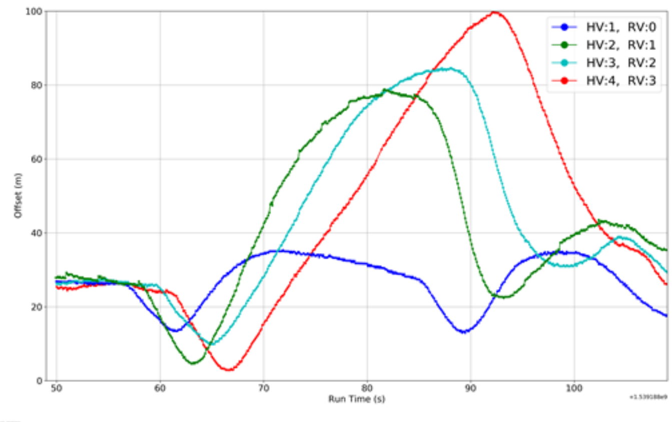
Figure 73 depicts the acceleration plot for a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 57 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of ACC vehicles became progressively harsher since they each have a progressively shorter amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 73: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, ACC Time Series Plot for Acceleration

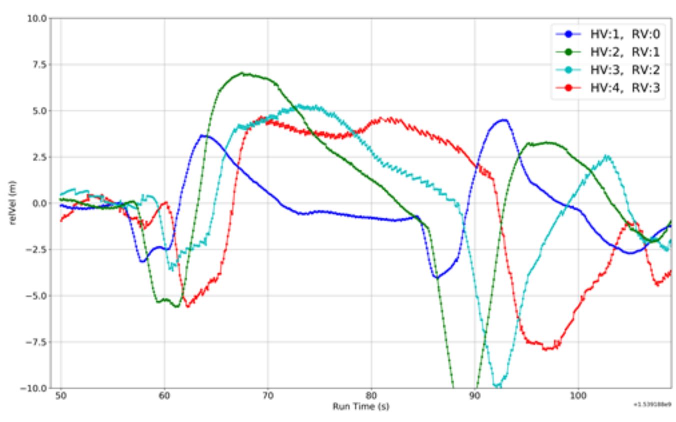
Figure 74 depicts the relative longitudinal offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 57 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each ACC vehicle relative to its preceding vehicle decreased down the string due to increasingly longer response times.



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

Figure 74: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, ACC Time Series Plot for Relative Longitudinal Offset

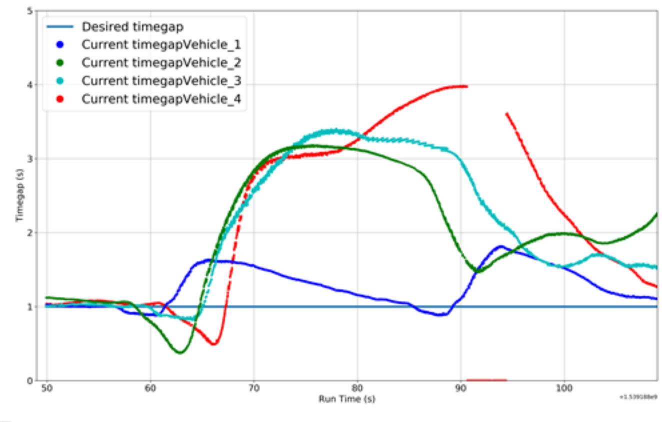
Figure 75 depicts the relative speed offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 57 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each ACC vehicle relative to its preceding vehicle decreased down the string in the deceleration maneuver due to increasingly longer response times.



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

Figure 75: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, ACC Time Series Plot for Relative Speed

Figure 76 depicts the time gap plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 777 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each ACC vehicle's time gap significantly decreased below the desired time gap and then corrected accordingly to return to its set time gap of 1 second.

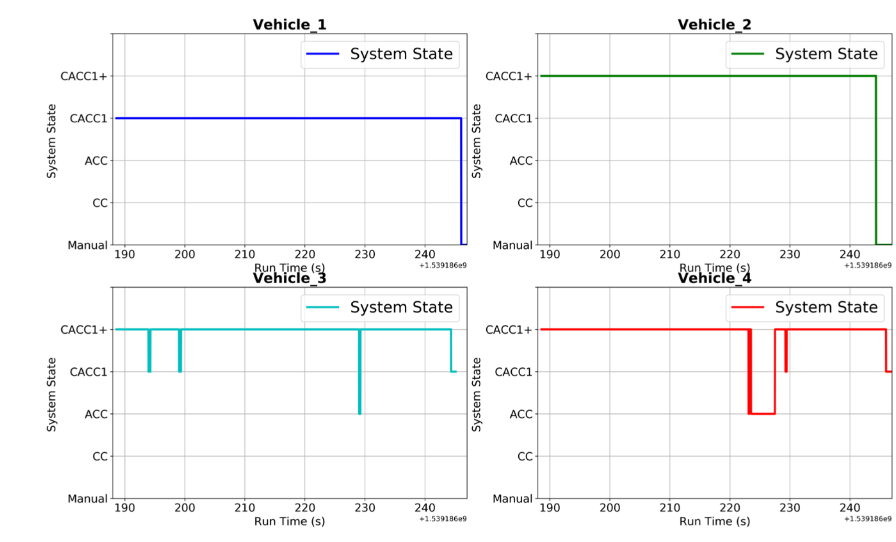


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 76: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, ACC Time Series Plot for Time Gap

7.2.1.2.2 CACC

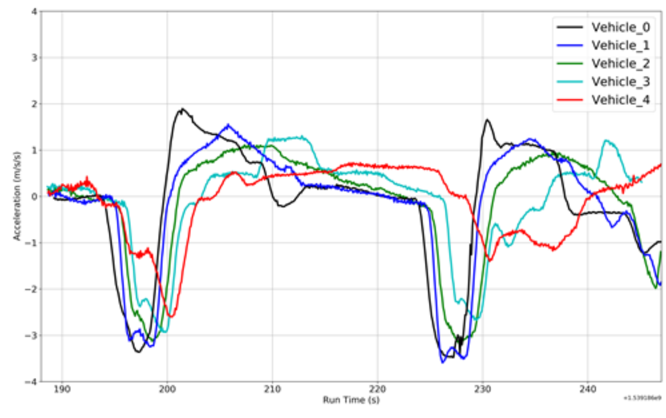
Figure 77 depicts the system state that each CACC vehicle was in for the duration of the test. This shows that each vehicle was completely in CACC mode for the duration of the test, with small changes in Vehicle 3 due to minor time synchronization issues, and the same commanded acceleration limits for Vehicle 4 as shown in Section 7.2.1.1.



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

Figure 77: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for System State

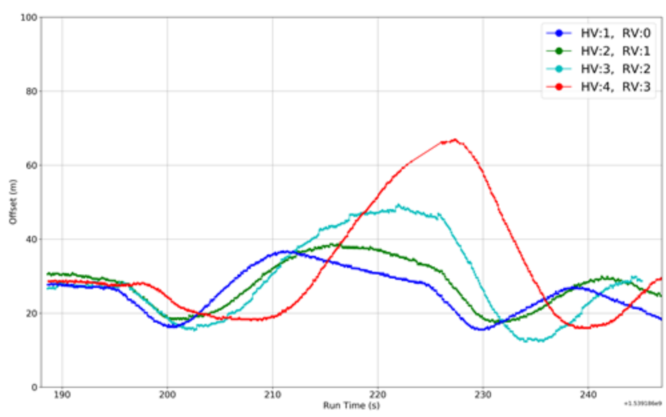
Figure 78 depicts the acceleration plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 195 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of CACC vehicles remained relatively consistent since they each have a longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle compared to ACC.



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

Figure 78: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Acceleration

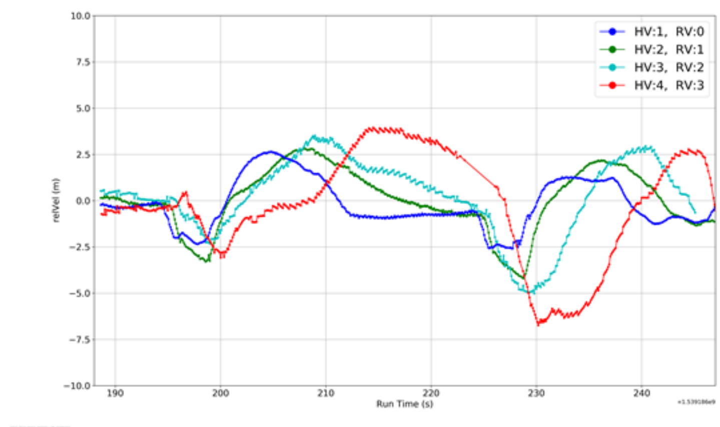
Figure 79 depicts the relative longitudinal offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 195 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each CACC vehicle relative to its preceding vehicle remained constant down the string due to the increasingly longer times to respond.



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

Figure 79: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Relative Longitudinal Offset

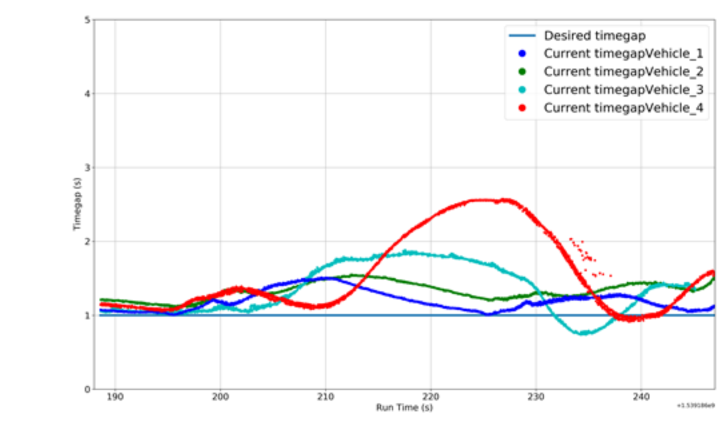
Figure 80 depicts the relative speed offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 195 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each CACC vehicle relative to its preceding vehicle remained constant down the string in the deceleration maneuver due the increasingly longer times to respond.



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

Figure 80: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Relative Speed

Figure 81 depicts the time gap plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 195 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each CACC vehicle's time gap remained at or above the desired time gap.

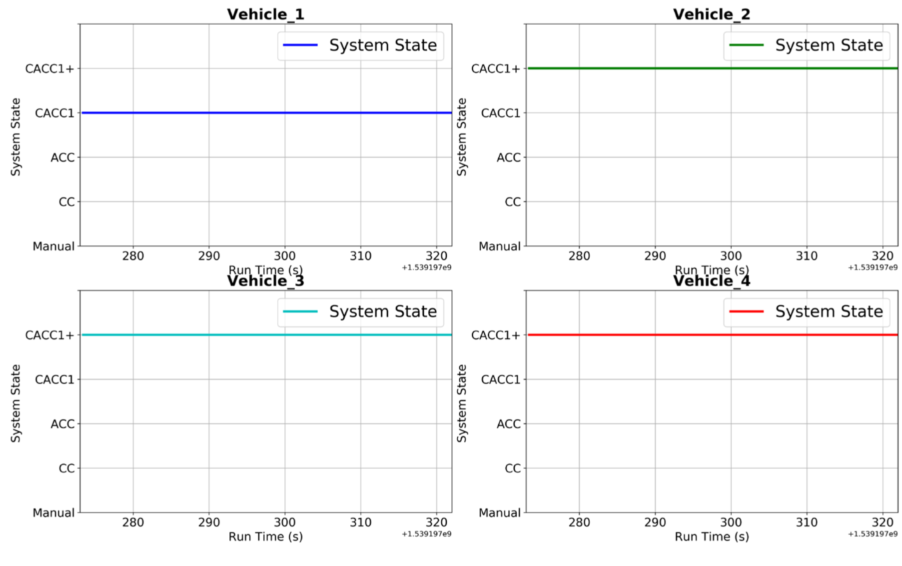


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 81: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Time Gap

7.2.1.2.3 CACC with 0.6 Second Time Gap

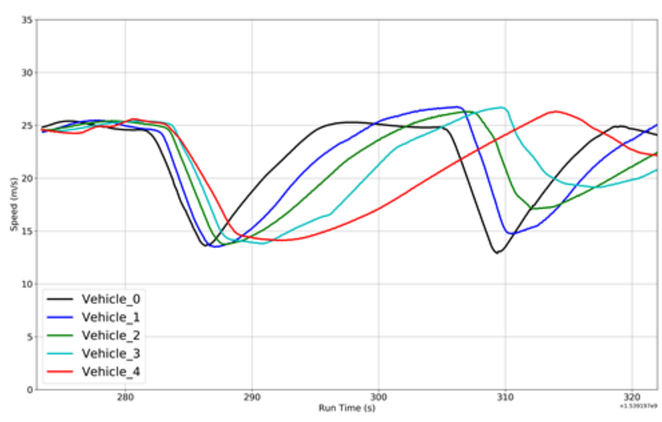
Figure 82 depicts the system state that each CACC vehicle was in for the duration of the test. This shows that each vehicle was completely in CACC mode for the duration of the maneuver.



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

Figure 82: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for System State, 0.6 Second Time Gap

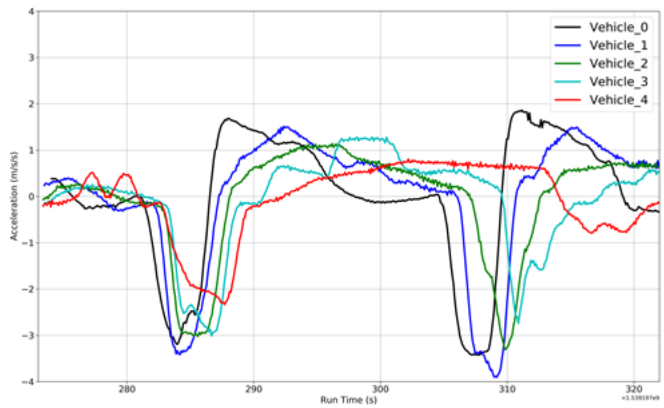
Figure 83 depicts the speed plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 283 seconds, Vehicle 0 decelerates to 13.6 m/s, followed by an acceleration back to 25 m/s. Vehicles 1-4 decelerate to 13.4, 13.75, 13.8, and 14.1 m/s, respectively. These vehicles decelerate to relatively consistent or higher speeds down the string since they each have a progressively longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 83: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Speed, 0.6 Second Time Gap

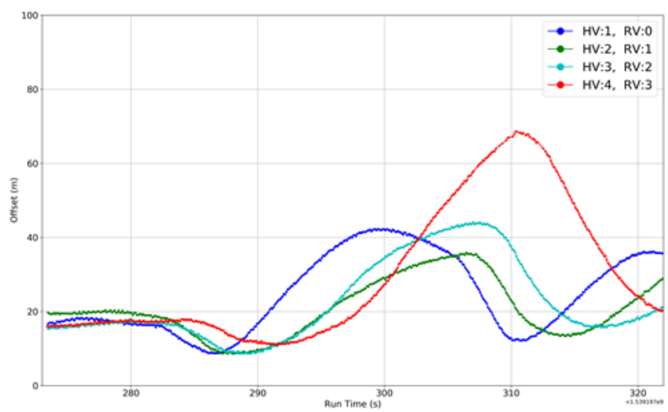
Figure 84 depicts the acceleration plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 283 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of CACC vehicles remained relatively consistent since they each have a longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle compared to ACC.



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

Figure 84: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Acceleration, 0.6 Second Time Gap

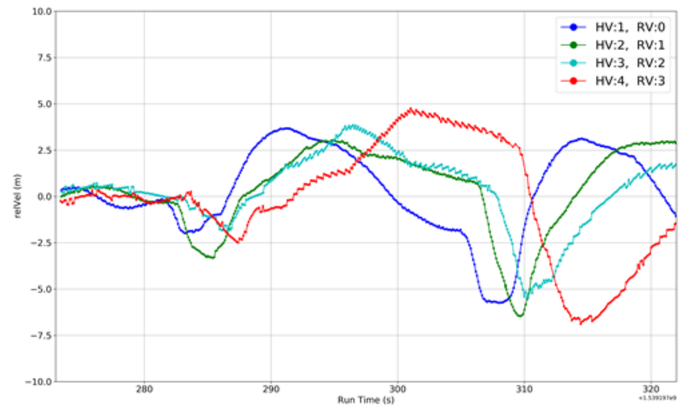
Figure 85 depicts the relative longitudinal offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 283 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each CACC vehicle relative to its preceding vehicle remained relatively consistent down the string due to the increasingly longer times to respond.



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

Figure 85: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Relative Longitudinal Offset, 0.6 Second Time Gap

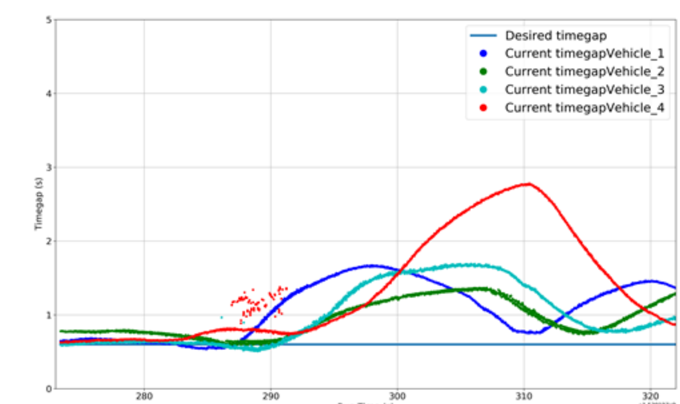
Figure 86 depicts the relative speed offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 33 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each CACC vehicle relative to its preceding vehicle remained constant down the string in the deceleration maneuver due to the increasingly longer times to respond.



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

Figure 86: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Relative Speed, 0.6 Second Time Gap

Figure 87 depicts the time gap plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 283 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each CACC vehicle's time gap remained relatively close to the desired time gap.



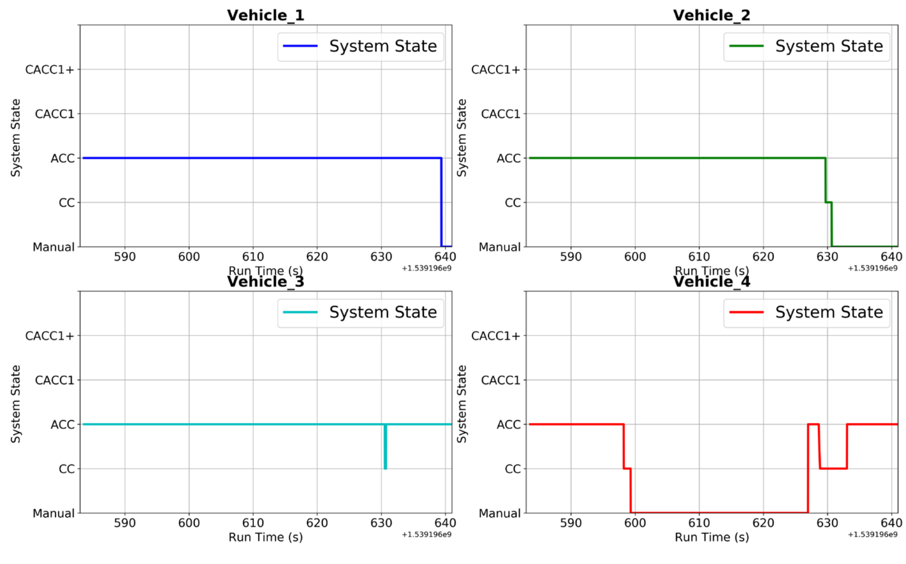
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 87: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Series Plot for Time Gap, 0.6 Second Time Gap

7.2.2 String Stability Scenario, 60 mph to 25 mph

7.2.2.1 ACC

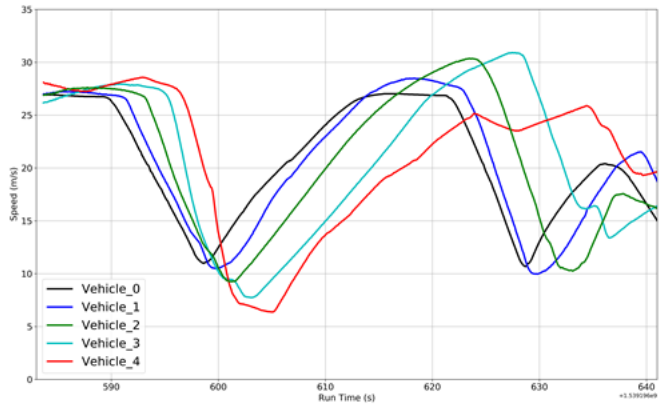
Figure 88 depicts the system state that each ACC vehicle was in for the duration of the test. This shows that each vehicle was completely in ACC mode for the duration of the test, with small changes in Vehicle 3 due to minor time synchronization issues, and the same commanded acceleration limits for Vehicle 4 as shown in Section 7.2.1.1. Vehicle 2 manually braked near the end of the test run.



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

Figure 88: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, ACC Time Series Plot for System State

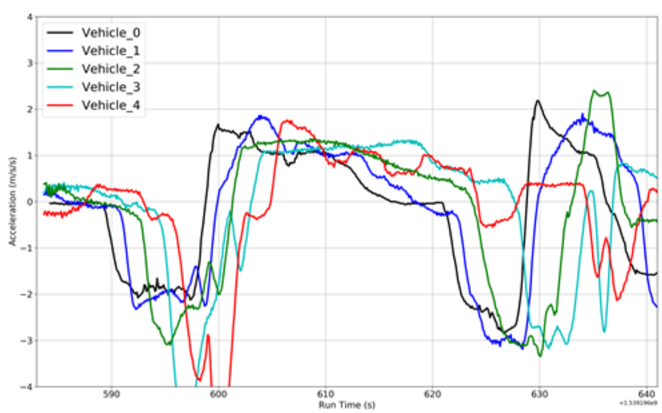
Figure 89 depicts the speed plot for a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 590 seconds, Vehicle 0 decelerates to 10.9 m/s, followed by an acceleration back to 25 m/s. Vehicles 1-4 decelerate to 10.5, 9.3, 7.7, and 6.4 m/s, respectively. These vehicles decelerate to slower speeds down the string since they each have a progressively shorter amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 89: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, ACC Time Series Plot for Speed

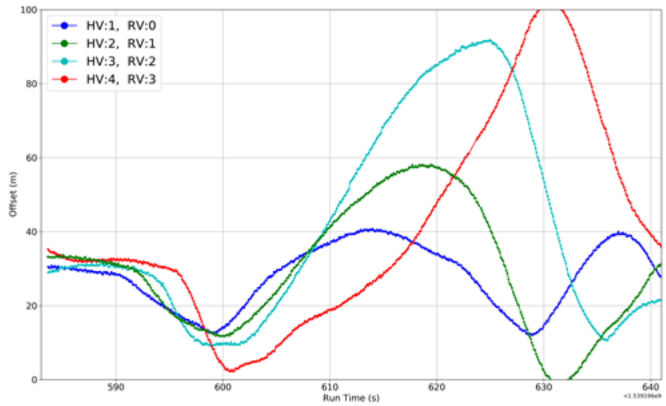
Figure 90 depicts the acceleration plot for a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 590 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of ACC vehicles became progressively harsher since they each have a progressively shorter amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 90: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, ACC Time Series Plot for Acceleration

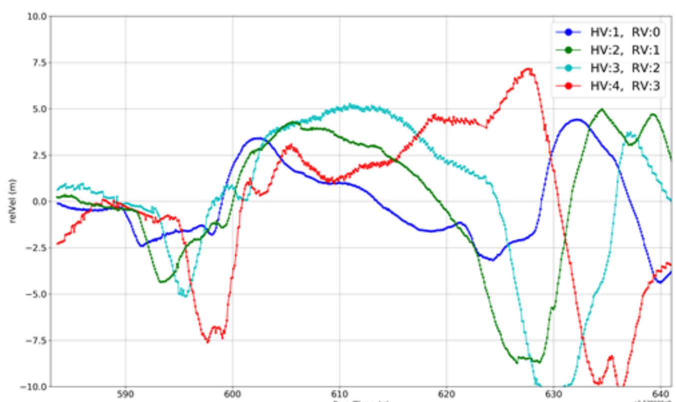
Figure 91 depicts the relative longitudinal offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 590 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each ACC vehicle relative to its preceding vehicle decreased down the string due to increasingly longer response times.



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

Figure 91: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, ACC Time Series Plot for Relative Longitudinal Offset

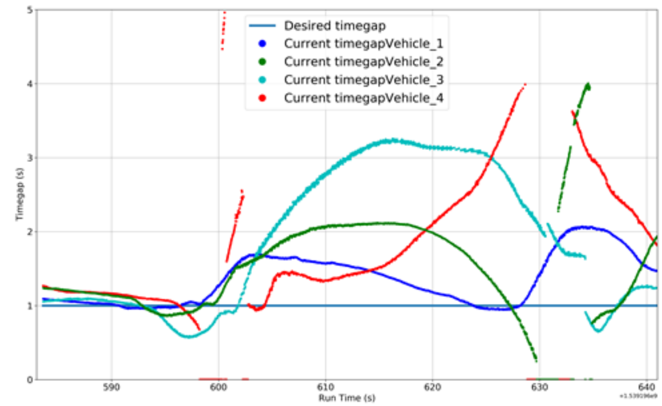
Figure 92 depicts the relative speed offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 590 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each ACC vehicle relative to its preceding vehicle decreased down the string in the deceleration maneuver due to increasingly longer response times.



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

Figure 92: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, ACC Time Series Plot for Relative Speed

Figure 93 depicts the time gap plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 590 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each ACC vehicle's time gap decreased below the desired time gap and then corrected accordingly to return to its set time gap of one second.

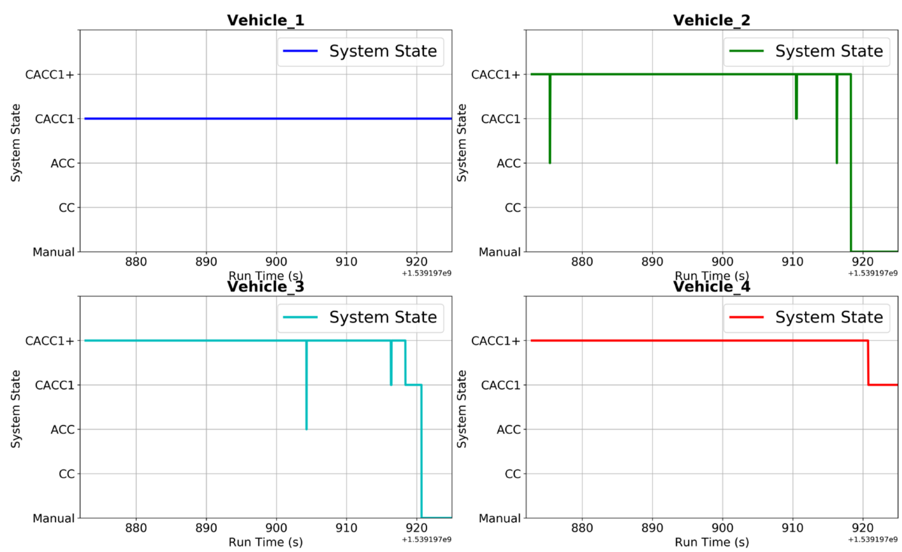


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 93: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, ACC Time Series Plot for Time Gap

7.2.2.2 CACC

Figure 94 depicts the system state that each CACC vehicle was in for the duration of the test. This shows that each vehicle was completely in CACC mode for the duration of the test, with small changes in Vehicles 2 and 3 due to minor time synchronization and object fusion issues.

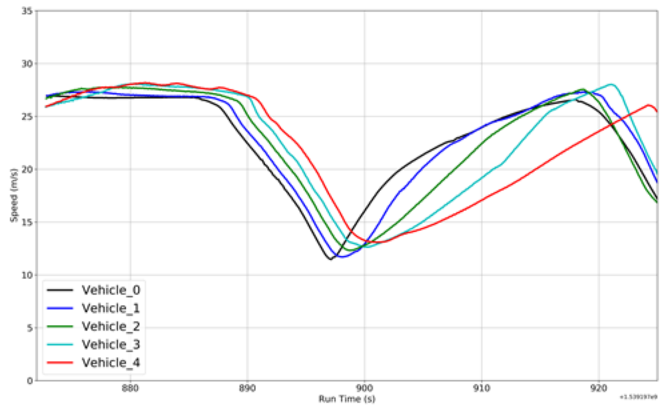


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 94: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, CACC Time Series Plot for System State

Figure 95 depicts the speed plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 887 seconds, Vehicle 0 decelerates to 11.5 m/s, followed by an acceleration back to

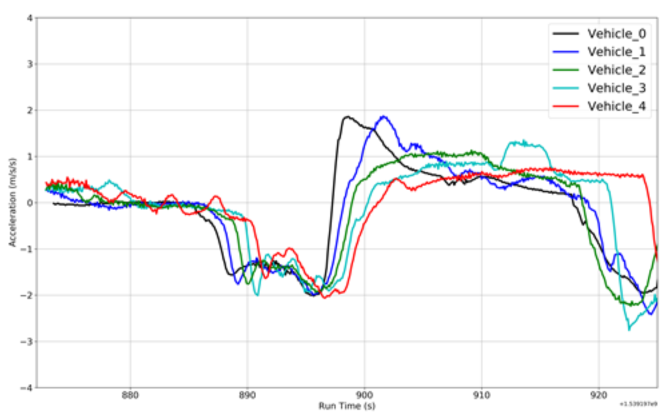
25 m/s. Vehicles 1-4 decelerate to 11.7, 12.3, 12.7, and 13.1 m/s, respectively. These vehicles decelerate to higher speeds down the string since they each have a progressively longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 95: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, CACC Time Series Plot for Speed

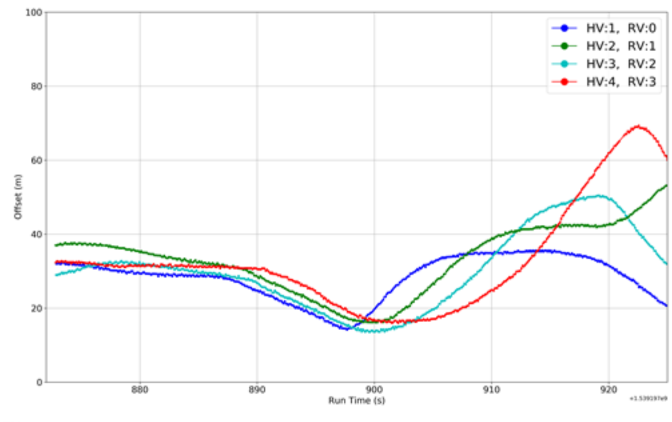
Figure 96 depicts the acceleration plot for a string of vehicles in CACC mode, with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s; at approximately 887 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of CACC vehicles remained relatively consistent since they each have a longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle compared to ACC.



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

Figure 96: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, CACC Time Series Plot for Acceleration

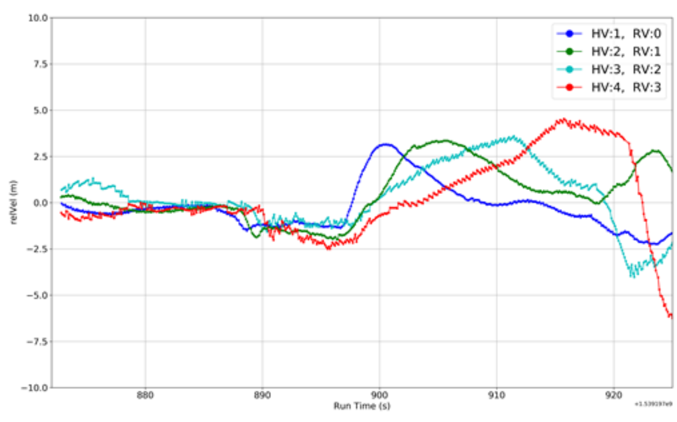
Figure 97 depicts the relative longitudinal offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 887 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each CACC vehicle relative to its preceding vehicle remained constant down the string due to the increasingly longer times to respond.



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

Figure 97: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, CACC Time Series Plot for Relative Longitudinal Offset

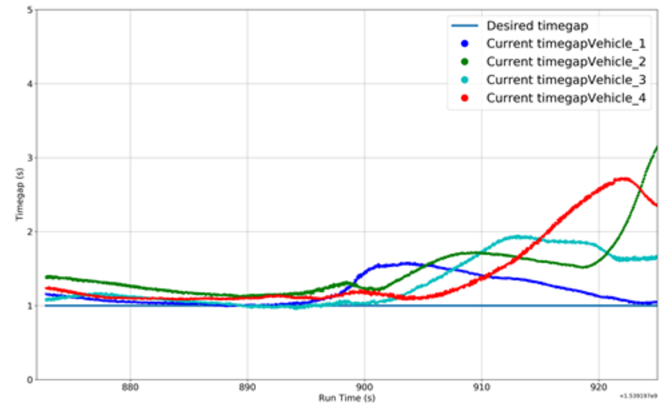
Figure 98 depicts the relative speed offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 887 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each CACC vehicle relative to its preceding vehicle remained constant down the string in the deceleration maneuver due the increasingly longer times to respond.



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

Figure 98: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, CACC Time Series Plot for Relative Speed

Figure 99 depicts the time gap plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 887 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each CACC vehicle’s time gap remained at or above the desired time gap.



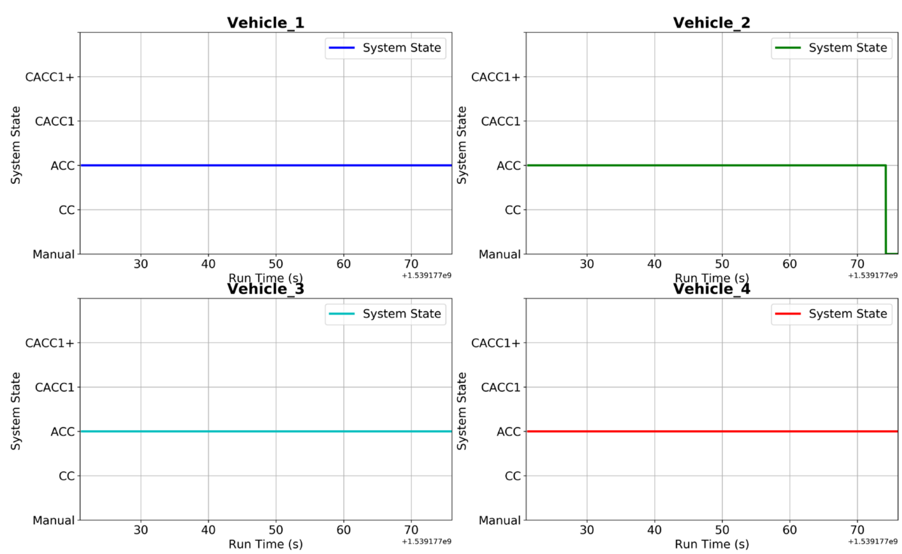
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 99: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, CACC Time Series Plot for Time Gap

7.2.3 String Stability Scenario, 55 mph to Rolling Stop

7.2.3.1 ACC

Figure 100 depicts the system state that each ACC vehicle was in for the duration of the test. This shows that each vehicle was completely in ACC mode for the duration of the test.

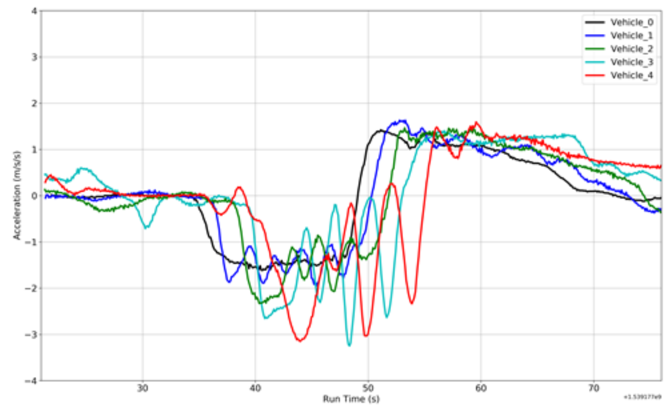


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 100: String Stability Scenario, 55 mph to Rolling Stop: ACC Time Series Plot for System State

Figure 101 depicts the acceleration plot for a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s.

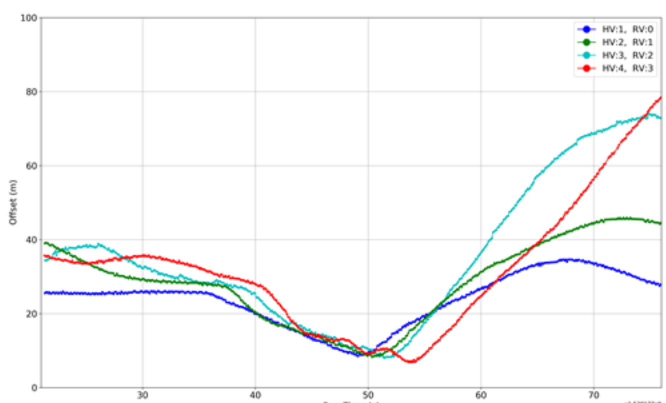
At approximately 36 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of ACC vehicles became progressively harsher since they each have a progressively shorter amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 101: String Stability Scenario, 55 mph to Rolling Stop: ACC Time Series Plot for Acceleration

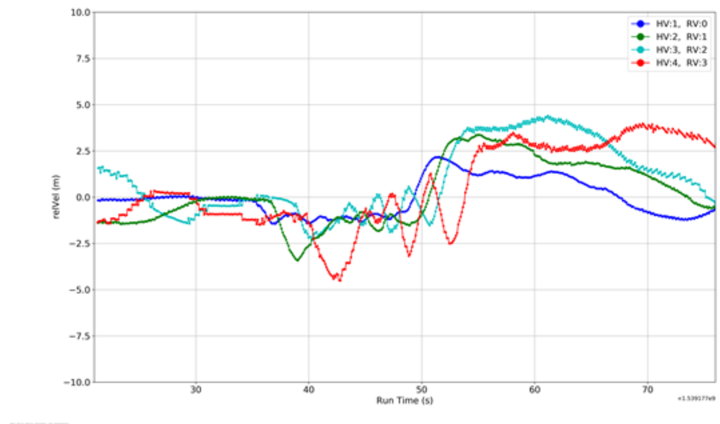
Figure 102 depicts the relative longitudinal offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 36 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each ACC vehicle relative to its preceding vehicle decreased down the string due to increasingly longer response times.



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

Figure 102: String Stability Scenario, 55 mph to Rolling Stop: ACC Time Series Plot for Relative Longitudinal Offset

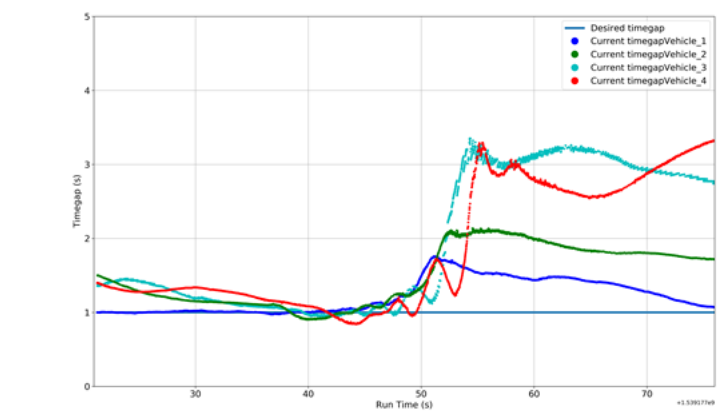
Figure 103 depicts the relative speed offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 36 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each ACC vehicle relative to its preceding vehicle decreased down the string in the deceleration maneuver due to increasingly longer response times.



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

Figure 103: String Stability Scenario, 55 mph to Rolling Stop: ACC Time Series Plot for Relative Speed

Figure 104 depicts the time gap plot for a string of vehicles in ACC mode. All vehicles are travelling at 25 m/s. At approximately 590 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each ACC vehicle's time gap decreased below the desired time gap and then corrected accordingly to return to its set time gap of 1 second.

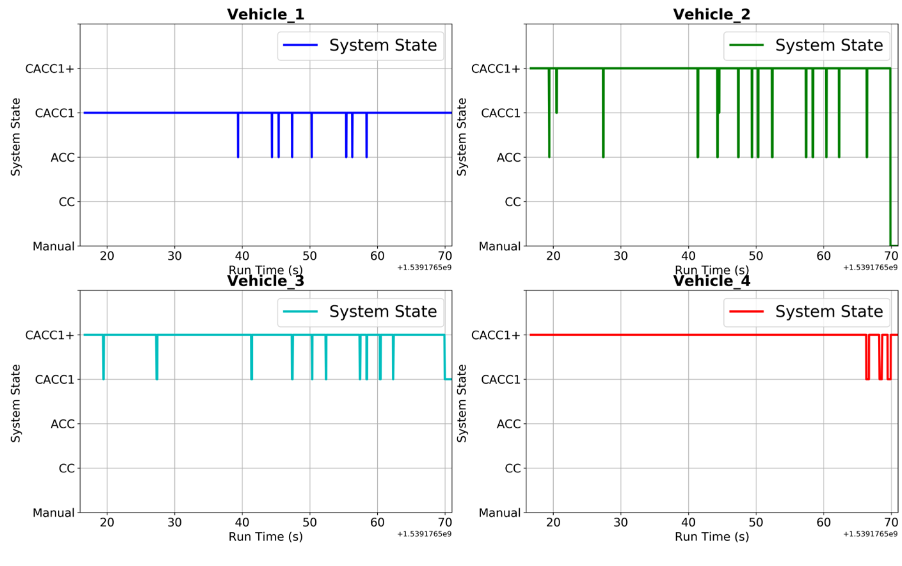


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 104: String Stability Scenario, 55 mph to Rolling Stop: ACC Time Series Plot for Time Gap

7.2.3.2 CACC

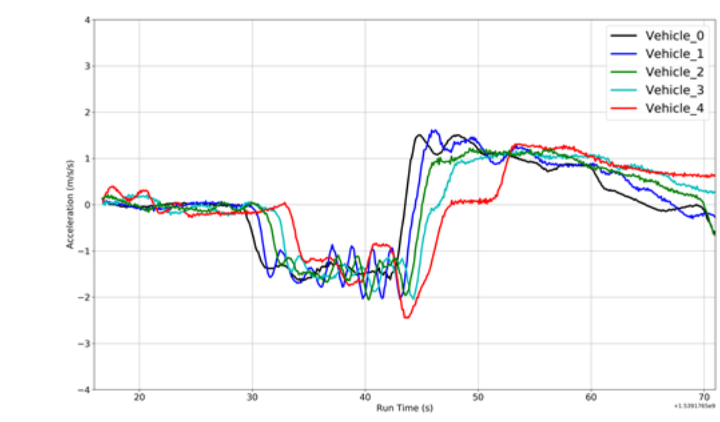
Figure 105 depicts the system state that each CACC vehicle was in for the duration of the test. This shows that each vehicle was completely in CACC mode for the duration of the test, with small changes in Vehicles 2-4 due to minor time synchronization issues, and object fusion issues in Vehicles 1 and 2.



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

Figure 105: String Stability Scenario, 55 mph to Rolling Stop: CACC Time Series Plot for System State

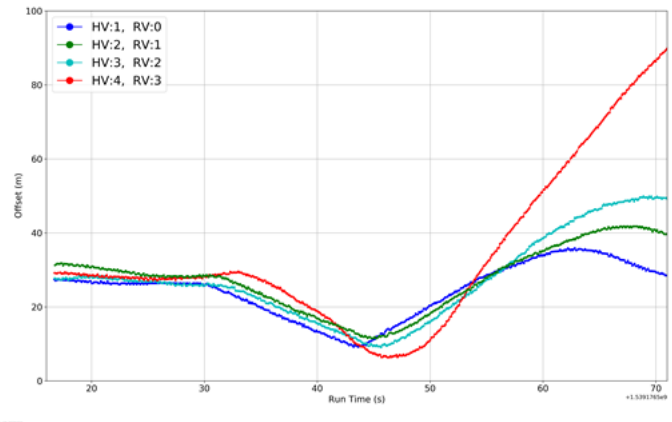
Figure 106 depicts the acceleration plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 25 m/s. At approximately 30 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The maximum decelerations down the string of CACC vehicles remained relatively consistent since they each have a longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle compared to ACC.



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

Figure 106: String Stability Scenario, 55 mph to Rolling Stop: CACC Time Series Plot for Acceleration

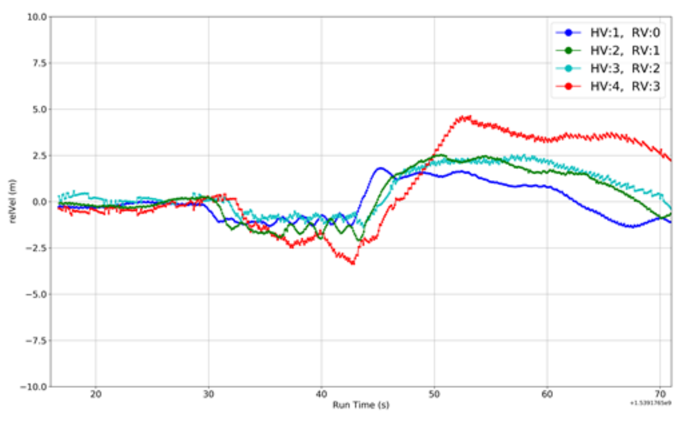
Figure 107 depicts the relative longitudinal offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 887 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative longitudinal offset for each CACC vehicle relative to its preceding vehicle remained constant down the string due to the increasingly longer times to respond.



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

Figure 107: String Stability Scenario, 55 mph to Rolling Stop: CACC Time Series Plot for Relative Longitudinal Offset

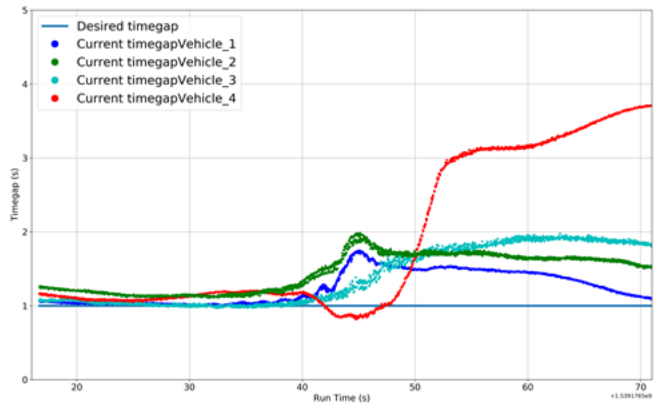
Figure 108 depicts the relative speed offset plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 30 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. The minimum relative speed offset for each CACC vehicle relative to its preceding vehicle remained constant down the string in the deceleration maneuver due the increasingly longer times to respond.



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

Figure 108: String Stability Scenario, 55 mph to Rolling Stop: CACC Time Series Plot for Relative Speed

Figure 109 depicts the time gap plot for a string of vehicles in CACC mode. All vehicles are travelling at 25 m/s. At approximately 30 seconds, Vehicle 0 decelerates, followed by an acceleration back to 25 m/s. Each CACC vehicle's time gap remained at or above the desired time gap.



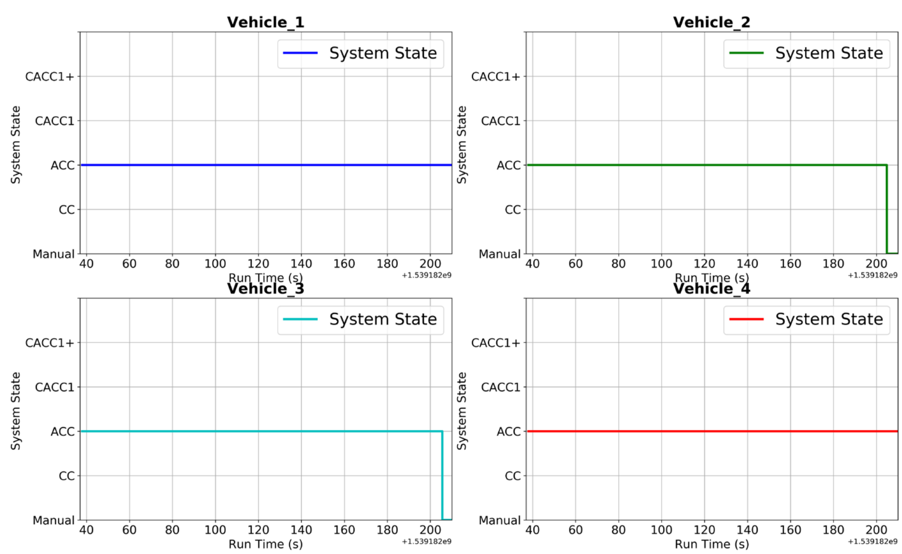
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 109: String Stability Scenario, 55 mph to Rolling Stop: CACC Time Series Plot for Time Gap

7.2.4 FHWA String Stability Scenario, 45 mph to 60 mph

7.2.4.1.1 ACC

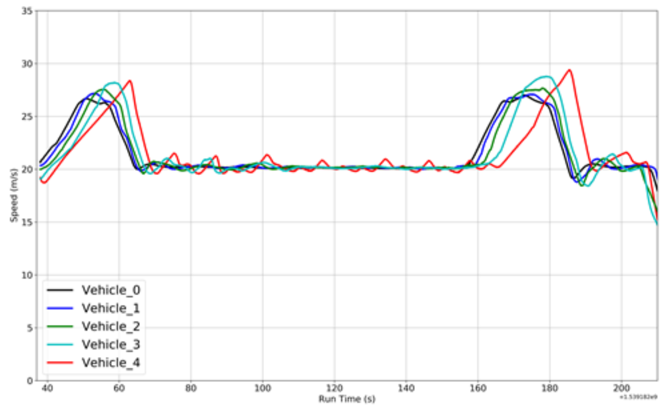
Figure 110 depicts the system state that each ACC vehicle was in for the duration of the test. This shows that each vehicle was completely in ACC mode for the duration of the test.



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

Figure 110: FHWA String Stability Scenario, 45 mph to 60 mph: ACC Time Series Plot for System State

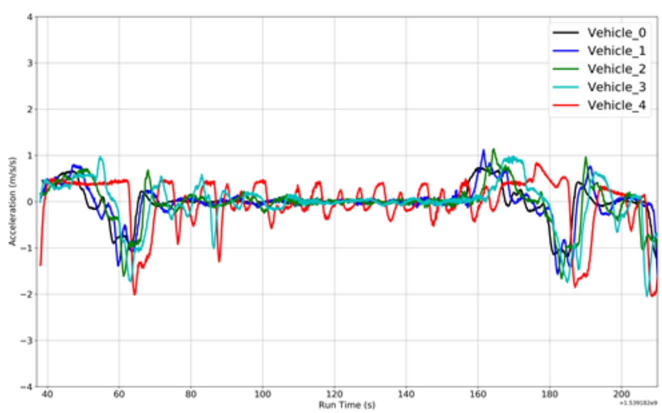
Figure 111 depicts the speed plot for a string of vehicles in ACC mode, with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 20 m/s. At approximately 40 seconds, Vehicle 0 accelerates to 26 m/s, followed by a deceleration back to 20 m/s.



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

Figure 111: FHWA String Stability Scenario, 45 mph to 60 mph: ACC Time Series Plot for Speed

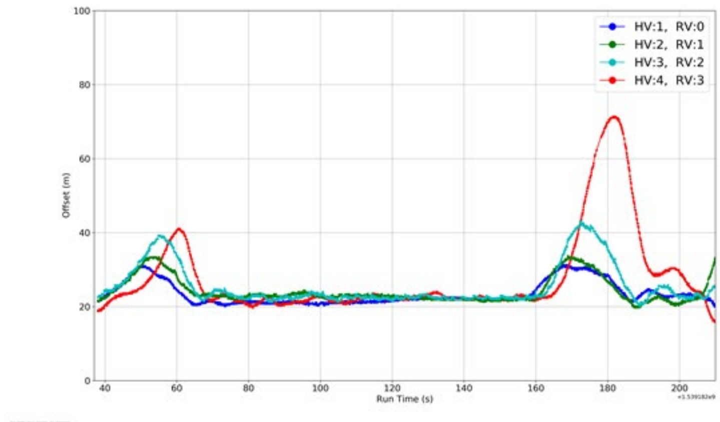
Figure 112 depicts the acceleration plot for a string of vehicles in ACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 20 m/s. At approximately 40 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s. The maximum decelerations down the string of ACC vehicles became progressively harsher since they each have a progressively shorter amount of time to respond to the deceleration of each vehicle’s respective preceding vehicle.



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

Figure 112: FHWA String Stability Scenario, 45 mph to 60 mph: ACC Time Series Plot for Acceleration

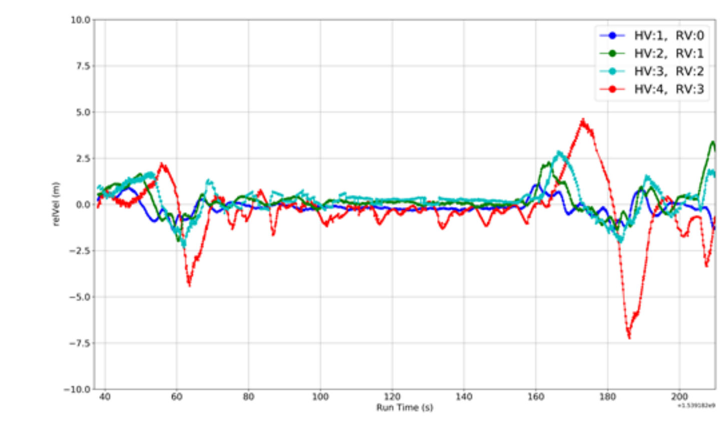
Figure 113 depicts the relative longitudinal offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 40 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s.



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

Figure 113: FHWA String Stability Scenario, 45 mph to 60 mph: ACC Time Series Plot for Relative Longitudinal Offset

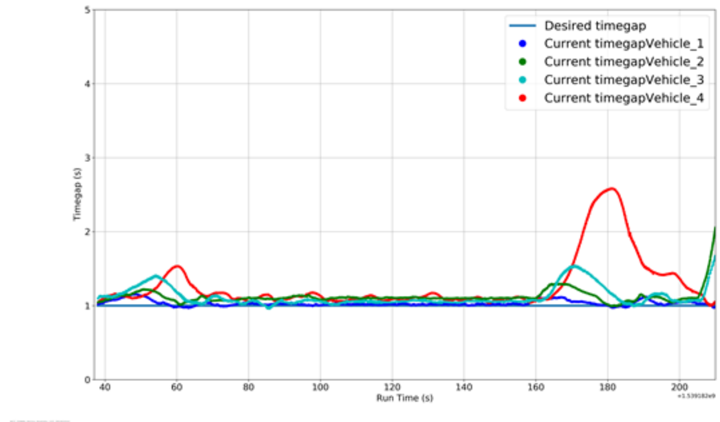
Figure 114 depicts the relative speed offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 40 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s. The minimum relative speed offset for each ACC vehicle relative to its preceding vehicle decreased down the string in the deceleration maneuver due to increasingly longer response times.



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

Figure 114: FHWA String Stability Scenario, 45 mph to 60 mph: ACC Time Series Plot for Relative Speed

Figure 115 depicts the time gap plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 40 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s.

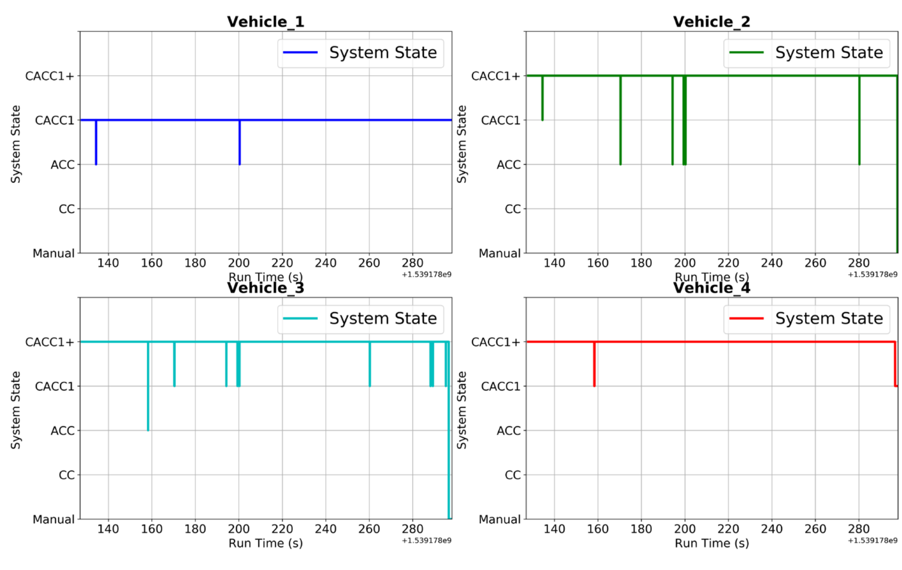


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 115: FHWA String Stability Scenario, 45 mph to 60 mph: ACC Time Series Plot for Time Gap

7.2.4.1.2 CACC

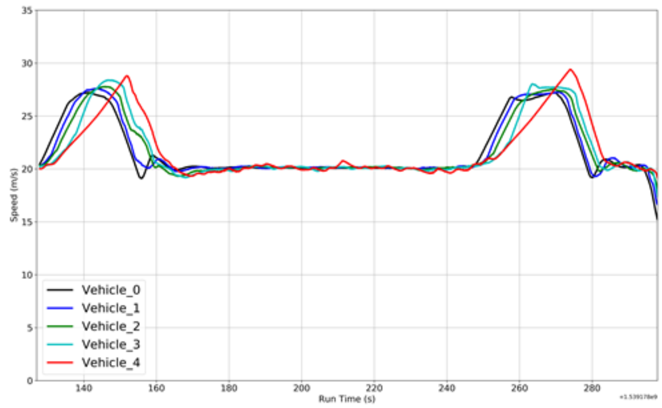
Figure 116 depicts the system state that each CACC vehicle was in for the duration of the test. This shows that each vehicle was completely in CACC mode for the duration of the test with small changes due to minor time synchronization and object fusion issues.



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

Figure 116: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for System State

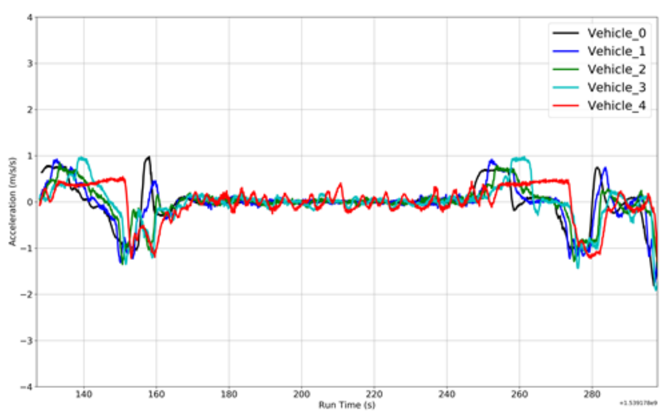
Figure 117 depicts the speed plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 20 m/s. At approximately 130 seconds, Vehicle 0 accelerates to 27 m/s, followed by a deceleration back to 20 m/s.



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

Figure 117: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Speed

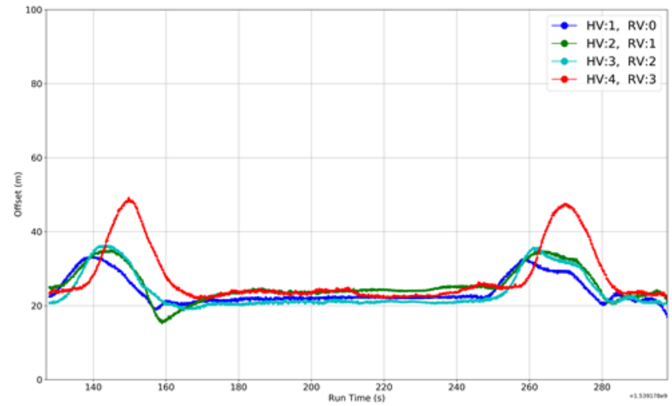
Figure 118 depicts the acceleration plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 20 m/s. At approximately 130 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s. The maximum decelerations down the string of CACC vehicles remain relatively constant since they each have a longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 118: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Acceleration

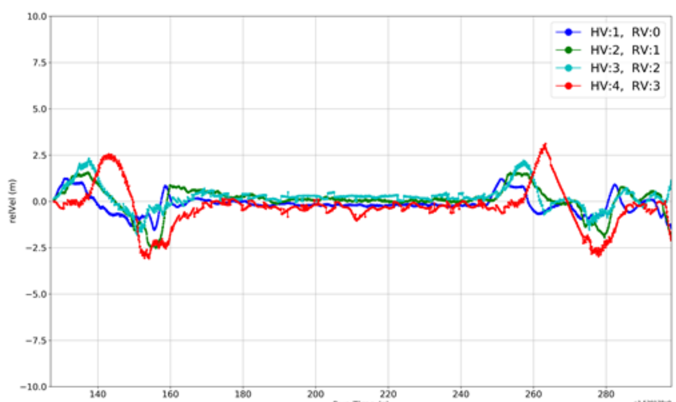
Figure 119 depicts the relative longitudinal offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 130 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s.



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

Figure 119: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Relative Longitudinal Offset

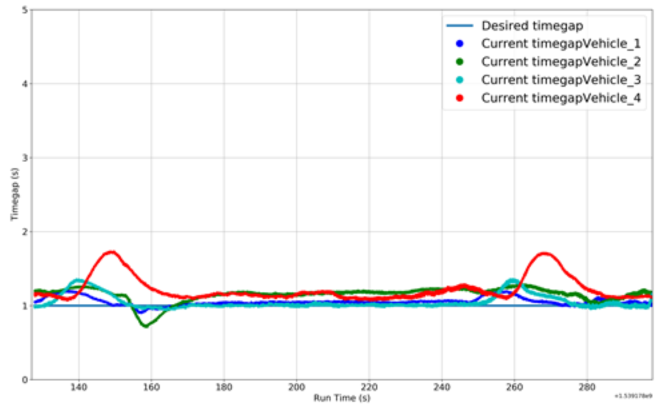
Figure 120 depicts the relative speed offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 130 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s. The minimum relative speed offset for each ACC vehicle relative to its preceding vehicle remained relatively constant down the string in the deceleration maneuver as compared to ACC.



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

Figure 120: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Relative Speed

Figure 121 depicts the time gap plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 40 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s.

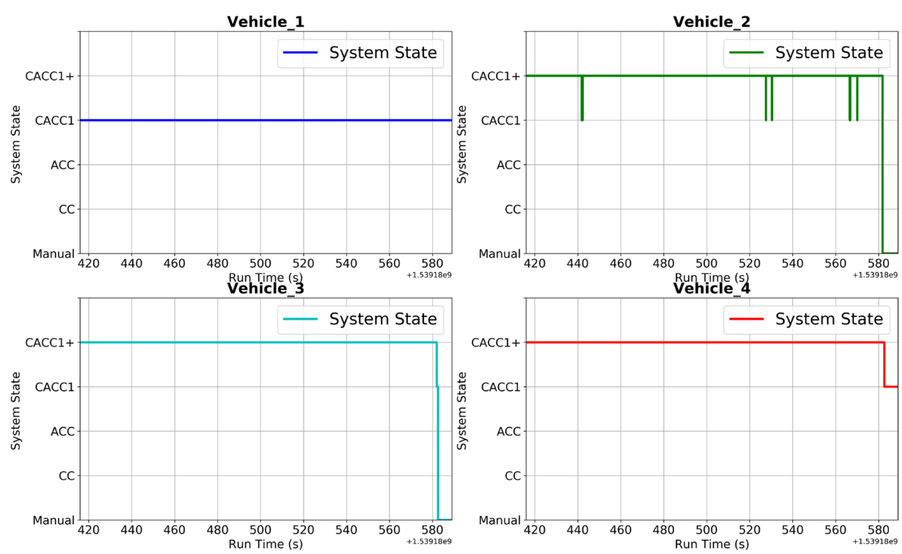


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 121: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Time Gap

7.2.4.1.3 CACC with 0.6 Second Time Gap

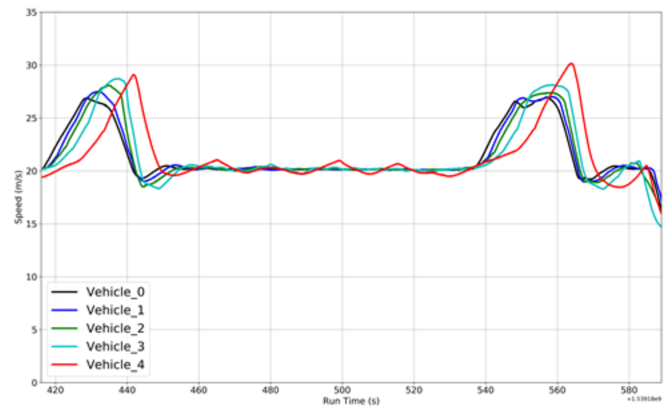
Figure 122 depicts the system state that each CACC vehicle was in for the duration of the test. This shows that each vehicle was completely in CACC mode for the duration of the test with small changes in Vehicle 2 due to minor time synchronization issues.



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

Figure 122: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for System State, 0.6 Second Time Gap

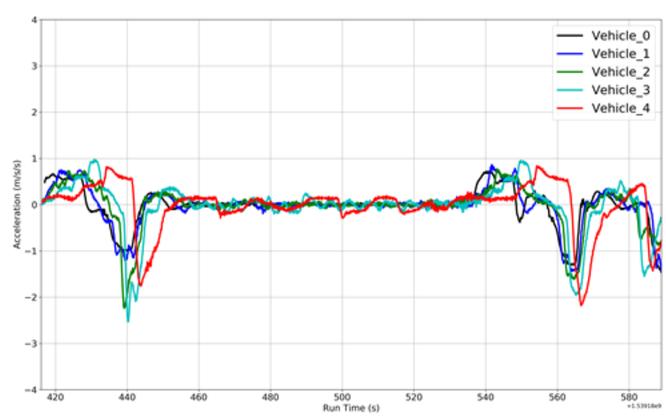
Figure 123 depicts the speed plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 20 m/s. At approximately 418 seconds, Vehicle 0 accelerates to 27 m/s, followed by a deceleration back to 20 m/s.



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

Figure 123: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Speed, 0.6 Second Time Gap

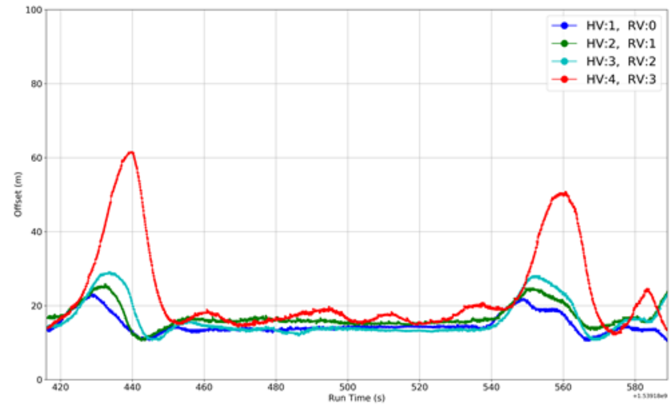
Figure 124 depicts the acceleration plot for a string of vehicles in CACC mode with Vehicle 0, depicted in black, as a vehicle with only DSRC communication. All vehicles are travelling at 20 m/s. At approximately 418 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s. The maximum decelerations down the string of CACC vehicles remain relatively constant since they each have a longer amount of time to respond to the deceleration of each vehicle's respective preceding vehicle.



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

Figure 124: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Acceleration, 0.6 Second Time Gap

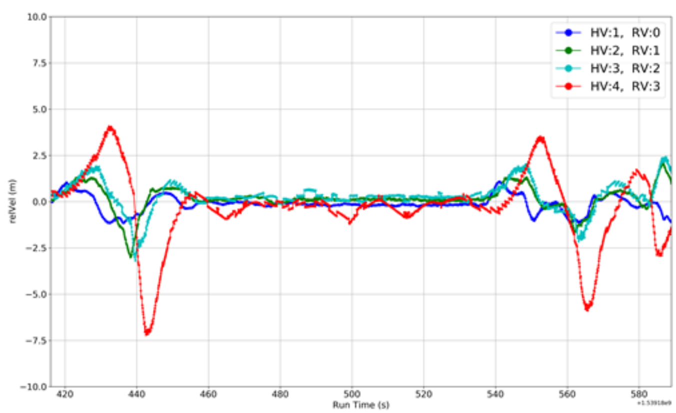
Figure 125 depicts the relative longitudinal offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 418 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s.



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

Figure 125: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Relative Longitudinal Offset, 0.6 Second Time Gap

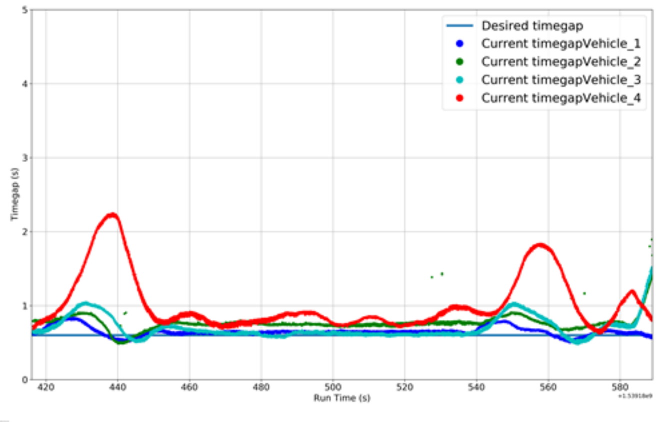
Figure 126 depicts the relative speed offset plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 418 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s. The minimum relative speed offset for each ACC vehicle relative to its preceding vehicle remained relatively constant down the string in the deceleration maneuver, as compared to ACC, with the exception of Vehicle 4, which experienced the maximum commanded acceleration limits as outlined in 2.4.



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

Figure 126: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Relative Speed, 0.6 Second Time Gap

Figure 127 depicts the time gap plot for a string of vehicles in ACC mode. All vehicles are travelling at 20 m/s. At approximately 418 seconds, Vehicle 0 accelerates, followed by a deceleration back to 20 m/s.



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

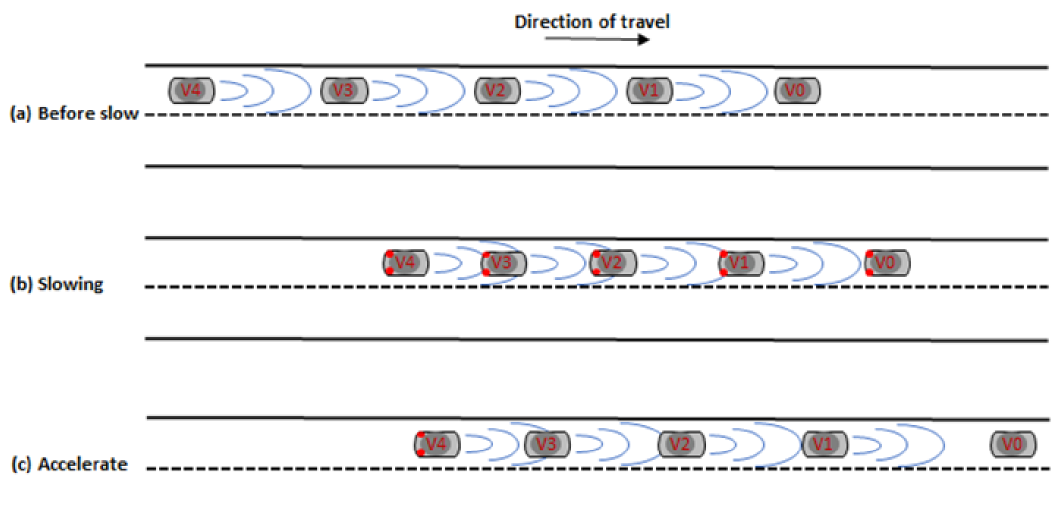
Figure 127: FHWA String Stability Scenario, 45 mph to 60 mph: CACC Time Series Plot for Time Gap, 0.6 Second Time Gap

7.3 Aggregated Plots, String Stability Scenario, 55 mph to 30 mph, Moderate Deceleration (-2.5 m/s²)

7.3.1 Scenario Description

7.3.1.1 String Stability Scenario: 55 mph to 30 mph with Moderate Deceleration

In this scenario (as shown in Figure 128), a string of vehicles with CACC activated travels along a straightaway at 55 mph. The lead vehicle slows down to 30 mph at a deceleration of -2.5 m/s^2 and then accelerates to its original speed. This process is repeated once, and the behavior of the string is observed.

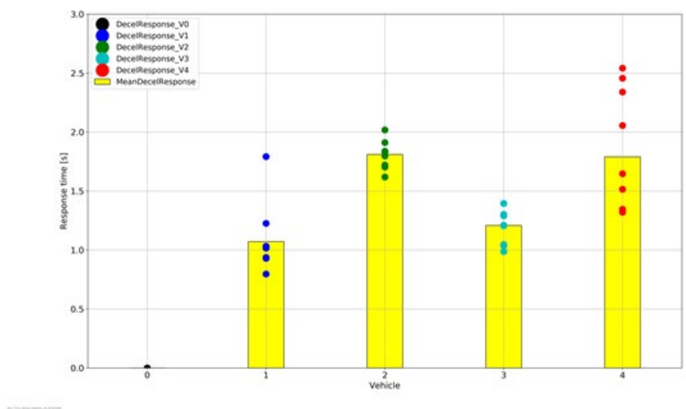


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 128: String Stability Scenario, 55 mph to 30 mph with Moderate Deceleration

7.3.2 Deceleration Response Delay

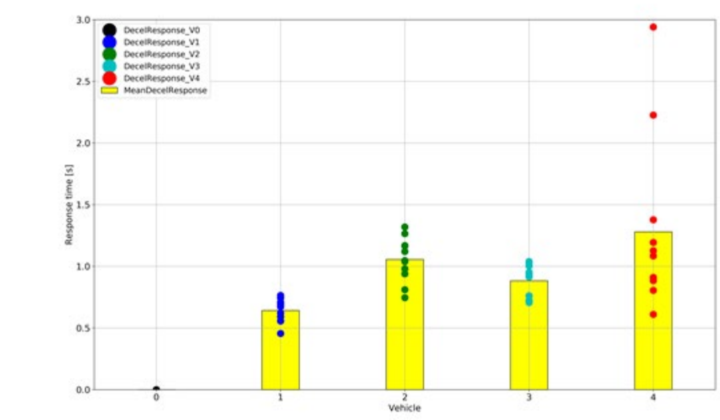
Figure 129 depicts the difference, for a string of ACC vehicles, in time between the time where each HV reaches a deceleration of -1.2 m/s^2 and where its respective preceding vehicle reaches a deceleration of -1.2 m/s^2. For each vehicle, the average value over all runs is shown in the bar graph. The average values for Vehicles 1-4 are 1.07, 1.81, 1.21, and 1.79 m/s^2, respectively.



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

Figure 129: String Stability Scenario, 55 mph to 30 mph, Moderate Deceleration: ACC Deceleration Response Time

Figure 130 depicts the difference, for a string of CACC vehicles, in time between the time where each HV reaches a deceleration of -1.2 m/s^2 and where its respective preceding vehicle reaches a deceleration of -1.2 m/s^2. For each vehicle, the average value over all runs is shown in the bar graph. The average values for Vehicles 1-4 are 0.64, 1.05, 0.88, and 1.28 m/s^2, respectively. Vehicles in CACC have a much lower response time than ACC due to the information communicated in the BSM, and the response time decreases down the string, as each vehicle has progressively more time to respond.

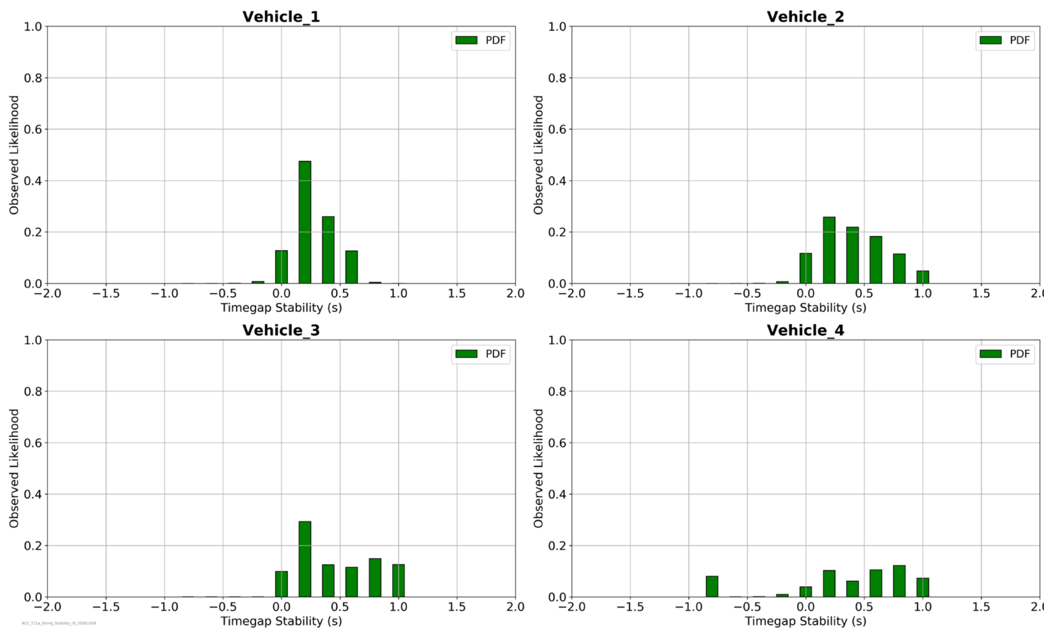


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 130: String Stability Scenario, 55 mph to 30 mph, Moderate Deceleration: CACC Deceleration Response Time

7.3.3 Time Gap Stability

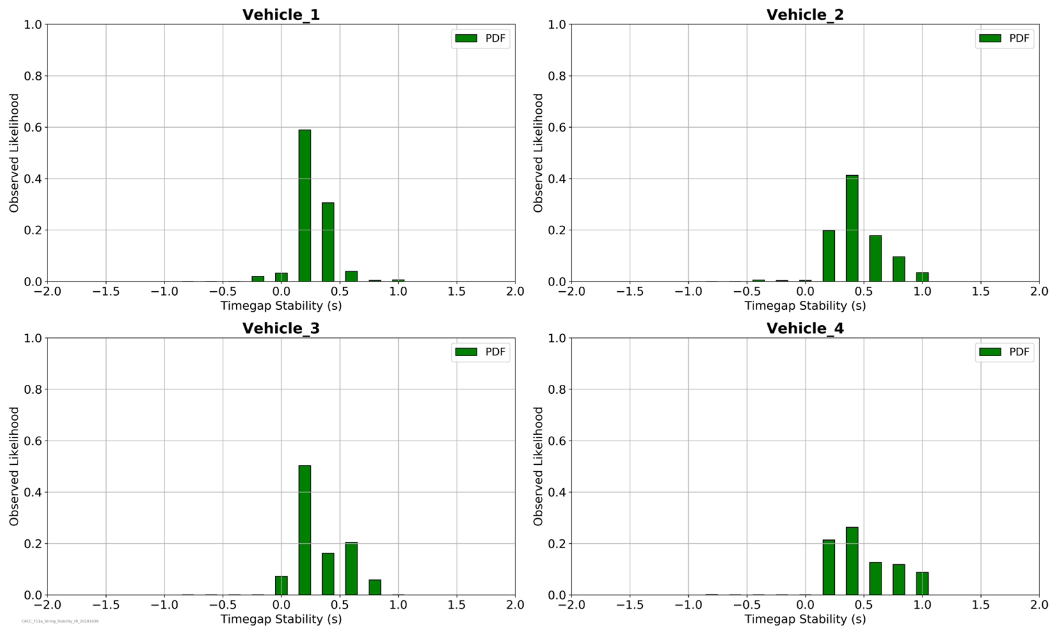
Figure 131 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each ACC vehicle in the string. The mean values for each PDF are 0.17, 0.36, 0.44, and 0.91 seconds difference for Vehicles 1-4, respectively, showing that in ACC, the vehicles deviate progressively more from the set time gap down the string. The standard deviations for each PDF are 0.17, 0.35, 0.41, and 1.00 seconds for Vehicles 1-4, respectively, showing that in ACC, the stability for each vehicles' time gaps progressively decrease down the string.



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

Figure 131: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, ACC Time Gap Stability

Figure 132 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each CACC vehicle in the string. The mean values for each PDF are 0.15, 0.41, 0.23, and 0.58 seconds difference for Vehicles 1-4, respectively, showing that in CACC, the vehicles deviate progressively more from the set time gap down the string, but significantly less so than the same scenario in ACC. The standard deviations for each PDF are 0.17, 0.29, 0.21, and 0.43 seconds for Vehicles 1-4, respectively, showing that in CACC, the stability for each vehicles' time gaps progressively decrease down the string, but significantly less so than ACC.

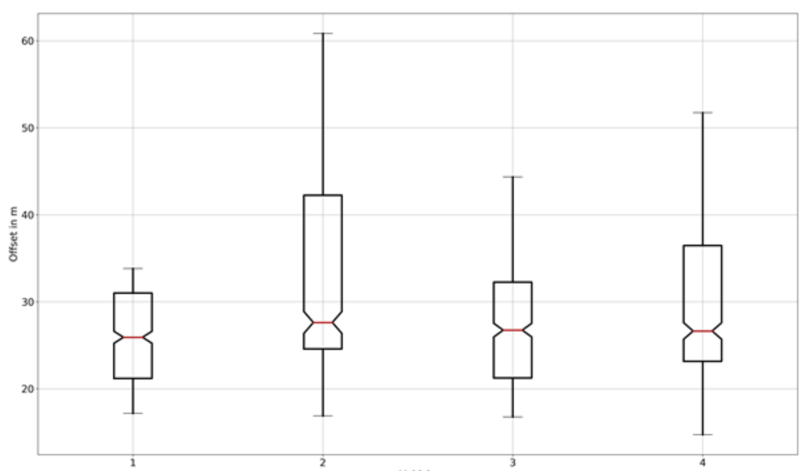


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 132: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Time Gap Stability

7.3.4 Relative Longitudinal Offset

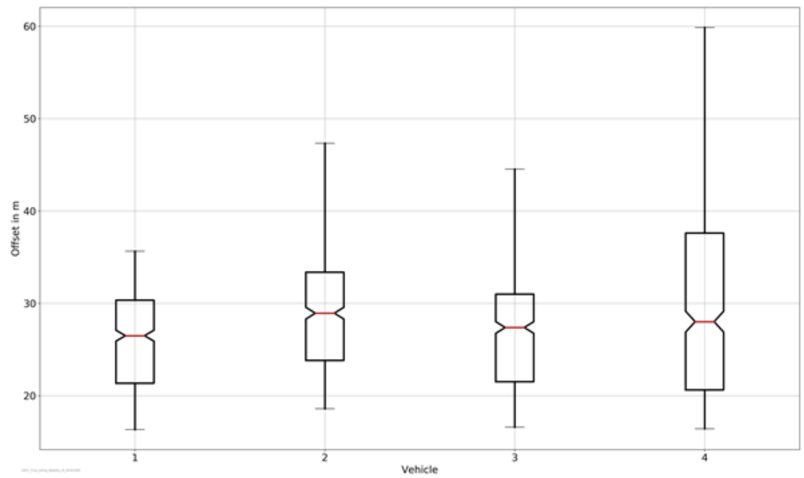
Figure 133 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each ACC vehicle in the string. The inter-quartile ranges for each box plot are 9.81, 17.67, 11.01, and 13.31 meters for Vehicles 1-4, respectively, showing that in ACC, the stability for each vehicles' time gaps progressively decreases down the string.



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

Figure 133: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, ACC Relative Longitudinal Offset

Figure 134 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each CACC vehicle in the string. The inter-quartile ranges for each box plot are 8.99, 9.55, 9.48, and 16.98 meters for Vehicles 1-4, respectively, showing that in CACC, the stability for each vehicles' time gaps progressively decreases down the string, but significantly less so than ACC.



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

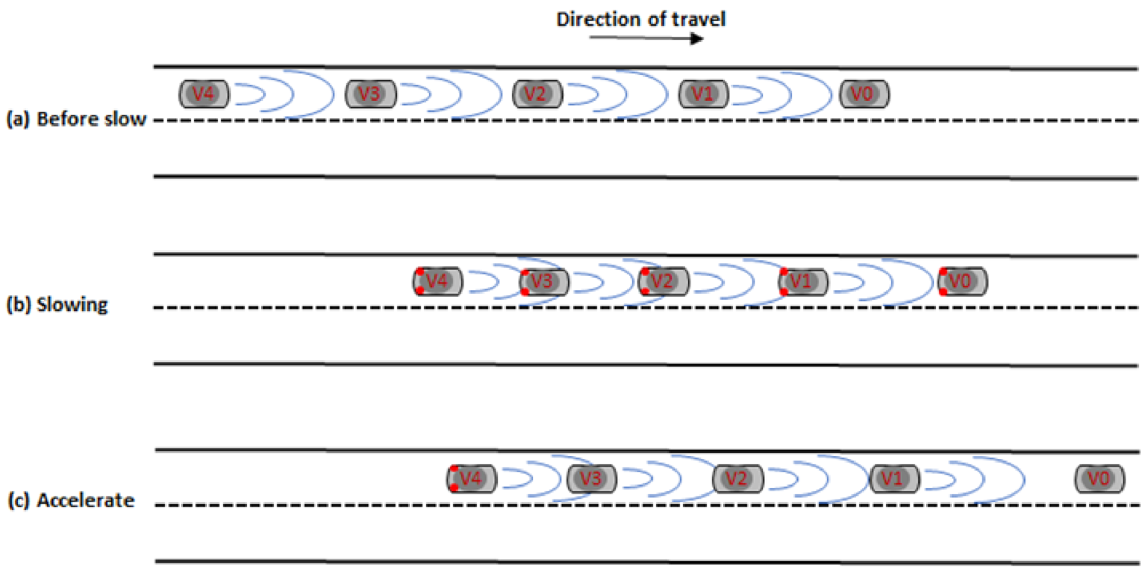
Figure 134: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Relative Longitudinal Offset

7.4 Aggregated Plots, String Stability Scenario, 60 mph to 25 mph

7.4.1 Scenario Description

7.4.1.1 String Stability Scenario: 60 mph to 25 mph with Moderate Deceleration

In this scenario (as shown in Figure 135), a string of vehicles with CACC activated travels along a straightaway at 60 mph. The lead vehicle slows down to 25 mph at a deceleration of -2.5 or m/s^2 and then accelerates to its original speed. This process is repeated once, and the behavior of the string is observed.

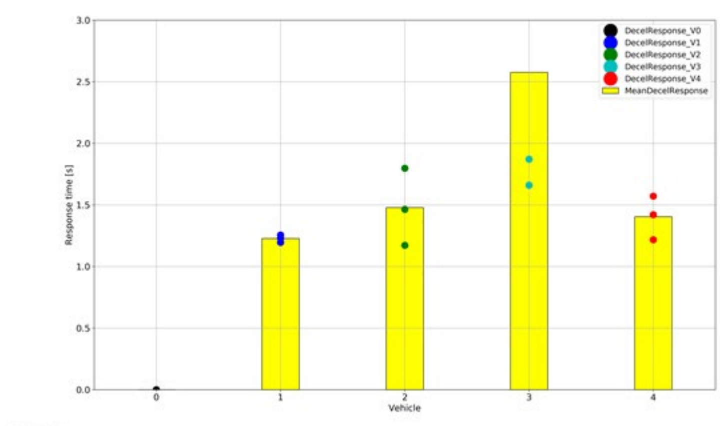


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 135: String Stability Scenario: 60 mph to 25 mph with Moderate Deceleration

7.4.2 Deceleration Response Delay

Figure 136 depicts the difference, for a string of ACC vehicles, in time between the time where each HV reaches a deceleration of -1.2 m/s^2 and where its respective preceding vehicle reaches a deceleration of -1.2 m/s^2. For each vehicle, the average value over all runs is shown in the bar graph. The average values for Vehicles 1-4 are 1.22, 1.48, 2.58, and 1.40 m/s^2, respectively.

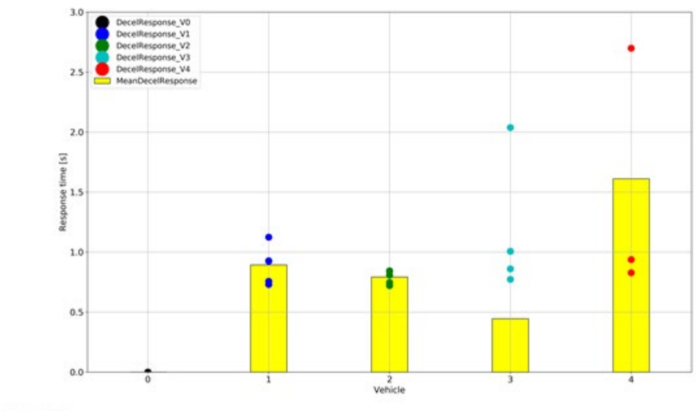


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 136: String Stability Scenario, 60 mph to 25 mph, ACC Deceleration Response Time

Figure 137 depicts the difference, for a string of CACC vehicles, in time between the time where each HV reaches a deceleration of -1.2 m/s^2 and where its respective preceding vehicle reaches a deceleration of -1.2 m/s^2. For each vehicle, the average value over all runs is shown in the bar graph. The average values for Vehicles 1-4 are 0.89, 0.79, 0.45, and 1.61 m/s^2, respectively.

Vehicles in CACC have a much lower response time than ACC due to the information communicated in the BSM, and the response time decreases down the string, as each vehicle has progressively more time to respond.

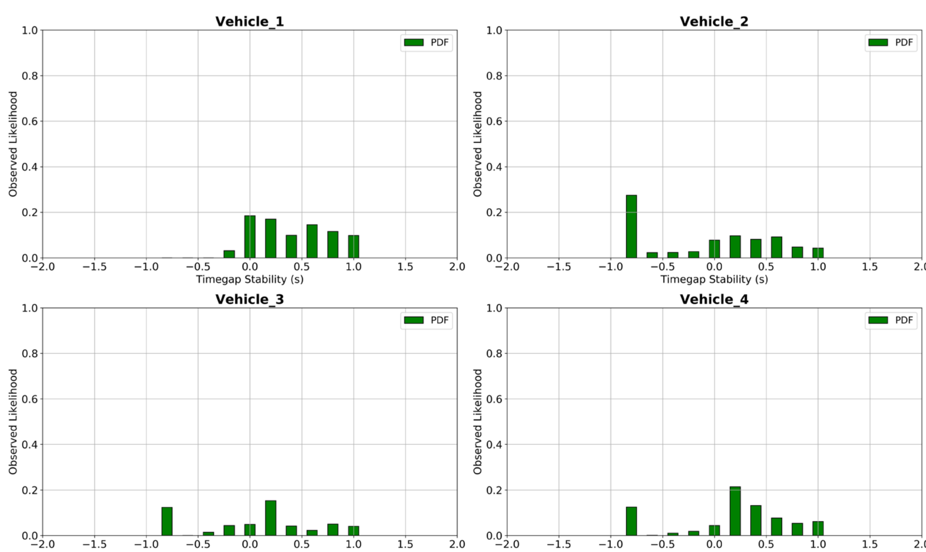


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 137: String Stability Scenario, 60 mph to 25 mph, CACC Deceleration Response Time

7.4.3 Time Gap Stability

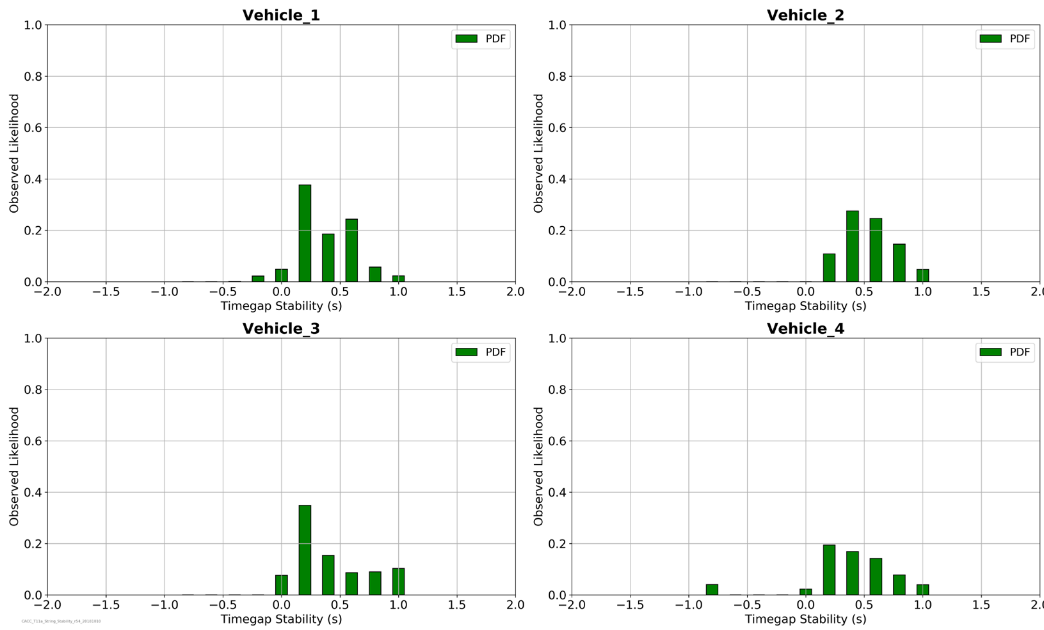
Figure 138 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each ACC vehicle in the string. The mean values for each PDF are 0.44, 0.26, 1.42, and 0.74 seconds difference for Vehicles 1-4, respectively, showing that in ACC, the vehicles deviate progressively more from the set time gap down the string. The standard deviations for each PDF are 0.44, 1.14, 2.73, and 2.93 seconds for Vehicles 1-4, respectively, showing that in ACC, the stability for each vehicles' time gaps progressively decrease down the string.



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

Figure 138: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, ACC Time Gap Stability

Figure 139 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each CACC vehicle in the string. The mean values for each PDF are 0.31, 0.62, 0.43, and 0.77 seconds difference for Vehicles 1-4, respectively, showing that in CACC, the vehicles deviate progressively more from the set time gap down the string. The standard deviations for each PDF are 0.31, 0.43, 0.39, and 0.85 seconds for Vehicles 1-4, respectively, showing that in CACC, the stability for each vehicles' time gaps progressively decrease down the string, but significantly less so than ACC.

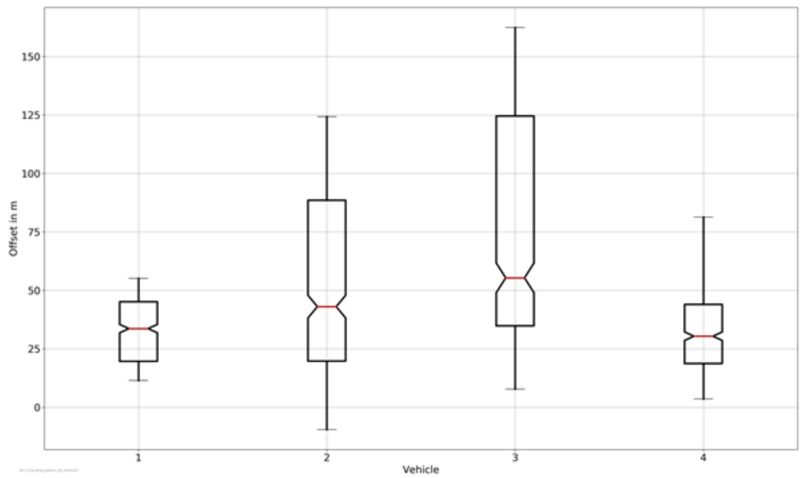


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 139: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, CACC Time Gap Stability

7.4.4 Relative Longitudinal Offset

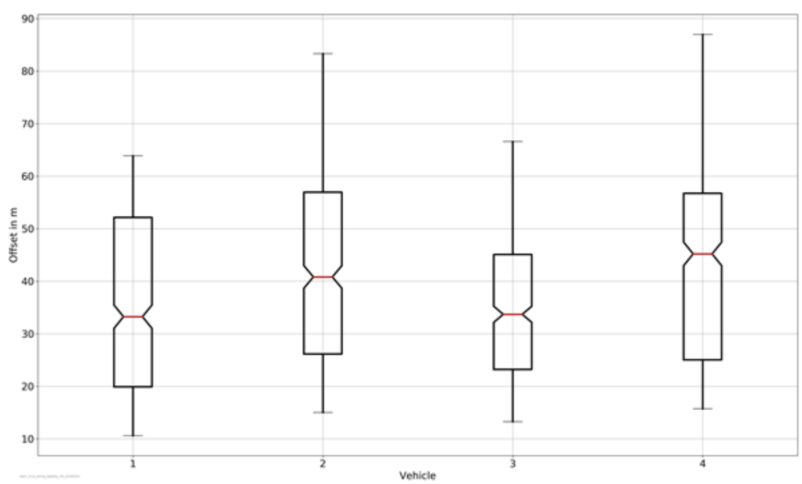
Figure 140 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each ACC vehicle in the string. The inter-quartile ranges for each box plot are 25.48, 68.78, 89.71, and 25.27 meters for Vehicles 1-4, respectively, showing that in ACC, the stability for each vehicles' time gaps progressively decreases down the string.



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

Figure 140: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, ACC Relative Longitudinal Offset

Figure 141 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each CACC vehicle in the string. The inter-quartile ranges for each box plot are 32.24, 30.80, 21.88, and 31.69 meters for Vehicles 1-4, respectively, showing that in CACC, the stability for each vehicles' time gaps progressively decreases down the string, but significantly less so than ACC.



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

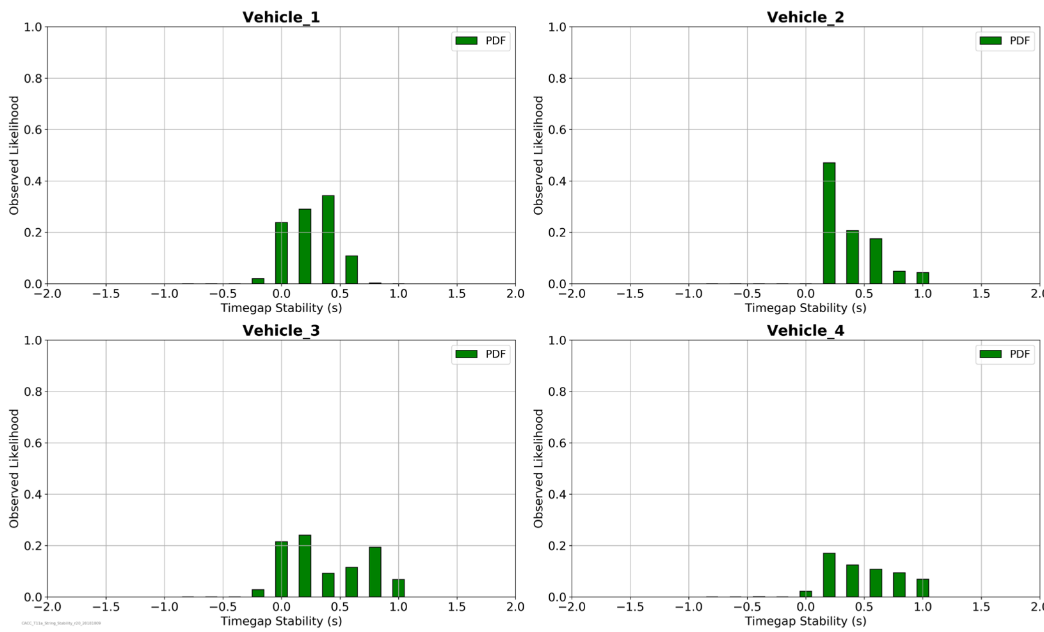
Figure 141: String Stability Scenario from 60 mph to 25 mph with Moderate Deceleration, CACC Relative Longitudinal Offset

7.5 Aggregated Plots, String Stability Scenario 55 mph to 30 mph, CACC with 0.6 Second Time Gap

7.5.1 Moderate Deceleration (-2.5 m/s^2)

7.5.1.1 Time Gap Stability

Figure 142 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each CACC vehicle in the string. The mean values for each PDF are 0.16, 0.33, 0.33, and 1.07 seconds difference for Vehicles 1-4, respectively, and the standard deviations for each PDF are 0.19, 0.28, 0.38, and 0.93 seconds for Vehicles 1-4, respectively.

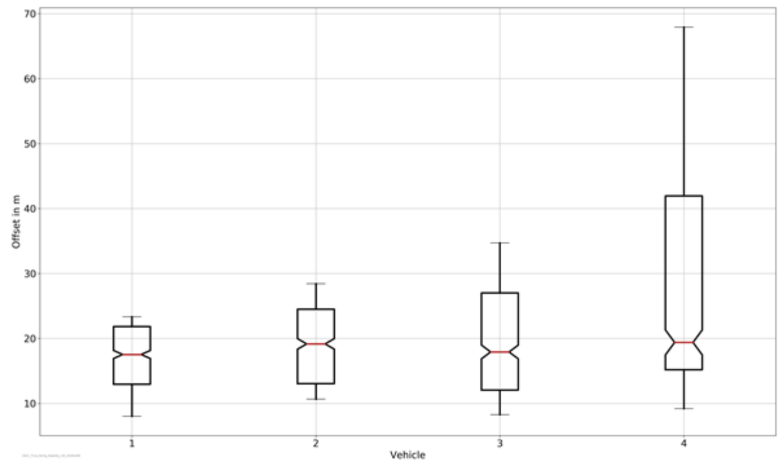


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 142: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Time Gap Stability, 0.6 Second Time Gap

7.5.1.2 Relative Longitudinal Offset

Figure 143 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each CACC vehicle in the string. The inter-quartile ranges for each box plot are 8.88, 11.46, 14.96, and 26.76 meters for Vehicles 1-4, respectively.



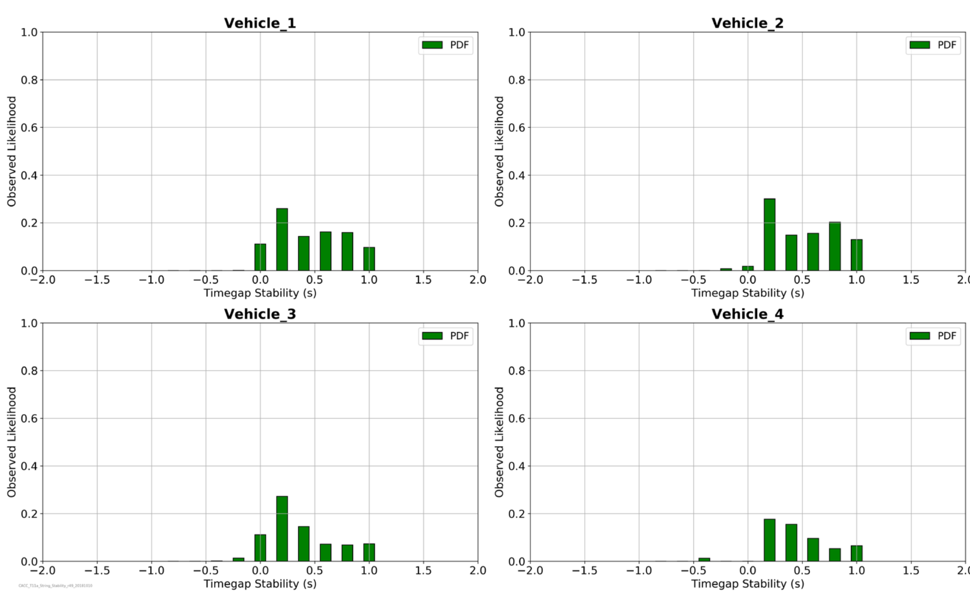
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 143: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Relative Longitudinal Offset, 0.6 Second Time Gap

7.5.2 Harsh Deceleration (-3.5 m/s^2)

7.5.2.1 Time Gap Stability

Figure 144 shows a PDF for the aggregated values for the difference in each HV's actual and set time gaps, separated for each CACC vehicle in the string. The mean values for each PDF are 0.41, 0.46, 0.48, and 1.13 seconds difference for Vehicles 1-4, respectively, and the standard deviations for each PDF are 0.37, 0.33, 0.48, and 0.99 seconds for Vehicles 1-4, respectively.

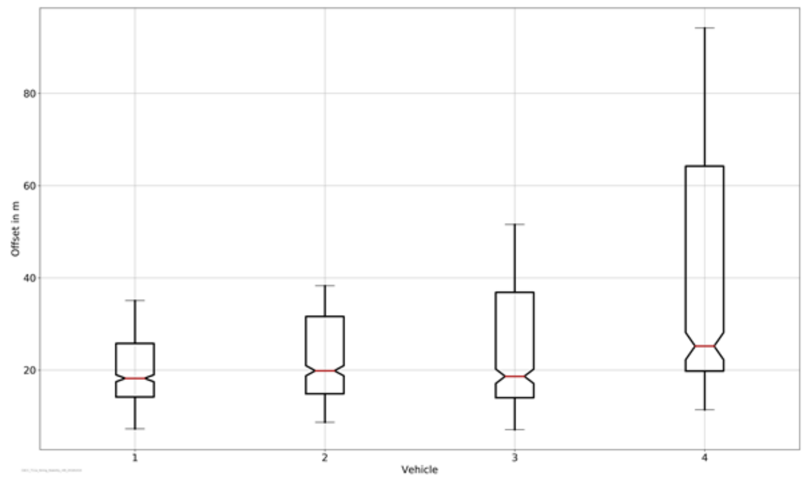


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 144: String Stability Scenario from 55 mph to 30 mph with Harsh Deceleration, CACC Time Gap Stability, 0.6 Second Time Gap

7.5.2.2 Relative Longitudinal Offset

Figure 145 shows a set of box plots for the aggregated values for the difference in each HV's distance to its respective preceding vehicle, separated for each CACC vehicle in the string. The inter-quartile ranges for each box plot are 11.61, 16.76, 22.85, and 44.44 meters for Vehicles 1-4, respectively.



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

Figure 145: String Stability Scenario from 55 mph to 30 mph with Moderate Deceleration, CACC Relative Longitudinal Offset, 0.6 Second Time Gap

7.6 Test Scenarios

This section provides detailed information for each of the test scenarios in terms of scenario description, test variants, execution steps, and expected outcome.

7.6.1 T-1 Lane-Change Detection

The goal of this test is to study the latency between lead vehicle activity and C/ACC response to it. The test is summarized in Table 6.

Table 6: Test summary - T-1 Lane-Change Detection

Description	Five vehicles are driving behind each other with activated CACC 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 four rear vehicles detects the lane change and accelerates to the desired set speed of the new lead vehicle, which in this case is the second vehicle in the original CACC 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 CACC response?
Applicable To	ACC, CACC

7.6.1.1 Variants

This test case differs by the used time gap setting of the CACC system. The driver can set the time gap as one of five predefined settings (Table 7). For the i^{th} time gap setting, the distance d_i shall be used as inter vehicle gap while vehicles are stationary before test execution.

Table 7: Time Gap setting - T-1 Lane Change Detection

i^{th} time gap setting	1	2	3
$d_{i,ACC}$	25	37.5	do not execute
ACC (in s) - 1 time each	1.0	1.5	do not execute
$d_{i,CACC}$	15	25	37.5
CACC (in s) - 3 times each	0.6	1.0	1.5

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

7.6.1.2 Test Execution

Detailed test execution instructions can be found in Table 8

Table 8: Test Execution Instruction - T-1 Lane Change Detection

	V0	V1	V2	V3	V4
1.	Stage at Cone 1+4xd_i	Stage at Cone 1+3xd_i	Stage at Cone 1+2xd_i	Stage at Cone 1+1xd_i	Stage at Cone 1
2.	Accelerate manually to 55 mph.	Accelerate manually to 55 mph. Remain distance d_i towards preceding vehicle.			
3.	Engage and set ACC to 55 mph before passing cone 3. Alternatively: Resume the ACC.	Engage and set CACC to 65 mph and i^{th} time gap setting according to test variant before cone 3.			
4.	Activate right turn indicator at cone 4 and perform a smooth lane change within a distance of 50 meters (approximately 2.0s at 55 mph). Deactivate turn indicator after completion of lane change.	---			
5.	Deactivate the CACC system by actuating the brake pedal manually at cone 6 and come to a full stop at cone 7.		Deactivate the CACC system by actuating the brake pedal manually as soon as the brake lights of any preceding vehicle light up and come to a full stop behind the preceding vehicle.		

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

7.6.1.3 *Expected Results*

The expected outcome of the testing is as shown in Table 9.

Table 9: Expected Test Result - T-1 Lane Change Detection

	Source of Information	V1	V2	V3	V4
1.	CustomerHMI	At cone 3 in CACC-1 mode.	At cone 3 in CACC-1+ mode.		
2.	CustomerHMI	Before V0 performs the lane change maneuver, the target time gap and the current time gap are similar (+/- 0.1s) for at least 100 m.			
3.	CustomerHMI	CACC system is active throughout the path from cone 3 until the manual system deactivation in the reset area.			
4.	CustomerHMI	Speed up to 65 mph after V0 has performed the lane change.			
5.	CustomerHMI	Lane Change Icon visualized while V0 changes lanes.	---		
6.	Driver or CoPilot	Show no reaction to slower travelling V0 on right lane while passing this vehicle.			

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

7.6.1.4 Test Combinations

- Number of tests = 5 (three different CACC time-gaps + two different ACC time-gaps)
- Time per test = 5 minutes
- Number of repetitions = 4 (three per CACC + one per ACC)
- Total test runs = 11 (3*3 +2*1)
- Test time = 55 minutes
- Buffer time = 15 minutes
- Total test time = 70 minutes

7.6.2 T-2 Lane-Change Detection 2

The goal of this test is to study the latency between lead vehicle activity and CACC response, and the test is summarized in Table 10

Table 10: Test summary - T-1 Lane-Change Detection 2

Description	Four CACC 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. At the moment 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

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

7.6.2.1 Variants

This test case differs by the used TimeGap setting of the CACC system. The driver can set the TimeGap as one of five predefined setting (Table 11). For the i-th TimeGap setting, the distance $d_i$shall be used as inter-vehicle gap while vehicles are stationary before test execution.

Table 11: Time Gap setting - T-1 Lane Change Detection 2

i^{th} time gap setting	2	3
$d_{i,ACC}$	37.5	do not execute
ACC (in s) - 1 time each	1.5	do not execute
$d_{i,CACC}$	do not execute	37.5
CACC (in s) - 3 times each	do not execute	1.5

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

7.6.2.2 Test Execution

Detailed test execution instructions can be found in Table 12.

Table 12: Test Execution Instruction - T-1 Lane Change Detection 2

	V0	V1	V2	V3	V4
1.	Stage at Cone 1a	Stage at Cone 1+3xd_i	Stage at Cone 1+2xd_i	Stage at Cone 1+2xd_i	Stage at Cone 1
2.	Accelerate manually to 45 mph.	Accelerate manually to 55 mph. Remain distance d_i between following vehicles.			
3.	Engage and set ACC to 45 mph. Alternatively: Resume the ACC.	Engage and set CACC to 55 mph and i^{th} time gap setting according to test variant.	Engage and set CACC to 65 mph and i^{th} time gap setting according to test variant.		
4a.	---	Notify V0 to begin lane change if absolute distance between V0 and V1 is less than d_i.	---		
4b.	After notification, activate left turn indicator and perform a smooth lane change within a distance of 50 meters (approximately 2.5s at 45 mph). Deactivate turn indicator after completion of lane change.	---			
5a.	Deactivate the ACC system by actuating the brake pedal manually at cone 6 and come to a full stop at cone 7.	---			
5b.	---	Deactivate the CACC system by actuating the brake pedal manually as soon as the brake lights of any preceding vehicle light up.			

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

7.6.2.3 Expected Results

The expected outcome of the testing is as shown in Table 13.

Table 13: Test Execution Instruction - T-1 Lane Change Detection 2

	Source of information	V1	V2	V3	V4
1.	CustomerHMI	At cone 3 in CC mode.	At cone 3 in CACC-1 mode.	At cone 3 in CACC-1+ mode.	
2.	CustomerHMI		Before V0 performs the lane change maneuver, the target time gap and the current time gap are similar (+/- 0.1s) for at least 100 m.		
3.	CustomerHMI	CACC system is active throughout the path from cone 2 until the manual system deactivation in the reset area.			
4.	Driver or CoPilot	Do not overtake or fall behind V0 at any time.			
5.	CustomerHMI	Lane Change Icon visualized while V0 changes lanes.	---		
6.	Driver or CoPilot	V0 enters left lane in front of V1.	---		
7.	CustomerHMI	Slow down to match V0's speed (45 mph) and remain CACC controlled headway gap corresponding to i-th setting.			

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

7.6.2.4 Test combinations

- Number of tests = 5 (three different CACC time-gaps + two different ACC time-gaps)
- Time per test = 5 minutes
- Number of repetitions = 4 (three per CACC + one per ACC)
- Total test runs = 11 (3*3+2*1)
- Test time = 55 minutes
- Buffer time = 15 minutes

Total test time = 70 minutes

7.6.3 T-3 Vehicle Cut-In Maneuver

The goal of this test is to study the latency between lead vehicle activity and CACC response to, and the test is summarized in Table 14.

Table 14: Test Summary - Vehicle Cut-In Maneuver

Description	Four vehicles are driving behind each other with activated CACC systems on the left lane. The set time-gap between the vehicles supports a fifth 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 systems in the second and 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

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

7.6.3.1.1 Variants

This test case differs by the used time gap setting of the CACC system. The driver can set the time gap as one of five predefined setting (Table 15). For the i^{th} time gap setting, the distance d_i shall be used as inter vehicle gap while vehicles are stationary before test execution.

Table 15: Time Gap Setting - Vehicle Cut-In Maneuver

i^{th} time gap setting	2	3
$d_{i,ACC}$	37.5	do not execute
ACC (in s) - 1 time each	1.5	do not execute
$d_{i,CACC}$	do not execute	37.5
CACC (in s) - 3 times each	do not execute	1.5

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

7.6.3.1.2 Test Execution

Detailed test execution instructions can be found in Table 16.

Table 16: Test Execution Instruction - Vehicle Cut-In Maneuver

	V0	V1	V2	V3	V4
1.	Stage at Cone $1+3xd_i$	Stage at Cone 1a	Stage at Cone $1+2xd_i$	Stage at Cone $1+1xd_i$	Stage at Cone 1
2.	Accelerate manually to 55 mph.	Accelerate manually to 55 mph. Remain distance d_i / 2 towards preceding vehicle.	Accelerate manually to 55 mph. Remain distance d_i towards preceding vehicle.		
3.	Engage and set ACC to 55 mph before cone 3. Alternatively: Resume the ACC	Engage and set ACC to 55 mph and i^{th} time gap setting according to test variant before cone 3.	Engage and set CACC to 65 mph and i^{th} time gap setting according to test variant before cone 3.		
4.	---	Activate left turn indicator at cone 4 and perform a smooth lane change within a distance of 50 meters (approximately 2.0s at 55 mph). Deactivate turn indicator after completion of lane change.	---		
5.	Deactivate the ACC system by actuating the brake pedal manually at cone 6 and come to a full stop at cone 7.	Deactivate the CACC system by actuating the brake pedal manually as soon as the brake lights of any preceding vehicle light up and come to a full stop behind the preceding vehicle.			

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

7.6.3.1.3 Expected Results

The expected outcome of the testing is as shown in Table 17.

Table 17: Expected Results - Vehicle Cut-In Maneuver

	Source of information	V1	V2	V3	V4
1.	CustomerHMI	At cone 3 in CC mode.	At cone 3 in CACC-1 mode.	At cone 3 in CACC-1+ mode.	
2.	CustomerHMI		Before V1 performs the lane change maneuver, the target time gap and the current time gap are similar (+/- 0.1s) for at least 100 m.		
3.	CustomerHMI	CACC system is active throughout the path from cone 3 until the manual system deactivation in the reset area.			
4.	Driver or CoPilot	---	Do not overtake or fall behind V1 at any time.		
5.	CustomerHMI	---	Lane Change Icon visualized while V1 changes lanes.	---	
6.	Driver or CoPilot	---	V1 enters left lane in front of host vehicle.	---	
7.	CustomerHMI	After completed lane change at cone 6 switch into CACC-1 mode and slow down to reestablish time gap towards V0.	Use V1 as target vehicle for CACC-1 mode and slow down to reestablish time gap towards it.	Slow down to reestablish time gap towards preceding vehicle.	

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

7.6.3.1.4 Test Combinations

- Number of tests = 2 (one CACC + one ACC)
- Time per test = 5 minutes
- Number of repetitions = 4 (three per CACC + one per ACC)
- Total test runs = 4
- Test time = 20 minutes
- Buffer time = 5 minutes
- Total test time = 25 minutes

7.6.4 T-5 Overtaking

The goal of this test is to study the slow moving vehicle detection times and CACC system response to it, and the test is summarized in Table 18.

Table 18: Test summary - T-5 Overtaking

Description	A slow vehicle is on the road ahead. A string of four 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 slow down behind the slow moving vehicle.
Expected Outcome	It can be verified if the deceleration suppression based on the turn signal in the lead vehicle of the string 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

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

7.6.4.1.1 Variants

This test case differs by the used time gap setting of the CACC system. The driver can set the time gap as one of five predefined settings (see Table 19). For the i^{th} time gap setting, the distance d_i shall be used as inter vehicle gap while vehicles are stationary before test execution.

Table 19: Time Gap Setting - T-5 Overtaking

i^{th} time gap setting	1	2	3
$d_{i,ACC}$	25	37.5	do not execute
ACC (in s) - 1 time each	1.0	1.5	do not execute
$d_{i,CACC}$	15	25	37.5
CACC (in s) - 3 times each	0.6	1.0	1.5

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

7.6.4.1.2 Test Execution

Detailed test execution instructions can be found in Table 20.

Table 20: Test Execution Instruction - T-5 Overtaking

	V0	V1	V2	V3	V4
1.	Stage at Cone 1a	Stage at Cone $1+3xd_i$	Stage at Cone $1+2xd_i$	Stage at Cone $1+1xd_i$	Stage at Cone 1
2.	Accelerate manually to 5 mph. Alternatively: let the vehicle run at idle RPM in D of automatic transmission.	Accelerate manually to 55 mph. Remain distance d_i towards preceding vehicle.			
3.	---	Engage and set CACC to 55 mph and i^{th} time gap setting according to test variant before cone 3.			
4.	---	As soon as V0 is detected as target, activate right turn indicator.	---		
5.	---	As soon as vehicle begins to decelerate, perform a smooth lane change within a distance of 50 meters (approximately 2.0s at 55 mph). Deactivate turn indicator after completion of lane change.	---		
6.	Come to a comfortable stop at cone 5.	Deactivate the ACC system by actuating the brake pedal manually at cone 5 and come to a full stop at cone 6.	Follow V0 and deactivate the CACC system by actuating the brake pedal manually as soon as the host vehicle comes to a full stop behind the preceding vehicle.		

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

7.6.4.1.3 Expected Results

The expected outcome of the testing is as shown in Table 21.

Table 21: Expected Results - T-5 Overtaking

	Source of Information	V1	V2	V3	V4
1.	CustomerHMI	At cone 3 in CC mode.	At cone 3 in CACC-1 mode.	At cone 3 in CACC-1+ mode.	
2.	CustomerHMI	Before V0 performs the lane change maneuver, the target time gap and the current time gap are similar (+/-0.1s) for at least 100 m.			
3.	CustomerHMI	---	Lane Change Icon visualized while V1 changes lanes.	---	
4.	CustomerHMI	CACC system is active throughout the path from cone 3 until the manual system deactivation.			
5.	CustomerHMI	Speed up to 55 mph after lane change is completed.	CACC slows down the host vehicle as a reaction to slow travelling V0 without necessary driver interaction.		
6.	CustomerHMI	Show no reaction to slow travelling V0 on left lane while passing this vehicle.	Come to a full stop behind V0.		

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

7.6.4.1.4 Test Combinations

- Number of tests = 5 (three different CACC time-gaps + two different ACC time-gaps)
- Time per test = 5 minutes
- Number of repetitions = 4 (three per CACC + one per ACC)
- Total test runs = 11 (3*3 +2*1)
- Test time = 55 minutes
- Buffer time = 15 minutes
- Total test time = 70 minutes

7.6.5 T-11a String Stability: Acceleration/Deceleration

The goal of this test is to study the latency between lead vehicle activity and CACC response, and the test is summarized in Table 22.

Table 22: Test Execution Instruction - T-11a String Stability: Acceleration/Deceleration

Description	Five CACC 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

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

7.6.5.1 Variants

This test case differs by the used time gap setting of the CACC system. The driver can set the time gap as one of five predefined settings as shown in Table 23). For the i^{th} time gap setting, the distance d_i shall be used as inter vehicle gap while vehicles are stationary before test execution.

Table 23: Time Gap setting - T-11a String Stability: Acceleration/Deceleration

i^{th} **time gap setting**	**1**	**2**	**3**
$d_{i,ACC}$	25	37.5	do not execute
ACC (in s) - 1 time each	1.0	1.5	do not execute
$d_{i,CACC}$	15	25	37.5
CACC (in s) - 3 times each	0.6	1.0	1.5

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

7.6.5.2 Test Execution

Detailed test execution instructions can be found in Table 24.

Table 24: Test Execution Instruction - T-11a String Stability: Acceleration/Deceleration

	V0	V1	V2	V3	V4
1.	Stage at Cone 1 + 4 x d_i	Stage at Cone 1+3xd_i	Stage at Cone 1+2xd_i	Stage at Cone 1+1xd_i	Stage at Cone 1
2.	Accelerate manually to 55 mph.	Accelerate manually to 55 mph. Remain distance d_i towards preceding vehicle.			
3.	Engage and set CC to 55 mph before passing cone 3. Alternatively: Resume the CC.	Engage and set CACC to 65 mph and i^{th} time gap setting according to test variant before cone 3.			
4.	At cone 4, decelerate with $a_{n,decel}$ down to 30 mph.	---			
5.	As soon as 30 mph is reached, accelerate with $a_{n,accel}$ up to 55 mph.	---			
6.	As soon as 55 mph is reached, decelerate with $a_{n,decel}$ down to 30 mph.	---			
7.	As soon as 30 mph is reached, accelerate with $a_{n,accel}$ up to 55 mph.	---			
8.	As soon as 55 mph is reached, decelerate with $a_{n,decel}$ down to 30 mph.	---			
9.	As soon as 30 mph is reached, accelerate with $a_{n,accel}$ up to 55 mph.	---			
10.	Engage and set CC to 55 mph before passing cone 3. Alternatively: Resume the CC.	---			
11.	Deactivate the ACC system by actuating the brake pedal manually at cone 6 and come to a full stop at cone 7.	Deactivate the CACC system by actuating the brake pedal manually as soon as the brake lights of any preceding vehicle light up and come to a full stop behind the preceding vehicle.			

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

7.6.5.3 Expected Results

The expected test results as shown in Table 25.

Table 25: Expected Test Result - T-11a String Stability: Acceleration/Deceleration

	Source of information	V1	V2	V3	V4
1.	CustomerHMI	At cone 3 in CACC-1 mode	At cone 3 in CACC-1+ mode	At cone 3 in CACC-1+ mode	At cone 3 in CACC-1+ mode
2.	CustomerHMI	Before passing cone 4, the target time gap and the current time gap are similar (+/- 0.1s) for at least 100 m.			
3.	Driver or CoPilot	No driver intervention is necessary while traveling between cone 3 and cone 6.			
4.	CustomerHMI	CACC system is active throughout the path from cone 3 until the manual system deactivation in the reset area.			

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

7.6.5.4 Test Combinations

- Number of tests = 6 (three different time gaps for CACC and two different time gaps for ACC, each with two deceleration/acceleration combinations)
- Time per test = 5 minutes
- Number of repetitions = 4 (three per CACC + one per ACC)
- Total test runs = 22
- Test time = 110 minutes
- Buffer time = 30 minutes
- Total test time = 140 minutes

7.6.6 T-11b String Stability: Stop and Go

The goal of this test is to study the latency between lead vehicle activity and CACC response to, and the test is summarized in Table 26.

Table 26: Test Summary - T-11b String Stability: Stop and Go

Description	Five CACC enable vehicles follow each other in the same lane. At some point, the first vehicle starts repeated stop and go 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

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

7.6.6.1 Variants

This test case differs by the used time gap setting of the CACC system. The driver can set the time gap as one of five predefined settings (Table 27). For the i^{th} time gap setting the distance d_i shall be used as inter vehicle gap while vehicles are stationary before test execution.

Table 27: Time Gap Setting - T-11b String Stability: Stop and Go

i^{th} **time gap setting**	**1**	**2**	**3**
$d_{i,ACC}$	25	37.5	do not execute
ACC (in s) - 1 time each	1.0	1.5	do not execute
$d_{i,CACC}$	15	25	37.5
CACC Time Gap - 3 times each	0.6	1.0	1.5

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

7.6.6.2 *Test Execution*

Detailed test execution instructions can be found in Table 28.

Table 28: Test Execution Instruction - T-11b String Stability: Stop and Go

	V0	V1	V2	V3	V4
1.	Stage at Cone 1+4xd_i	Stage at Cone 1+3xd_i	Stage at Cone 1+2xd_i	Stage at Cone 1+1xd_i	Stage at Cone 1
2.	Accelerate manually to 55 mph.	Accelerate manually to 55 mph. Remain distance d_i towards preceding vehicle.			
3.	Engage and set CC to 55 mph before passing cone 3. Alternatively: Resume the CC.	Engage and set CACC to 65 mph and i^{th} time gap setting according to test variant before cone 3.			
4.	At cone 4, decelerate with $a_{n,decel}$ down to full stop.	---			
5.	Wait for all following vehicles to come to a full stop.	---			
6.	After receiving notification from V4, wait another 2 seconds at standstill.	---			Notify V0 after host vehicle comes to a full stop.
7.	Accelerate manually with $a_{n,accel}$ up to 55 mph.	Accelerate manually with $a_{n,accel}$ up to 25 mph.			
8.	Engage and set CC to 55 mph. Alternatively: Resume the CC.	Engage and set CACC to 65 mph and i^{th} time gap setting according to test variant. Alternatively: Resume the CACC.			
9.	Deactivate the ACC system by actuating the brake pedal manually at cone 6 and come to a full stop at cone 7.	Deactivate the CACC system by actuating the brake pedal manually as soon as the brake lights of any preceding vehicle light up and come to a full stop behind the preceding vehicle.			

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

7.6.6.3 Expected Results

The expected outcome of the testing is as shown in Table 29.

Table 29: Expected Test Result - T-11b String Stability: Stop and Go

	Source of information	V1	V2	V3	V4
1.	CustomerHMI	At cone 3 in CACC-1 mode.	At cone 3 in CACC-1+ mode.	At cone 3 in CACC-1+ mode.	At cone 3 in CACC-1+ mode.
2.	CustomerHMI	Before passing cone 4 the target time gap and the current time gap are similar (+/- 0.1s) for at least 100 m.			
3.	Driver or CoPilot	Vehicle comes to a full stop behind preceding vehicle.			
4.	CustomerHMI	CACC system is active throughout the path from cone 3 until coming to a full stop.			
5.	CustomerHMI	CACC system is active after resumption until the manual system deactivation in the reset area.			

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

7.6.6.4 Test combinations

- Number of tests = 6 (three different time gaps for CACC and two different time gaps for ACC, each with one deceleration/acceleration combination)
- Time per test = 5 minutes
- Number of repetitions = 4 (three per CACC + one per ACC)
- Total test runs = 11
- Test time = 55 minutes
- Buffer time = 15 minutes

Total test time = 70 minutes

7.6.7 Collaborative String Stability Scenario: 60 mph to 45 mph

The goal of this test is to study the latency between lead vehicle activity and CACC response to, and the test is summarized in Table 30.

Table 30: Test Summary - Collaborative String Stability Scenario: 60 mph to 45 mph

Description	Five CACC 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

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

7.6.7.1 Variants

This test case differs by the used time gap setting of the CACC system. The driver can set the time gap as one of five predefined settings (Table 31). For the i^{th} time gap setting, the distance d_i shall be used as inter-vehicle gap while vehicles are stationary before test execution.

Table 31: Time Gap Setting - Collaborative String Stability Scenario: 60 mph to 45 mph

i^{th} time gap setting	1	2	3
$d_{i,ACC}$	25	do not execute	do not execute
ACC Time Gap (s) - 1 time each	1.0	do not execute	do not execute
$d_{i,CACC}$	15	25	do not execute
CACC Time Gap - 3 times each	0.6	1.0	do not execute

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

7.6.7.2 Test Execution

Detailed test execution instructions can be found in **Table** 32.

Table 32: Test Execution Instruction - Collaborative String Stability Scenario: 60 mph to 45 mph

	V0	V1	V2	V3	V4
1.	Stage at Cone 1 + 4 x di	Stage at Cone 1+3xd_i	Stage at Cone 1+2xd_i	Stage at Cone 1+1xd_i	Stage at Cone 1
2.	Accelerate manually to 45 mph.	Accelerate manually to 45 mph. Remain distance d_i towards preceeding vehicle.			
3.	Engage and set CC to 45 mph before passing Pt 1. Alternatively: Resume the CC.	Engage and set CACC to 55 mph and i^{th} time gap setting according to test variant before pt 1.			
4.	At Pt 2, initiate accel and accel up to 60 mph. As soon as 60 mph is reached, set new CC to 60 mph and continue to Pt 3.	---			
5.	At Pt 3, initiate decel and decel down to 45 mph. As soon as 45 mph is reached, set new CC to 45 mph and continue to Pt 4.	---			
6.	At Pt 4, initiate accel and accel up to 60 mph. As soon as 60 mph is reached, set new CC to 60 mph and continue to staging area.	---			
7.	At Pt 5, initiate decel and decel down to 45 mph. As soon as 45 mph is reached, set new CC to 45 mph and continue to staging area.	---			
8.	Deactivate the ACC system by actuating the brake pedal manually at cone 6 and come to a full stop at cone 7.	Deactivate the CACC system by actuating the brake pedal manually as soon as the brake lights of any preceding vehicle light up and come to a full stop behind the preceding vehicle.			
9.	Stage at Cone 1+4xd_i	Stage at Cone1+3xd_i			

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

7.6.7.3 Expected Results

The expected outcome of the testing is as shown in Table 33.

Table 33: Expected Test Result - Collaborative String Stability Scenario: 60 mph to 45 mph

	Source of information	V1	V2	V3	V4
1.	CustomerHMI	At cone 3 in CACC-1 mode.	At cone 3 in CACC-1+ mode.	At cone 3 in CACC-1+ mode.	At cone 3 in CACC-1+ mode.
2.	CustomerHMI	Before passing cone 4, the target time gap and the current time gap are similar (+/- 0.1s) for at least 100 m.			
3.	Driver or CoPilot	No driver intervention is necessary while traveling between cone 3 and cone 6.			
4.	CustomerHMI	CACC system is active throughout the path from cone 3 until the manual system deactivation in the reset area.			

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

7.6.7.4 Test Combinations

- Number of tests = 6 (three different time gaps for CACC and two different time gaps for ACC, each with one deceleration/acceleration combination)
- Time per test = 5 minutes
- Number of repetitions = 4 (three per CACC + one per ACC)
- Total test runs = 11
- Test time = 55 minutes
- Buffer time = 15 minutes

Total test time = 70 minutes

8 Bibliography

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9 List of Acronyms

Acronym	Definition
ACC	Adaptive Cruise Control
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CACC-1	Cooperative Adaptive Cruise Control Mode, Lead Vehicle
CACC-1+	Cooperative Adaptive Cruise Control Mode, Following Vehicle
CACC	Cooperative Adaptive Cruise Control or Adaptive Cruise Control
CAN	Controller Area Network
CAMP	Crash Avoidance Metrics Partners LLC
CSV	Comma Separated Values
DSRC	Dedicated Short Range Communication
FHWA	Federal Highway Administration
FTTA	FT Techno of America Proving Grounds
GPS	Global Positioning System
HMI	Human Machine Interface
HV	Host Vehicle
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
OEM	Original Equipment Manufacturer
NTP	Network Time Protocol
V2V	Vehicle-to-Vehicle