Test and Evaluation of Vehicle Platooning Proof-of-Concept Based on Cooperative Adaptive Cruise Control

Final Report

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13. ABSTRACT
This report presents a high-level test and evaluation framework for cooperative driving automation systems that have the potential to significantly improve mobility and enhance traffic flow stability with better safety. It focuses on the test and evaluation of vehicle platooning that uses cooperative adaptive cruise control (CACC) and vehicle-to-vehicle communications to enable the automatic synchronization of longitudinal movements of a string of vehicles. This report defines comprehensive test procedures to facilitate the deployment of vehicle platooning concepts along an evolutionary path of enhanced system functions and capabilities, which consist of a progressive series of testing from very basic testing under closed track and normal driving conditions to more complex test scenarios and driving conditions on a test track and public roads. Results from first-pass, test-the-test procedures are summarized for a 5-car platooning proof-of-concept that was tested in July 2016 at a test track. This report delineates performance measures for car platooning and explains the test data analysis. Based on test results, this report offers several recommendations for features of the CACC-based vehicle platooning system that should be further assessed and potentially improved upon in the next iteration of the application.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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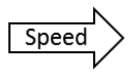
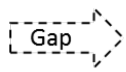
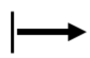
List of Abbreviations

ACC	Adaptive Cruise Control
AL	Automation Level
ATC	Aberdeen Test Center
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAN	Controller Area Network
CARMA	Connected Automated Research and Mobility Applications
CC	Production ACC at constant set speed
CCW	Counter-Clockwise
CV	Coefficient of Variation
CW	Clockwise
DAS	Data Acquisition System
DSRC	Dedicated Short-Range Communications
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standards
FOT	Field Operational Test
FV	Following Vehicle
GPS	Global Positioning System
I2V	Infrastructure-to-Vehicle
ISO	International Standards Organization
km	Kilometer
km/h	Kilometer per hour
LV	Lead Vehicle
m	Meter
M	Multiple
mph	miles per hour
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
PV	Preceding Vehicle
s	Second
S	Single
SAE	Society of Automotive Engineers
TFHRC	Turner-Fairbank Highway Research Center
V2V	Vehicle-to-Vehicle
Volpe	John A. Volpe National Transportation Systems Center

Legend of Images used in Figures

Lead Vehicle 	Vehicle at constant speed 
Follow Vehicle 	Vehicle accelerating 
Vehicle under Speed control 	Vehicle decelerating 
Vehicle under Gap control 	Driver applied braking 
Stopped Vehicle	Driver applied turn signal 
Vehicle accel. from a stop 	Reserved for future use

Executive Summary

This report provides a high-level test and evaluation framework for cooperative driving automation systems, delineates evolutionary concepts and test procedures for passenger car platooning based on cooperative adaptive cruise control (CACC), presents the test track results of a car platooning proof-of-concept system, and discusses lessons learned and recommendations to advance car platooning from the proof-of-concept to a prototype system for further test and evaluation. This research effort establishes a systems-engineering foundation that contributes to the development and deployment of effective CACC-based vehicle platooning.

The United States Department of Transportation's John A. Volpe National Transportation Systems Center (Volpe Center) supports the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center (TFHRC) in a research effort to advance cooperative driving automation systems that have the potential to significantly improve mobility and enhance traffic flow stability with better safety. Such mobility applications involve the automatic control and coordination of a cluster of motor vehicles to perform vehicle platooning, eco-approach and departure at signalized intersections, speed harmonization, and other functions using vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) dedicated short-range communications. The focus of this report is on the test and evaluation of vehicle platooning that utilizes CACC and V2V communications to enable the automatic synchronization of longitudinal movements of a string of vehicles.

This report identifies a baseline car platooning concept and evolutionary steps that enhance the functions and capabilities of the concept toward more advanced prototype systems. The building blocks of car platooning consist of vehicle control and driver role (automation level, speed range, and acceleration intensity), infrastructure (roadway and lane types), information (ranging, V2V and I2V exchange, and data sharing), and platooning strategy (coordination mode, gap regulation, formation, dissolution, and vehicle mix). The length limit and safety strategy of the platoon are also considered. In addition, this report provides a high-level framework for comprehensive test procedures that consist of a progressive series of testing from very basic testing under closed track and normal driving conditions to more complex test scenarios and driving conditions on a test track and public roads. Based on this framework, the report describes general test procedures for track testing that can be used to characterize the performance of various car platooning systems. Such characterization test procedures progress from initial test scenario concepts, first-pass test-the-test, second-pass test-the-test, dry-run characterization testing, to final characterization testing phases.

Specifically, this report develops track test procedures for the first-pass test-the-test phase that were applied to a car platooning proof-of-concept system under normal driving conditions. The procedures comprise the test approach, daily start-up and shut-down requirements, environmental and standard test conditions, test suspension and resumption criteria, testing safety plan, and specific test choreography and instructions. Detailed test procedures are described for four fundamental platooning functions: platoon formation, constant time gap with varying speeds, constant speed with varying time gaps, and platoon dissolution. In testing the platooning proof-of-concept, these procedures were

applied to three different types of platooning modes:

1. *Adaptive Cruise Control (ACC)-only in Lead Vehicle (LV) and Following Vehicles (FVs)* – The FV speed is set above the LV set speed. As they encounter the slower-moving LV ahead, the FVs automatically change to the time gap mode when joining the platoon.
2. *Hybrid CACC in LV and ACC in FVs* – The LV speed is automatically controlled by a prescribed speed profile and the FVs are in ACC with a set speed above the LV profile-controlled speeds. As they encounter the slower-moving LV ahead, the FVs automatically change to the time gap mode when joining the platoon.
3. *CACC-only in LV and FVs* – The LV speed is automatically controlled by the speed profile and the FVs are automatically put into time gap mode simultaneously via V2V command from the LV.

The Volpe Center evaluated the car platooning proof-of-concept based on data collected from the first-pass test-the-test characterization tests that were performed in July 2016 on a 7.2-kilometer (4.5 miles), two-lane test track at the U.S. Army's Aberdeen Test Center (ATC) in Maryland. The tests involved five passenger vehicles (2013 Cadillac SRX) that the TFHRC's Saxton Transportation Operations Laboratory had equipped with CACC controls and the car platooning proof-of-concept. Under an agreement with TFHRC, the U.S. Army provided the test track, acquired and installed data acquisition systems, executed the test procedures with professional drivers, and collected and transferred the data to the Volpe Center for analysis.

The following results are observed for various car platooning performance measures, based on the July 2016 characterization testing of the proof-of-concept:

- *Time Gap Accuracy/Stability*: FVs in ACC and CACC modes maintain stable time gaps while at constant speed, but are less stable during speed changes (i.e., acceleration and deceleration).
- *Speed Accuracy/Stability*: FVs in ACC and CACC modes maintain stable speeds while at constant speed. During deceleration, the difference between the LV's and each FV's speeds generally increases toward the end of the platoon. During acceleration, the speed of the FVs in CACC mode appears stable while it is slightly less stable in ACC mode. The difference between the LV's and each FV's maximum speeds increases toward the end of the platoon. While CACC is generally more stable during deceleration and acceleration, there is more variation between the minimum and maximum CACC speeds, as opposed to ACC where the minimum and maximum values are quite close.
- *Acceleration Accuracy/Stability*: FVs in ACC and CACC modes maintain stable acceleration while at constant speed. During deceleration and acceleration periods, FVs in ACC mode exhibit a clear growth trend between the LV and FV minimum and maximum toward the tail of the platoon. This is pronounced for FVs in ACC mode during deceleration. In contrast, while CACC runs exhibit large increases between the LV and FV1, there are only small increases between FVs. During deceleration periods, the CACC minima appear to be stable between FVs, with growing maxima. The inverse occurs during acceleration periods.

- *Initial Response Delay*: FVs in neither ACC nor CACC mode maintain stable initial response delays during deceleration. FVs in ACC mode are similarly unstable during acceleration, but FVs in CACC mode appear stable, with short initial response delays.
- *Transient Settling Durations*: FVs in ACC and CACC modes exhibit similarly poor settling durations following transient periods. FVs in CACC achieve the ±5% following speed trend sooner that FVs in ACC, while FVs in CACC take longer to achieve the 0% following speed trend.

The Volpe Center also assessed the LC speed controller and different CACC subsystems and made the following observations:

- *LV Speed Controller*: The custom CACC LV controller maintains the prescribed speed profiles very accurately. However, a potential concern is that the CACC controller has much more abrupt speed transitions than the production ACC controller. During periods of constant speed, the LV in CACC mode consistently maintains tighter deadbands than in the production ACC mode. While this results in more accurate speed control, it is less precise and may contribute to the FVs' instability due to the more frequent speed adjustments that must be commanded.
- *Position*: The PinPoint GPS position data appear to be very accurate and stable. While the vehicles are at rest, the position data remain tightly clustered. While the vehicles are in motion, the position measurements appear relatively close to a survey map of the track for each of the assessed data runs, except for one FV.
- *Speed*: At rest, production wheel speed data and CACC measurements remain zero while the PinPoint measurements exhibit very little noise and no significant bias. In motion, all speed measurements appear to be accurate, although the wheel sensors are biased slightly above the PinPoint and CACC measurements.
- *Acceleration*: PinPoint measurements exhibit significant noise and bias when the vehicles are at rest and in motion. These measurements were considered unusable in the analysis due to the significant unexplained errors. The acceleration moving average was calculated from the GPS-based speed measurements as an alternative.
- *Torque Controller*: The CACC torque controller frequently exhibits significant jumps in the commanded torque when compared to the production ACC controllers. As expected, the torque commands increase at the start of acceleration periods and decrease at the start of deceleration periods. There are fairly consistent torque levels commanded during constant speed periods. When the torque changes significantly, it is generally over a short duration and not instantaneous. In contrast with the production ACC, the CACC exhibits significant modulation between positive torque and negative torque. In addition, brake light commands are observed more frequently during deceleration periods and during periods of constant speed. The frequent braking and jittery motion are also observed by the vehicle occupants.

Finally, this report provides several recommendations for features of the CACC-based vehicle platooning system that should be further assessed and potentially improved upon in the next iteration of the application. The report also lists some lessons learned and recommendations for test and evaluation procedures, performance measures, and data elements.

1. Introduction

The United States Department of Transportation's John A. Volpe National Transportation Systems Center (Volpe Center) supports the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center (TFHRC) research effort to advance cooperative driving automation systems that have the potential to significantly improve mobility and enhance traffic flow stability with better safety [1]. Such mobility applications involve the automatic control and coordination of a cluster of motor vehicles to perform platooning, eco-approach and departure at signalized intersections, speed harmonization, and other functions. The focus of this report is on the test and evaluation of vehicle platooning that uses cooperative adaptive cruise control (CACC) and vehicle-to-vehicle (V2V) communications to enable the automatic synchronization of longitudinal movements of a string of vehicles. The CACC represents an advancement of adaptive cruise control (ACC) systems by utilizing V2V dedicated short-range communications (DSRC) to exchange information among vehicles in a string.

TFHRC has equipped a fleet of five 2013 Cadillac SRX vehicles with a prototype CACC system and a vehicle platooning proof-of-concept, and has been conducting an iterative process of designing and evaluating the platoon to advance the vehicle platooning application and determine its potential benefits. The Volpe Center, in conjunction with TFHRC, has been performing a thorough evaluation of CACC-based vehicle platooning by developing a comprehensive test framework that gradually expands the breadth of test scenarios and test environments from the proof-of-concept stage to more advanced prototype systems. In collaboration with TFHRC, the U.S. Army has provided a paved 7.2-kilometer (km) (4.5 miles), two-lane test track at the Aberdeen Test Center (ATC) in Maryland, acquired and installed data acquisition systems (DAS), executed the test procedures, and collected and transferred the data to TFHRC and the Volpe Center for analysis.

This report provides a high-level framework for comprehensive test procedures to facilitate the deployment of vehicle platooning concepts along an evolutionary path of enhanced system functions and capabilities. The test procedures consist of a progressive series of testing from very basic testing under closed track and normal driving conditions to more complex test scenarios and driving conditions on a test track and public roads. This report also summarizes the first phase of the test and evaluation of the vehicle platooning proof-of-concept, supporting data elements, and analysis results. In addition, this report delineates the approach that was used for assessing the proof-of-concept, including basic sensor and system performance assessments and the evaluation of overall system stability. Finally, this report provides several recommendations for features of the CACC-based vehicle platooning system that should be further assessed and potentially improved upon in the next iteration of the application.

1.1 Cooperative Driving Automation Systems

This report describes a high-level test and evaluation framework and a process for cooperative driving automation systems to advance their evolution into mature products and determine their potential benefits. TFHRC, in conjunction with the Volpe Center and ATC, has planned to apply this framework and process to the following three mobility applications: vehicle platooning, eco-approach and departure at signalized intersections, and speed harmonization.

1.1.1 Vehicle Platooning

The vehicle platooning application can decrease the following distances between motor vehicles using CACC by wirelessly coupling vehicles together [2]. The CACC allows drivers the convenience of setting their desired speed and having the vehicle safely maintain that speed automatically. The CACC also recognizes the presence of a slower vehicle ahead and then automatically adjusts the speed to follow the other vehicle safely at a headway set by the driver. If the vehicle ahead should stop suddenly, or if another vehicle cuts in ahead too closely, the CACC vehicle can react in time to allow it to brake immediately using the combination of the sensors and the communication system. In addition to maintaining a set cruise speed and/or a set following distance or time gap behind another vehicle, the CACC-based platooning concepts allow equipped vehicles to cooperate by communicating with each other. This communication provides enhanced information so that V2V CACC-equipped vehicles can follow their preceding vehicles with higher accuracy, faster response, and shorter gaps, resulting in enhanced traffic flow stability, increased roadway capacity, and improved safety.

1.1.2 Eco-Approach and Departure at Signalized Intersections

The eco-approach and departure at signalized intersections application decreases fuel consumption, greenhouse gas, and criteria air pollutant emissions by reducing vehicle idling, the number of stops, and unnecessary accelerations and decelerations and by improving traffic flow at signalized intersections [3]. A foundational component of this application concept uses wireless data communications sent from a roadside equipment unit to connected and enabled vehicles to encourage 'green' approaches to signalized intersections. The application, located in a vehicle, collects 'signal phase and timing' and 'geographic information description' messages using infrastructure-to-vehicle (I2V) communications and data from nearby vehicles using V2V communications. Upon receiving these messages, the application would perform calculations to determine the vehicle's optimal speed to pass the next traffic signal on a green light or to decelerate to a stop in the most eco-friendly manner. This information is then sent to longitudinal vehicle control capabilities in the vehicle to support partial automation. The application may also consider a vehicle's acceleration as it departs from a signalized intersection and engine start-stop technology when the vehicle is stopped at a traffic signal. Engine start-stop capabilities allow the vehicle to automatically shut down and restart its engine when stopped thus reducing the amount of time the engine spends idling, thereby reducing fuel consumption and emissions. This is advantageous for the vehicle as it spends time waiting at traffic lights.

1.1.3 Speed Harmonization

The speed harmonization application implements a method that reduces congestion and improve traffic performance [4]. This method is applied at points where lanes merge and form bottlenecks; the greatest cause of congestion nationwide. The strategy involves gradually lowering speeds before a heavily congested area to reduce the stop-and-go traffic that contributes to frustration and crashes. Speed harmonization has the potential to smooth traffic, increase the number of vehicles that a roadway can handle, and improve safety by making it easier for drivers to change lanes when necessary. It also has the potential to reduce the number of rear-end crashes caused by drivers who do not brake early enough when they encounter slow-moving or stopped vehicles.

1.2 General Deployment Framework for Automotive Systems

Figure 1 illustrates a general framework of key steps and factors that lead to the deployment of advanced-technology automotive systems. Typically, the successful deployment of systems depends on many engineering factors that include, but are not limited to, safety, reliability, interoperability, security, and consistent performance. The availability of standards and guidelines by the industry or government enables the development of deployable systems that meet these engineering factors. From a systems perspective, the specification of minimum system performance levels and the establishment of concomitant objective test procedures form an essential input to standards and guidelines. In addition to engineering factors, product deployment decisions rely on other important factors such as user acceptance, cost and benefits, technical maturity, operation logistics, and suitable solutions to institutional and policy barriers.

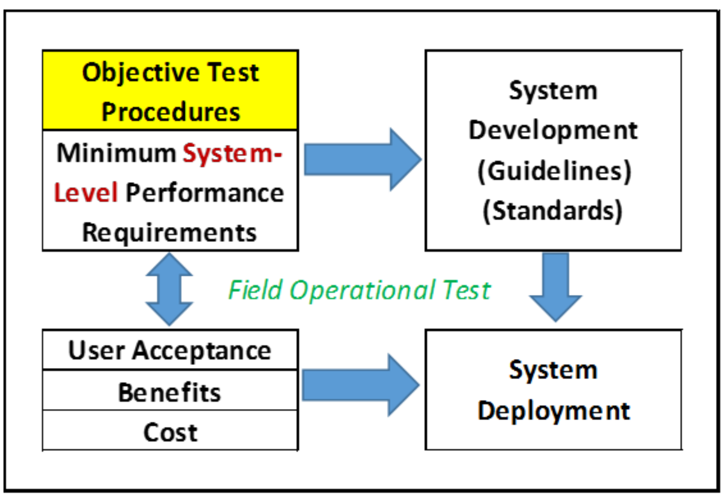


Figure 1. General System Deployment Framework

Before a system proceeds into deployment, a field operational test (FOT) is generally conducted to project or confirm that the system will have, or has achieved, the required operational capabilities and characteristics when placed in service [5]. This activity is normally conducted in the intended operational environment, under realistic conditions, and on a production-representative system by typical users with the same qualifications and training that would be expected of those who will operate the system. The degree of realism that can be achieved in the FOT is a primary factor in the usefulness, credibility, and validity of the test and independent evaluation results. An independent evaluation consists primarily of the following three objectives:

1. Assess the performance and capability of the system.
2. Estimate the costs and potential benefits of the system for its impact on traffic mobility, safety, and energy consumption.
3. Gauge driver acceptance of the system.

Other evaluation elements may include the logistics, cost, legal barriers, and institutional issues for the operation and deployment of the system [6].

This project focuses on the test procedures and performance measures that help support the development of system-level standards and guidelines. In addition, the test procedures consist of different phases of testing that will allow the collection of data to characterize the capability, obtain user feedback, and project the potential benefits of CACC-based vehicle platooning.

The current draft standard on CACC by the International Standards Organization (ISO) addresses the following requirements for V2V- and I2V-based CACC:

- Classification of CACC types (i.e., V2V and I2V)
- Definition of performance requirements for each CACC type (i.e., Region of interest, potential vehicle of interest, state transition diagram, and control operation strategy)
- Minimum set of wireless data requirements
- Basic driver interface and intervention capabilities
- Performance evaluation test methods (i.e., range, accuracy, target discrimination, curve capability, V2V cooperative operating modes/states, and I2V tests)

The scope of the draft ISO standard includes CACC that performs only longitudinal vehicle speed control via throttle and brake controls, uses time gap control strategy similar to ACC, has similar engagement criteria as ACC, and operates under driver responsibility and supervision. Coordinated strategies to control vehicle platoons, in which vehicle controllers base their control actions on how they affect other vehicles, and may have very short following clearance gaps are not within the scope of this standard [7]. This ISO standard is applicable to CACC systems of different curve capabilities.[1]

The National Highway Traffic Safety Administration (NHTSA) issues federal motor vehicle safety standards (FMVSS) that need to be practicable, meet the need for motor vehicle safety, and stated in objective terms. To state the standard in objective terms, NHTSA generally establishes performance requirements for motor vehicles (or motor vehicle equipment) and establishes specific test conditions under which the motor vehicle (or motor vehicle equipment) needs to meet those requirements. The tests specified in FMVSS enable both the manufacturer and NHTSA to determine whether a product

[1] ISO 22179: Intelligent transport systems — Full speed range adaptive cruise control (FSRA) systems — Performance requirements and test procedures.

complies. In addition to FMVSS, NHTSA has developed the New Car Assessment Program (NCAP) that provides comparative safety rating information on new vehicles to assist consumers with their vehicle purchasing decisions. The NCAP incorporates repeatable performance tests and procedures to ensure a certain level of performance.

1.3 Test and Evaluation of Cooperative Driving Automation Systems

Figure 2 illustrates the test and evaluation process for automated vehicle applications of individual automated vehicles (e.g., automated lane and headway keeping) or cluster of cooperative driving automation systems (e.g., vehicle platoon).

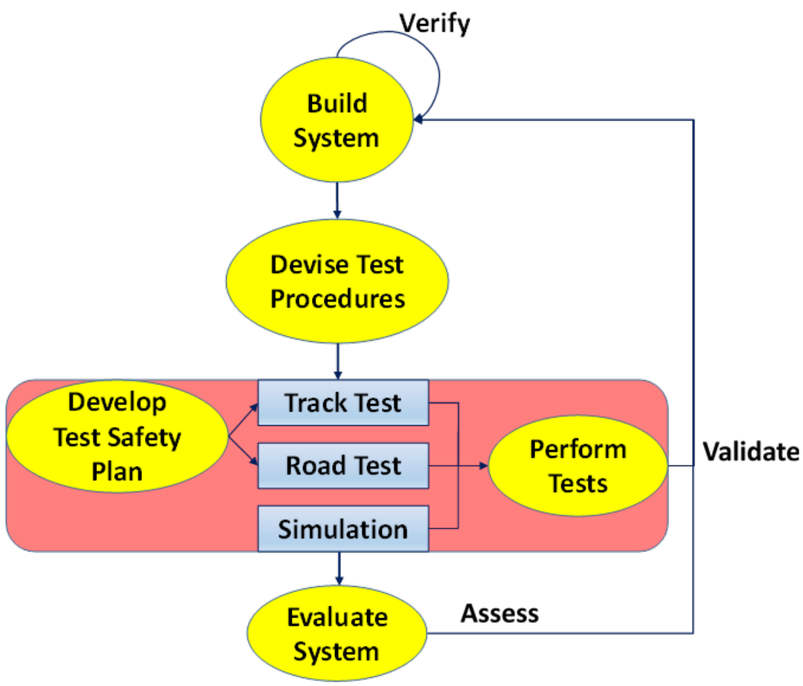


Figure 2. Test and Evaluation Process

1.3.1 Build System

Manufacturers (original equipment manufacturers and suppliers) build automated vehicle systems and verify their design to ensure that the subsystems and system meet design specifications/requirements. In addition, manufacturers and research organizations modify automated vehicle systems to implement more advanced automation such as vehicle platooning. In this project, the TFHRC's Saxton Transportation Operations Laboratory has developed a platform technology for automated vehicle research and modified production ACC vehicles to perform cooperative driving automation systems, including vehicle platooning, speed harmonization, and eco-approach and departure at signalized intersections [8].

1.3.2 Devise Test Procedures

Manufacturers and independent evaluators prepare controlled and naturalistic test procedures to validate and evaluate the system. System validation ensures that the system/prototype meets the user/business needs translated into design specifications/requirements for product acceptance. System evaluation assesses the performance of the system in the whole spectrum of the operational environment. In this project, the TFHRC's Saxton Transportation Operations Laboratory has prepared controlled tests to validate their system. The Volpe Center has devised controlled and naturalistic test procedures to evaluate the system.

1.3.3 Perform Tests

Test procedures typically call for different test settings that include track tests, on-road tests, and hardware-in-the-loop/software-in-the-loop simulations. In addition, the test procedures incorporate graded test scenarios that encompass benign, potentially-hazardous, and potentially-dangerous driving scenarios to assess the full functionality and potential benefits of the system. For track and on-road tests, a test safety plan is required prior to conducting the tests to ensure the safety of the test drivers and their surroundings. In this project, ATC performed the tests on a closed-course test track and prepared test safety plans for benign test procedures. For potentially-hazardous test scenarios, ATC requires safety evidence of the system under test before allowing the conduct of such tests. The Volpe Center provided input to ATC for the preparation of the test safety plan for benign test procedures. As for system safety evidence for potentially-hazardous test scenarios, functional and system safety analyses must be undertaken to identify hazards, assess risks, derive safety requirements, and create hazard mitigation schemes for the system and its testing. It is recognized that simulations are the preferred setting to test potentially-dangerous driving scenarios given that the proper system models are built and validated with empirical data from the benign and potentially-hazardous test scenarios.

1.3.4 Evaluate System

System evaluations assess whether the system under test has met its mobility, energy consumption, and safety objectives. The evaluation may also address additional characteristics of the system such as driver comfort, convenience, and satisfaction. This kind of evaluation uses data from different test settings collected from professional test drivers and regular drivers under a multitude of environmental factors.

Ultimately, the success of a CACC-based vehicle platooning system will be determined by its ability to increase highway capacity by reducing traffic flow disturbances and decreasing the net vehicle following distances [2]. To fully demonstrate the mobility gains, detailed simulations must be conducted to evaluate the benefits of a given system design. However, a shortcoming of previous simulations has been overly optimistic models of vehicle performance. To accurately estimate the mobility benefits of CACC, future simulations should be based on more realistic system performance characteristics [9]. While mobility simulations are outside the scope of this report, the core data collection and performance assessments outlined in this report can be used to validate the CACC-based platooning algorithms and settings and eventually be used to tune more representative simulations. Finally, previous research has suggested that fuel consumption and emissions may improve if a platooning system can operate stably at low time gaps [10]. While fuel consumption is not a primary objective of the analysis outlined in this report, several aspects of the assessment provide indirect feedback on fuel consumption, including assessing the acceleration profiles, smoothness of command inputs, and looking at whether unnecessary braking commands are issued. In addition, collecting and evaluating the production fuel consumption measurements is recommended for future assessments.

1.4 Report Focus

The focus of this report is on establishing and validating an approach to test and evaluate the string stability of a CACC-based car platooning proof-of-concept on a relatively flat, controlled roadway. The basic criteria are well outlined in the following excerpt from [10]:

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

The report expands on this description by enumerating the various performance measures that should remain stable and the specific data elements and metrics for assessing each performance measure. The assessment will address both the oscillation for a given position in the platoon and whether the magnitude of the oscillations grows as the tail of the platoon is approached, which can lead to actuator saturation [11].

The report also addresses the challenge of determining the acceptable level of stability for a given CACC-based system design. Specifically, the determination of whether a string ‘minimizes’ oscillation is subjective, as some oscillation will always occur due to inherent characteristics such as system latency, sensor errors, and variation between vehicle performance. While less oscillation is better, this requires a baseline from which to compare the CACC-based system performance. To address this issue, the report outlines a series of test scenarios that were executed to collect data from the production ACC system that can be directly compared to the CACC prototype.

Finally, while assessing the CACC subsystem performance is not an objective of this work, a limited assessment of the sensors and lead vehicle speed profile controller was performed to have confidence in the system data and the repeatability of the test scenarios. Future work should expand on the scenarios outlined in this report by addressing platoon formation and dissolution and changing the CACC settings, variations in terrain and topology, mixed traffic, etc.

2. Vehicle Platooning Concepts and Testing

This section describes different vehicle platooning concepts and delineates the proof-of-concept that was tested in July 2016 at ATC [12] using FHWA's platform technology for automated vehicle research [8]. The report refers to this concept as the "baseline" concept and discusses its evolutionary enhancements. This section discusses the types, phases, and logistics of testing automated vehicle platooning proof-of-concept and prototypes based on system concepts of different capability levels. The testing part delineates test procedures that are devised to assess the capability, gauge driver acceptance, and project initial potential benefits of specific vehicle platooning systems. It also delineates the test framework of the baseline car platooning concept at increasing maturity levels of technology development.

2.1 Variants of Platooning Concepts

Variants of vehicle platooning concepts incorporate elements from the following four building blocks and other operational considerations [2] [10]:

1. Vehicle Control and Driver Role
2. Infrastructure
3. Information
4. Platooning Strategy

2.1.1 Vehicle Control and Driver Role

This building block includes the following three elements:

1. Automation Level:
    - *Longitudinal control at automation level (AL) 1*: Vehicle performs automatic longitudinal control of travel speed and distance to the vehicle in front using the brake and throttle systems. This automatic control corresponds to the Society of Automotive Engineers (SAE) AL 1, driver assistance, defined as the driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task [14].
    - *Longitudinal and lateral control at AL 2*: Vehicle performs automatic longitudinal control, as described above, and automatic lateral control that continuously steers the vehicle along a reference course, such as the lane centerline, using the vehicle's steering system. This automatic longitudinal and lateral control corresponds to SAE AL 2, partial automation, defined as the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task.

- *Longitudinal and lateral control at AL 4/5*: This corresponds to SAE AL 4, high automation, defined as the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene; or SAE AL 5, full automation, defined as the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.

2. Speed Range: Platooning may accommodate automatic speed control at either:
    - *Partial* vehicle speed (above a minimum and below a maximum speed thresholds), or
    - *Full* vehicle speed range from zero to maximum legal travel speeds.

3. Acceleration Intensity: Platooning may perform with:
    a. *Limited* automatic vehicle acceleration and deceleration intensity levels, or
    b. *Full* vehicle authority of braking and acceleration.

2.1.2 Infrastructure

This building block consists of the following two elements:

1. Roadway Type:
    - *Limited-access highways* that carry high-speed traffic with limited or no access to adjacent property (entry and exit ramps).
    - *Major multi-lane roads* that cross minor roads (no traffic control for major road and stop sign for minor road), with access to adjacent property.
    - *Multi-lane roads with signalized corridors* that contain intersections controlled by traffic signals.

2. Lane Type:
    - *Dedicated lanes* that are allocated exclusively for vehicle platooning operations.
    - *Dedicated lanes* that allow travel by all vehicles under various controls (manual and automated vehicle controls).

2.1.3 Information

This building block includes the following three elements:

1. Ranging:
    - *On-board sensor* that determines the range, relative speed, and relative acceleration to the vehicle in front, such as radar, lidar, or vision.
    - *On-board sensor with V2V* ranging that provides redundant range and relative speed

measurements from the on-board sensor and V2V for more reliable ranging under wider environmental conditions.

2. Exchange:
   - *V2V only* that allows data exchange among vehicles at a fast rate using DSRC (i.e., vehicle characteristics, position, speed, acceleration, yaw rate, brake status, throttle position, steering angle, etc.)
   - *V2V and I2V* that provide infrastructure information in addition to vehicle data. I2V may transmit static information, such as posted speed limit or maximum safe speed for a curve; and dynamic information such as variable speed limits, based on changes in weather, road surface, or traffic conditions. Since this information does not change rapidly for highway driving applications (updates on the order of multiple seconds (s) or minutes (min) or longer), it may be provided using a wide range of wireless communication media other than DSRC. For eco- or green driving on signalized corridors, I2V can send signal phase information to vehicles to reduce the number of stops and harmonize intersection crossings. Traffic signal status will require more frequent updates and lower latencies provided by DSRC.

3. Sharing:
   - Sharing of data *between the lead vehicle* (i.e., head of the platoon) *and all following vehicles* in the platoon (all following vehicles would be listening to the leader directly).
   - Sharing of data *among all vehicles* in the platoon where the following vehicles would exchange information with the lead vehicle and with each other.

2.1.4 Platooning Strategy

Platooning strategy is formulated using the following five elements:

1. Mode:
   - *Ad-hoc clustering* that allows vehicles to join or leave a platoon in a random sequence without any coordinated strategy.
   - *Local coordination* that instructs drivers to take some specific actions to couple with other vehicles, instructing some drivers to speed up or slow down to allow all the enabled vehicles to connect, and requiring lane changes for some drivers.
   - *Global coordination* that involves advance planning to coordinate vehicles traveling from similar origins to similar destinations before the vehicles enter the highway. Vehicle routes and speeds can be adjusted to time their arrivals at the highway entry points so that they are able to couple together from the start. This will require more extensive long-range communication and a back-office coordination functionality that would not be needed in the ad-hoc or local coordination cases.

2. Gap Regulation:
    - *Constant time gap* where the distance between vehicles is proportional to their speed (plus a small fixed offset distance).
    - *Constant clearance* where the separation between vehicles remains constant, and does not change as the vehicle speed changes.
    - *Constant safety factor* that depends on the separation criterion between platoons in an automated highway system.

3. Formation:
    - *From rear* that allows vehicles to join the platoon only when approaching from the rear.
    - *From middle or rear* that allows vehicles to join the platoon either when approaching from the rear or cutting in inside the middle.
    - *By destination* that corresponds to the global coordination strategy.

4. Dissolution:
    - *Single vehicle* leaving the platoon where the departing driver performs a simple lane change maneuver and the vehicle that was behind the departing vehicle in the original lane can then simply close the gap to its new preceding vehicle, and the length of the platoon decreases by one.
    - *Multiple consecutive vehicles* leaving the platoon that requires long enough gap in the adjacent lane to accommodate all departing vehicles. A local or global coordination strategy may be needed to perform such a dissolution action.

5. Vehicle Mix:
    - *Similar vehicle types* (i.e., passenger cars, trucks, or buses) are allowed to form a platoon.
    - *Different vehicle types* can join the same platoon.

2.1.5 Other Operational Considerations

There are other additional operational considerations for vehicle platooning:

- *Length limit of the platoon*: One upper limit that could be placed on length is based on the range of the wireless V2V communication system, assuming that all following vehicles will require direct communication from the lead vehicle in the platoon. The maximum length could also be established based on the number of vehicles or on the distance between the lead vehicle and the last following vehicle based on platoon stability [2].
- *Safety strategy*: The functional safety analysis of a specific vehicle platooning concept would require hazard mitigation strategies that address fault detection and failure mitigation, transition to safe states, fault tolerance mechanisms, and driver warning strategies [14]. The safety strategy would include manual and/or automatic fail-safe mechanisms.

Table 1 lists the various key blocks, categories, and elements that frame the different vehicle platooning concepts.

Table 1. Key Blocks of Vehicle Platooning Concepts

Block	Category	Element
Vehicle Control and Driver Role	*Automation Level*	• Longitudinal control @ AL 1 • Longitudinal and lateral control @ AL 2 • Longitudinal and lateral control @ AL 4 and 5
Vehicle Control and Driver Role	*Speed Range*	• Partial • Full
Vehicle Control and Driver Role	*Acceleration Intensity*	• Limited • Full
Infrastructure	*Roadway Type*	• Limited-access highways • Major multi-lane roads • Multi-lane roads with signalized corridors
Infrastructure	*Lane Type*	• Dedicated lanes • Shared lanes
Information	*Ranging*	• On-board sensor • On-board sensor + V2V
Information	*Exchange*	• V2V only • V2V + I2V
Information	*Sharing*	• Between lead and all followers • Among all vehicles
Platooning Strategy	*Mode*	• Ad-hoc clustering • Local coordination • Global coordination
Platooning Strategy	*Gap Regulation*	• Constant time gap • Constant clearance • Constant safety factor
Platooning Strategy	*Formation*	• From rear • From rear or middle • By destination
Platooning Strategy	*Dissolution*	• Single vehicle • Multiple vehicles
Platooning Strategy	*Vehicle Mix*	• Similar types • Different types

2.2 Baseline CACC Platooning Concept and Future Enhancements

Table 2 shows the key elements of the baseline car platooning concept that uses FHWA's automated vehicle research platform. This table marks these elements by an X in the "Baseline" column.

Table 2. Elements of Baseline Car Platooning Concept

Block	Category	Element	Baseline
Vehicle Control and Driver Role	*Automation Level*	Longitudinal control @ AL 1	**X**
Vehicle Control and Driver Role	*Automation Level*	Longitudinal & lateral control @ AL 2	
Vehicle Control and Driver Role	*Automation Level*	Longitudinal & lateral control @ AL 4 and 5	
Vehicle Control and Driver Role	*Speed Range*	Partial	**X**
Vehicle Control and Driver Role	*Speed Range*	Full	
Vehicle Control and Driver Role	*Acceleration Intensity*	Limited	**X**
Vehicle Control and Driver Role	*Acceleration Intensity*	Full	
Infrastructure	*Roadway Type*	Limited-access highways	**X**
Infrastructure	*Roadway Type*	Major multi-lane roads	
Infrastructure	*Roadway Type*	Multi-lane roads with signalized corridors	
Infrastructure	*Lane Type*	Dedicated lanes	**X**
Infrastructure	*Lane Type*	Shared lanes	
Information	*Ranging*	On-board sensor	**X**
Information	*Ranging*	On-board sensor + V2V	
Information	*Exchange*	V2V only	**X**
Information	*Exchange*	V2V only	
Information	*Sharing*	Between lead and all followers	**X**
Information	*Sharing*	Among all vehicles	
Platooning Strategy	*Mode*	Ad-hoc clustering	**X**
Platooning Strategy	*Mode*	Local coordination	
Platooning Strategy	*Mode*	Global coordination	
Platooning Strategy	*Gap Regulation*	Constant time gap	**X**
Platooning Strategy	*Gap Regulation*	Constant clearance	
Platooning Strategy	*Gap Regulation*	Constant safety factor	
Platooning Strategy	*Formation*	From rear	**X**
Platooning Strategy	*Formation*	From rear or middle	
Platooning Strategy	*Formation*	By destination	
Platooning Strategy	*Dissolution*	Single vehicle	**X**
Platooning Strategy	*Dissolution*	Multiple vehicles	
Platooning Strategy	*Vehicle Mix*	Similar types	**X**
Platooning Strategy	*Vehicle Mix*	Different types	

Table 3 illustrates possible paths of system enhancements for each element of vehicle platooning concepts in three evolutionary steps. Step 1 corresponds to the elements of the baseline car platooning concept in Table 2. One can devise different vehicle platooning concepts at increasing capability levels by highlighting the cells in Table 3. For example, Table 4 shows the highlighted cells that form a very advanced vehicle platooning concept.

Table 3. Evolutionary Steps for Elements of Vehicle Platooning Concepts

Block	Category	1st Step – Baseline	2nd Step	3rd Step
Vehicle Control and Driver Role	*Automation Level*	Longitudinal control @AL 1	Longitudinal control @AL 2	Longitudinal control @AL 4 and 5
Vehicle Control and Driver Role	*Speed Range*	Partial	Full	Full
Vehicle Control and Driver Role	*Acceleration Intensity*	Limited	Full	Full
Infrastructure	*Roadway Type*	Limited-access highways	Major multilane roads	Multilane roads with signalized corridors
Infrastructure	*Lane Type*	Dedicated Lanes	Shared lanes	Shared lanes
Information	*Ranging*	On-board sensor	On-board sensor + V2V	On-board sensor + V2V
Information	*Exchange*	V2V only	v2v + 12v	v2v + 12v
Information	*Sharing*	Between lead and all followers	Among all vehicles	Among all vehicles
Platooning Strategy	*Mode*	Ad-hoc clustering	Local coordination	Global coordination
Platooning Strategy	*Mode*	Constant time gap	Constant clearance	Constant safety factor
Platooning Strategy	*Mode*	From rear	From rear or middle	By destination
Platooning Strategy	*Mode*	Single vehicle	Multiple vehicles	Multiple vehicles
Platooning Strategy	*Mode*	Similar types	Different types	Different types

Table 4. Elements of an Advanced Vehicle Platooning Concept

Block	Category	1st Step – Baseline	2nd Step	3rd Step
Vehicle Control and Driver Role	*Automation Level*	Longitudinal control @AL 1	Longitudinal and lateral control @AL 2	Longitudinal and lateral control @AL 4 and 5
Vehicle Control and Driver Role	*Speed Range*	Partial	Full	Full
Vehicle Control and Driver Role	*Acceleration Intensity*	Limited	Full	Full
Infrastructure	*Roadway Type*	Limited-access highways	Major multilane roads	Multilane roads with signalized corridors
Infrastructure	*Roadway Type*	Dedicated Lanes	Shared lanes	Shared lanes
Information	*Ranging*	On-board sensor	On-board sensor + V2V	On-board sensor + V2V
Information	*Exchange*	V2V only	V2V + 12V	v2v + 12v

Block	Category	1st Step – Baseline	2nd Step	3rd Step
Information	*Sharing*	Between lead and all followers	Among all vehicles	Among all vehicles
Platooning Strategy	*Mode*	Ad-hoc clustering	Local coordination	Global coordination
Platooning Strategy	*Gap regulation*	Constant time gap	Constant clearance	Constant safety factor
Platooning Strategy	*Formation*	From rear	From rear or middle	By destination
Platooning Strategy	*Dissolution*	Single vehicle	Multiple vehicles	Multiple vehicles
Platooning Strategy	*Vehicle Mix*	Similar types	Different types	Different types

2.3 General Test Procedures

Based on systems engineering, the test and evaluation of technology concepts that have the potential to address certain problems (e.g., vehicle platooning solutions for traffic congestion) is an iterative process that guides the gradual development and testing of systems from the proof-of-concept, prototype, to product stages [5]. At each system development stage, various tests are conducted to collect data that inform design improvement of the system, further test and evaluation needs, and the impact of system design on the problem(s) (i.e., potential benefits) and user acceptance. Test procedures typically include:

1. Scope and objectives (i.e., system capability, driver acceptance, and benefits estimation)
2. Approach (i.e., experimental design)
3. Instrumentation, equipment installation, and calibration
4. Performance measures and data collection requirements
5. Environmental, ambient, and standard test conditions (i.e., consideration to road geometry, road surface condition, road structure, weather, and traffic level-of-service)
6. Test suspension criteria and resumption requirements
7. Test scenarios (i.e., overview, run validity criteria, test setup and driving instructions)
8. Safety procedures

2.4 Test Characteristics

Test characteristics consist of four elements: type, control, location, and participant.

2.4.1 Test Types

There are four test types that are performed in this sequential order:

1. *Safety assurance tests* that are initially conducted to ensure that the test participants perform the test procedures in a safe manner, following a safety/hazard mitigation plan.
2. *Characterization tests* that follow prescribed test procedures to better understand system performance under a wide range of driving scenarios and conditions.
3. *Confirmation (objective) tests* that measure whether or not the system meets system-level performance requirements in very specific test scenarios and conditions. Standards typically prescribe such tests that could be based on some characterization test scenarios. These tests, along with characterization and safety assurance tests, must be repeatable in a consistent manner.
4. *Field operational tests* in naturalistic settings as discussed in Section 1.2.

2.4.2 Test Controls

The following three test controls are typically performed in this sequential order:

1. *Controlled testing* that exactly specifies the test scenarios (initial and final conditions), choreography, driving instructions, and environmental conditions.
2. *Semi-controlled testing* that allows drivers to perform own driving maneuvers within generally-prescribed test conditions.
3. *Naturalistic testing* that eliminates any constraints on how and where the test participants drive, except for obeying traffic laws and following recommendations by the Independent Review Board on the use of human subjects in the test.

2.4.3 Test Locations

The following three test locations are typically used in this sequential order as systems are developed from the proof-of-concept stage to the product stage:

1. Closed-course test track or area
2. Public roadway
3. Driving simulator

2.4.4 Test Participants

There are two types of test participants:

1. *Professional drivers* that are trained to perform safe maneuvers in hazardous driving situations. Such drivers are typically employed to run "engineering" tests such as characterization and objective tests.
2. *Regular drivers* that represent the licensed driving population from younger to older drivers. Such drivers are typically recruited for "human factors" testing such as characterization and field operational tests.

2.5 Test Framework for Baseline Platooning Concept

Testing of the baseline car platooning concept is initially focused on controlled safety assurance and characterization tests using professional drivers on a test track. General test procedures contain information on the driving mode and independent factors, as listed below:

2.5.1 Driving Mode

The following four driving modes are considered:

1. Normal Driving:
    - *Steady-state driving*: Various speed and acceleration profiles of the lead vehicle as a function of traffic conditions (use of empirical data)
    - *Transient-state driving:*
        - Forming the platoon
        - Dissolving the platoon
        - One or more vehicles leaving the platoon
        - Lead vehicle leaving the platoon via lane change (cut-out)
        - Middle vehicle(s) leaving the platoon via lane change (cut-out)
        - One or more vehicles joining the platoon: Vehicles joining at the rear of the platoon (approaching in the same lane)

2. Conflict Driving within Control Limits:
    - *Braking* by the lead vehicle at the boundary of system operation
    - One platooning vehicle *swerving* within the travel lane

3. Conflict Driving outside Control Limits:
    - *Cut-in* by a non-platooning vehicle (DSRC-equipped or baseline vehicle)
    - *Hard braking* the lead vehicle outside the boundary of system operation
    - *Lane drop*/merging

4. Unsafe Control Actions and Failures:
    - Temporary *loss of information* exchange between vehicles
    - *Manual disabling* of CACC by one or more vehicles in the platoon
    - *Brake or acceleration control failures*

2.5.2 Independent Factors

The following is a list of independent factors that are typically considered for testing:

1. Speed and gap settings (Changing the gap setting in a steady-state driving)
2. Road Geometry:
    - Straight (Test track)
    - Curve (Test track and public roadway)
    - Up-grade (Public roadway)
    - Down-grade (Public roadway)
3. Road Surface:
    - Dry
    - Slippery
4. Weather:
    - Clear
    - Cloudy/rainy
5. Road Structure:
    - Under an overpass
    - Tunnel

The four sequential phases for testing the baseline car platooning concept are illustrated in Table 5

(Phase 1) and Table 6 (Phases 2 through 4). Each test phase consists of three parts that correspond to the test location and the traffic level-of-service state. Proceeding from the initial test phase to the next phase depends on the technical maturity of the car platooning system and the confidence in its stable and safe performance. The highlighted cells in Table 5 refer to the initial test plan of the baseline system that calls for professional drivers to perform the test modes of normal driving and conflict driving within control limits on the test track under clear weather on dry surface. After an acceptable system performance, the test plan can proceed into test phases 1b and 1c (normal driving and conflict driving within control limits) with professional drivers on public highways. For safety reasons, the car platooning system should incorporate additional fail-safe mechanisms and driver warning messages before proceeding with the test modes of driving conflicts outside the system control limits and unsafe automated vehicle control actions (1aii and 1aiv) on the test track. This is also true for all tests using regular drivers to monitor their interaction with the system and to survey their opinion about it.

Table 5. Test Phases of Baseline Car Platooning Concept: Phase 1

Concept Maturity/Confidence in Performance

Phase	Primary Objective	Location	Mode	Road Geometry	Weather/Surface	Driver
1a	Performance and Stability	Track	i – Normal Driving	Straight	Clear/Dry	Professional
1a	Performance and Stability	Track	i – Normal Driving	Tight curves (if available)	Clear/Dry	Professional
1a	Performance and Stability	Track	i – Normal Driving	Rolling hills (if available)	Clear/Dry	Professional
1a	Performance and Stability	Track	ii – Conflict Driving Within Control Limits (acceleration/deceleration $\leq$2.5 m/s^2)	Straight	Clear/Dry	Professional
1a	Performance and Stability	Track	ii – Conflict Driving Within Control Limits (acceleration/deceleration $\leq$2.5 m/s^2)	Tight curves (if available)	Clear/Dry	Professional
1a	Performance and Stability	Track	ii – Conflict Driving Within Control Limits (acceleration/deceleration $\leq$2.5 m/s^2)	Rolling hills (if available)	Clear/Dry	Professional
1a	Performance and Stability	Track	iii – Conflict Driving Outside Control Limits (acceleration/deceleration >2.5 m/s^2)	Straight	Clear/Dry	Professional
1a	Performance and Stability	Track	iii – Conflict Driving Outside Control Limits (acceleration/deceleration >2.5 m/s^2)	Tight curves (if available)	Clear/Dry	Professional
1a	Performance and Stability	Track	iii – Conflict Driving Outside Control Limits (acceleration/deceleration >2.5 m/s^2)	Rolling hills (if available)	Clear/Dry	Professional
1a	Performance and Stability	Track	iv – Unsafe Control Actions and Failures	Straight	Clear/Dry	Professional
1a	Performance and Stability	Track	iv – Unsafe Control Actions and Failures	Tight curves (if available)	Clear/Dry	Professional
1a	Performance and Stability	Track	iv – Unsafe Control Actions and Failures	Rolling hills (if available)	Clear/Dry	Professional
1b	Performance and Stability	Public Highway – no or limited traffic	i – Normal Driving	Straight	Clear/Dry	Professional
1b	Performance and Stability	Public Highway – no or limited traffic	i – Normal Driving	Tight curves (if available)	Clear/Dry	Professional
1b	Performance and Stability	Public Highway – no or limited traffic	i – Normal Driving	Rolling hills (if available)	Clear/Dry	Professional
1b	Performance and Stability	Public Highway – no or limited traffic	ii – Conflict Driving Within Control Limits	Straight	Clear/Dry	Professional

Concept Maturity/Confidence in Performance

Phase	Primary Objective	Location	Mode	Road Geometry	Weather/Surface	Driver
1b	Performance and Stability	Public Highway – no or limited traffic	ii – Conflict Driving Within Control Limits	Tight curves (if available)	Clear/Dry	Professional
1b	Performance and Stability	Public Highway – no or limited traffic	ii – Conflict Driving Within Control Limits	Rolling hills (if available)	Clear/Dry	Professional
1c	Performance and Stability	Public Highway – standard and heavy traffic	i – Normal Driving	Straight	Clear/Dry	Professional
1c	Performance and Stability	Public Highway – standard and heavy traffic	i – Normal Driving	Tight curves (if available)	Clear/Dry	Professional
1c	Performance and Stability	Public Highway – standard and heavy traffic	i – Normal Driving	Rolling hills (if available)	Clear/Dry	Professional
1c	Performance and Stability	Public Highway – standard and heavy traffic	ii – Conflict Driving Within Control Limits	Straight	Clear/Dry	Professional
1c	Performance and Stability	Public Highway – standard and heavy traffic	ii – Conflict Driving Within Control Limits	Tight curves (if available)	Clear/Dry	Professional
1c	Performance and Stability	Public Highway – standard and heavy traffic	ii – Conflict Driving Within Control Limits	Rolling hills (if available)	Clear/Dry	Professional

Table 6. Test Phases of Baseline Car Platooning Concept: Phases 2 through 4

Concept Maturity/ Confidence in Performance

Phase	Primary Objective	Location/Mode/Road Geometry	Weather/Surface	Driver
2 a-c	Driver Acceptance	Repeat 1ai, 1aii, 1b-c with regular drivers *Test modes iii and iv could be performed in a simulator for regular drivers*	Clear/Dry	Regular
3 a-c	Performance and Stability	Repeat 1 a-c with adverse conditions	Rain/Slippery	Professional
4 a-c	Driver Acceptance	Repeat 1ai, 1aii, 1b-c with regular drivers and adverse conditions. *Test modes iii and iv could be performed in a simulator for regular drivers*	Rain/Slippery	Regular

3. Development of Characterization Test Procedures

The process for developing the CACC-based platooning characterization test procedures is the same process the Volpe Center has used to develop procedures for advanced V2V research safety applications for NHTSA [15]. These procedures were developed this process in collaboration with NHTSA's Vehicle Research and Test Center, and with feedback from automotive original equipment manufacturers of the Crash Avoidance Metrics Partners and aftermarket safety device manufacturers who are responsible for the design and build of the safety applications. This section describes characterization test procedures for CACC-based vehicle platooning in the 'Normal Driving' mode, as explained in Table 5.

3.1 Process Elements and Test Development

The concept of operation, expected benefits, application performance measures, and safety mitigation plans are the cornerstones for developing characterization test procedures. Each is detailed and better understood as the development of the test procedures progresses through the following steps:

- *Initial Test Scenario Concepts* – Conceptualize and develop a set of test scenarios for each application under initial, dynamic, and final test conditions. This involves outlining the scenarios and their dynamics to be run on the test track, and conducting preliminary reviews by the stakeholders and the track "Safety Committee."
- *First-Pass Test-the-Test* – First test on the track to verify the DAS equipment installation and driver training including safety mitigation, application behavior, and performance measures.
- *Second-Pass Test-the-Test* – Revise and clarify the test procedures based on the results of the first-pass test-the-test, and conduct second reviews by the stakeholders and "Safety Committee." Then, perform the second test on the track to verify the DAS equipment installation, driver training including safety mitigation, application behavior, and performance measures.
- *Dry-Run Characterization Testing* – Update the application under test to the latest level. Revise and clarify the test procedures, conduct stakeholder and "Safety Committee" reviews if needed. Then, conduct on track testing based on the revised procedures.
- *Final Characterization Testing* – Typically run only if the application under test does not perform to design intent and the developer wants to revise the application and re-test.

3.2 Purpose of Characterization Testing

First-pass test-the-test procedures are developed and used for testing the CACC-based vehicle platooning proof-of-concept to help establish performance objectives for the next-level Phase 1 prototype system. The objectives are to be based on the performance of the Cadillac SRX production ACC system's automatic speed and gap maintenance capabilities while platooning. To collect the data needed to set target objectives for Phase 1 platooning prototype, single vehicle and four vehicles platooning with a lead vehicle were run under the following three modes:

- *Production ACC* – Only production steering wheel controls were manually used for automatic gap or speed maintenance control.
- *Hybrid* – Lead vehicle (LV) under CACC speed profile and following vehicles (FVs) under production ACC gap control.
- *Pure CACC* – LV under CACC speed profile and FVs under CACC-based platooning.

These test procedures are the first to be developed utilizing the test framework and are conducted under the following limitations:

- Speeds less than or equal to 96.6 kilometer/hour (km/h) (60 miles per hour (mph))[2]
- Target time gaps greater than or equal to 1.1 seconds (s)
- Closed track
- Professional drivers

The test procedures are preliminary, having only completed the First-Pass “Test-the-Test” development phase.

3.3 Test Approach

The Volpe Center, in collaboration with FHWA and ATC, conducted these test procedures with FHWA’s proof-of-concept platooning system implemented on the Connected Automated Research and Mobility Applications (CARMA) platform [8]. Several other FHWA I2V DSRC mobility applications utilize the CARMA platform. However, these applications are not presently allowed to run (initialized) at the same time as the CACC-based platooning application. For testing efficiency, the Volpe Center’s test design intent was to utilize the entire 7.2 km (4.5 miles) of track at ATC. Surface, grades, radius of curvature, lane width, and markings are similar to those seen on typical U.S. highways or highway-like roads. When in CACC mode, the LV has a prescribed speed profile application that uses geolocation information and Global Positioning System (GPS) positioning to automatically set its desired speed and other CACC parameters. The geolocations used to set or make changes are called ‘Waypoints.’ Thus, the LV was equipped with a custom speed controller to follow the tightly-controlled speed profile by using GPS to identify predefined waypoints that triggered the LV to change its speed to a predefined value. While the waypoints and speed changes were defined prior to a test run, they were easily configurable between runs. This provided both consistency and flexibility between runs, depending on the test objectives. Figure 3 shows a map of the 7.2-km test track and sample Waypoints.

ATC personnel provided and installed their DAS into each of the five Cadillac SRX vehicles. They also collected all data traffic from the four taps shown in Figure 4 at the end of each test day, and transferred them to an ATC database.

[2] Speeds are presented in this report using the Imperial System of Measurement for applicability to the speedometers in test vehicles. All other metrics are presented using the International System of Units (SI). It should be noted that 1 mph is roughly 1.6 km/h.

Figure 3. ATC Map with Waypoints[3]

[3] Map is from Google Images. Waypoints were added. Imagery: ©2017 DigitalGlobe, U.S. Geological Survey, USDA Farm Service Agency; Map data ©2017 Google

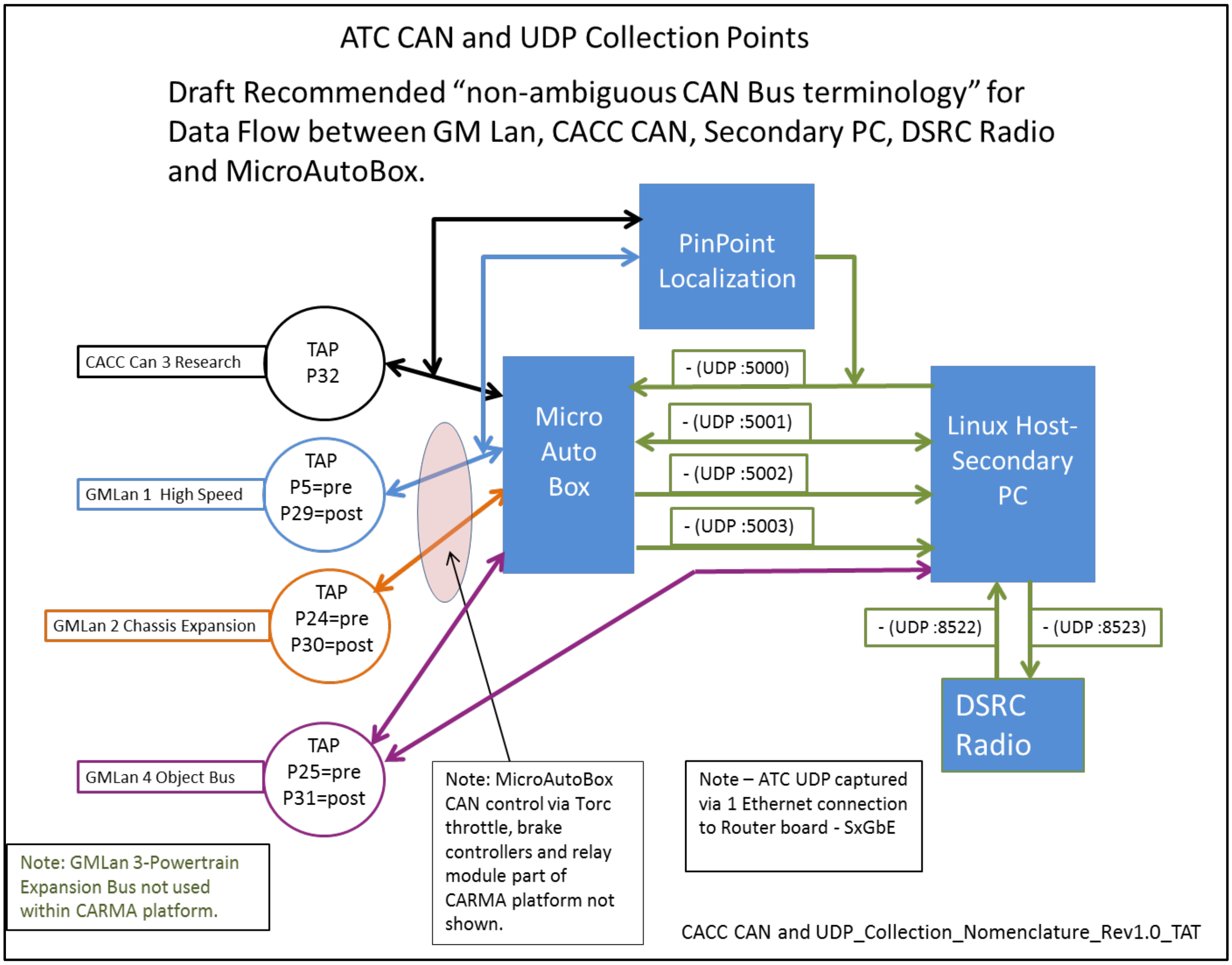


Figure 4. ATC Controller Area Network (CAN) and User Datagram Protocol Data TAPs

3.4 Daily Start-Up and Shut-Down Requirements

1. From the key off no-run position, assure that 120 VAC is being supplied to the inverter located behind the rear seat.
2. Power up the ATC DAS with 12 VDC battery.
3. CARMA platform:
   - Turn on using the switch located top rear seat back and wait 30 s for system to boot.
   - Start the engine and then remove 120 VAC power from the inverter.
4. CACC Start up: Appendix A provides a procedure for the CACC start-up in the LV and FVs.
5. Reverse the Start-Up order for Shut-Down.

3.5 Environmental, Ambient and Standard Test Conditions

The following requirements apply to all tests:

- Daytime illumination levels
- Atmospheric visibility of greater than 5,000 m
- Dry conditions (i.e., no precipitation, ice, snow or water on the track)
- Non-extreme temperatures at the track (between -7° C and 38° C)

3.6 Test Suspension and Resumption Criteria

During the present phase of system development, test suspension and resumption criteria are at the test team's (all driver's and support personnel's) discretion. In general, suspension and resumption criteria are developed in consideration of the "system under test" conforming to design intent, and the safety implications of a failure to meet design intent for any given scenario.

Typically, testing is suspended if the system under test fails to perform to design intent either in:

- Two consecutive valid runs
- Three valid runs in a group of ten runs

Testing continues to be suspended until an explanation for the error is provided and the issue is resolved.

3.7 Testing Safety

The CACC 'Normal Driving' characterization tests are designed to create conditions where the LV is under speed control mode and between one and four FVs are under gap control mode once a platoon is formed. Forming the platoon is done under manual control of the professional drivers. It is essential that professional drivers are alert in the test vehicles at all times so that they may conduct avoidance maneuvers and abort ('bailing') from the test run if necessary. 'Bailing' maneuvers are defined in the driver instructions of each procedure/scenario. The test vehicles do not require the driver to perform any manual action to take control of the vehicle (in addition to using normal driving) to avoid a real or perceived imminent collision. That is, the test driver is able to brake/steer/accelerate manually in a naturalistic manner without any need of pressing switches, buttons, etc., before taking control of the vehicle.

1. All testing is conducted at ATC in Aberdeen, Maryland, in compliance with ATC's Standard Operating Procedures that govern the safety protocols for all testing conducted there.
2. All new test procedures require review and approval by the ATC Hazard Analysis Working Group (Safety Committee). The Safety Committee reviews the procedures and assesses the ability of the test drivers to safely conduct the procedures, including alternatives identified for conflict resolution. An outline of the test procedures based on the application concept of operation are provided to the Safety Committee two to three months before any testing on the track. A safety mitigation plan and safety limits for procedures are developed. Requested changes to test limits or substantive changes to procedures are provided and reviewed by the Safety Committee approximately two weeks prior to track testing.

3. The Safety Committee specifies the level of driver rating required for each driver used in each procedure. More complex or time-critical maneuvers may require a Performance Driver rating—a higher classification than a Reliability Driver.
4. All drivers are briefed by the Volpe Center and ATC personnel on the procedures and allowed to practice the maneuvers prior to the start of testing. Each test procedure requires two people in the LV; the LV Driver and the Test Conductor who is knowledgeable of the test procedures and the application design intent capabilities.

3.8 Speed Profile Examples

Speed profiles set test conditions and scenario dynamics used for platooning. GPS position information collected along the centerline of the track is used to identify Waypoints. Waypoints are specific GPS positions used to initialize and change the LV robotic control system as the LV moves around the track. Figure 3 overlays seven Waypoints onto a map of the ATC track. Each Waypoint has associated data elements that are used in LV and FV CACC control. Data element descriptions, units, and ranges are shown in Table 7. Cones placed by the side of the track at each Waypoint are used as a visual aid to the test conductor and drivers. A series of Waypoints are used to make a Speed Profile.

Table 7. Waypoint Data Elements

Data Elements	Description	Unit	Range
Waypoint Label	Identifies a specific latitude and longitude on the track	integer	1 - 278
Waypoint Radius	Maximum distance around the Waypoint for it to be used	m	not defined
Desired Speed	Lead Vehicle target speed	mph	0 - 70
Target Acceleration	Lead Vehicle acceleration or deceleration limit (absolute value)	m/s^2	0.1 - 2.5
Desired Gap	Follow Vehicle target gap (65,000 use ACC gap)	ms	500 - 64999
Single or Multiple Use	Single use: ignores Waypoint once it is used	M=Multiple S=Single	M or S

Two examples of the LV speed profile are provided to illustrate how Waypoint data elements are used to control the Platoon behavior during test procedures:

1. Constant Speed, varying gap, single-use Speed Profile
2. Constant Gap, varying speed, multiple-use Speed Profile

3.8.1 Single-Lap, Constant Speed with Varying Gap Profile

Table 8 shows the data elements used to create the Single Lap, Constant Speed with Varying Gap speed profile, using the seven Waypoints shown previously to create an LV constant speed around the track.

Table 8. Single-Lap Constant Speed with Varying Gaps Using Seven Waypoints

Waypoint Label	Speed	Accel	Radius	Gap	Single
Point 1 - 150	60	1	6	2000	S
Point 2 - 720	60	1	6	1600	S
Point 3 - 620	60	1	6	1200	S
Point 4 - 520	60	1	6	1600	S
Point 5 - 450	60	1	6	1200	S
Point 6 - 345	60	1	6	1600	S
Point 7 - 239	60	1	6	2000	S

The entrance to the track is between Waypoints 1 and 7. By design, the speed profile is the same for moving clockwise (CW) or counter-clockwise (CCW) around the track. (For simplicity, the CW direction is used in these two examples.) Just past Waypoint 1, the first Waypoint moving in the CW direction, the LV driver, engages CACC after accelerating manually to ± 5 mph of Waypoint 1 targeted speed of 60 mph. The LV will accelerate or decelerate to the Waypoint 1 targeted speed shown in the **Speed** column (60 mph) at a rate limit shown in the **Accel** column (1 m/s^2), begin to broadcast DSRC FV desired gap message shown in the **Gap** column (2000 ms) as long as the LV has passed within the distance shown **Radius** column (6 m) of the Waypoint. Waypoint 1, **Single Use** column is S, meaning this will eliminate its use in future passes. (Until profile re-initialization.) Waypoint 1 data elements are used until the LV recognizes Waypoint 2. Waypoint 2 will be used until another Waypoint is recognized. The only data element that changes for Waypoints 1-7 is the gap resulting in a constant speed varying gap scenario. Time Gaps vary from 2000 to 1200 ms with a 400 ms change at each Waypoint. If the LV makes more than one lap, the data elements from Waypoint 7 will continue to be used.

3.8.2 Multiple-Lap, Constant Gap with Varying Speed Profile

Table 9 shows the data elements used to create a multiple-lap, constant gap with varying speed profile. Waypoints, track entrance, design for both CW and CCW rotations are the same as the previous example. The LV driver accelerates manually to ±5 mph of the Waypoint 1 targeted speed of 60 mph and engages CACC mode just past Waypoint 1. The LV will accelerate or decelerate to the Waypoint 1 targeted speed shown in the **Speed** column (60 mph) at a rate limit shown in the **Accel** column (0.5 m/s^2) and begin to broadcast DSRC FV desired gap message shown in the **Gap** column (1200 ms) as long as the LV has passed within the distance shown **Radius** column (6 m). Waypoint 1 **Single Use** column is M for multiple use and will continue to be used in future passes. Waypoint 1 data elements are used until the FV recognizes Waypoint 2. Waypoint 2 initiates a deceleration to 45 mph at a rate limit of 1 m/s^2. Waypoint 3 initiates an acceleration back to 60 mph at a rate limit of 0.5 m/s^2. The cycle continues for Waypoints 4-7, decelerating to 45 mph and accelerating to 60 mph at alternating Waypoints. As the LV moves from Waypoint 7 to Waypoint 1, the speed is not changed and will continue at 60 mph, thereby repeating the scenario of the previous lap.

Table 9. Multiple Lap Constant Gap at Varying Speed using Seven Waypoints

Waypoint Label	Speed (mph)	Accel (m/s^2)	Radius (m)	Gap (ms)	Single Use
Point 1 – 150	60	0.5	6	1200	M
Point 2 – 720	45	1	6	1200	M
Point 3 – 620	60	0.5	6	1200	M
Point 4 – 520	45	1	6	1200	M
Point 5 – 450	60	0.5	6	1200	M
Point 6 – 345	45	1	6	1200	M
Point 7 - 239	60	0.5	6	1200	M

3.9 Test Procedures for Performance Characterization of Platooning in Normal Driving

Characterization testing is intended to provide quantitative measures of how well the CACC-based platooning application under test meets its goals or design intent. Platooning under normal driving conditions is expected to be able to form, maintain, and dissolve in the absence of any driving conflict scenarios. The platoon under test is made up of one LV and from one to four FVs. The stability and consistent performance of the platoon should always be maintained to help realize driver acceptance and anticipated benefits. It is envisioned that the entire 7.2 km of test track be utilized in both the CW and CCW directions. When in CACC mode, the LV is under limited automatic speed control (i.e., throttle and braking only) and each of the FVs is under limited automatic gap (longitudinal) control. Test procedures are divided into two groups based on the maturity and amount of testing experience using them:

1. *Concept Phase* – Procedures are captured in outline/summary form, to be used for:
   - Illustration of the test framework hierarchy
   - Safety Committee review and initial evaluation of the CACC-based platooning application
   - Mini-Design Verification of application update/revisions installed on April 19, 2016, creating the proof-of-concept prototype
2. *First-Pass Test-the-Test Phase* – Detailed procedures are developed to set performance objectives of the next CACC-based platooning design iteration, Phase 1 prototype. Four procedures are considered:

- Platoon forming
- Constant time-gap with varying LV speeds
- Constant LV speed with varying time-gaps
- Platoon dissolving

3.9.1 Concept-Phase Procedures

Concept-phase procedures are used to describe the concept of operation of envisioned test procedures with project participants for use in test planning, performance measures, and development of safety mitigation plans. These procedures are captured at a higher level than the formal test procedures in an outline format (e.g., a series of Excel spreadsheets). There are three sets of procedures:

1. *Concept-Phase Test Framework* – The first envisioned procedures are developed to illustrate how the test procedures would evolve, build confidence, and increase complexity using the hierarchical phases described in the test framework shown in Table 5 and Table 6. Table 24 in Appendix B illustrates how the concept-phase procedures will be organized within the test framework. The procedures advance from 'Normal' to 'Conflict' Driving Modes for a baseline, Step 1a CACC-based platooning system.
2. *Concept-Phase Safety Mitigation* – Table 25 in Appendix B provides the envisioned procedures that are developed to support the approval of a comprehensive test safety mitigation plan by the ATC Hazard Analysis Working Group (i.e., Safety Committee) prior to testing.
3. *Concept-Phase Mini-Design Verification* – Table 26 in Appendix B shows the procedures for a simple functional verification that the software updates installed on April 19, 2016, into the LV and four FVs were installed correctly and provide the new features per design intent. A full verification was not practical at the time primarily due to test safety and time considerations. Only the Mini CACC Design Verification concept-phase procedures were run.

3.9.2 First-Pass Test-the-Test Phase Procedures

These procedures cover four fundamental platooning functions at their simplest level and have been used to capture performance data to aid in setting future performance objectives of the next CACC-based platooning design iteration (i.e., Phase 1 Prototype). To allow more time to reach stability, the number of Waypoints was reduced from seven to four. In addition, the direction of travel was specified as CCW. Figure 5 shows the four waypoints overlaid on the ATC map. The four procedures developed are:

- Platoon formation
- Constant time gap with varying speeds
- Constant speed with varying time gaps
- Platoon dissolution

Figure 5. ATC Map with Four Waypoints (CCW Direction)[4]

3.9.3 Platoon Formation

This procedure is used for forming the platoon with the LV and from one to four FVs for all normal driving test procedures. Three types of platoons are formed by combining ACC and CACC modes of the LV and FV:

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[4] Map is from Google Images. Waypoints were added. Imagery: ©2017 DigitalGlobe, U.S. Geological Survey, USDA Farm Service Agency; Map data ©2017 Google

1. *ACC-only in LV and FVs* – The FV speed is set above the LV set speed. As they encounter the slower-moving LV ahead, the FVs automatically change to the time gap mode when joining the platoon.
2. *Hybrid CACC in LV and ACC in FVs* – The LV speed is automatically controlled by the speed profile and the FVs are in ACC with a set speed above the LV profile-controlled speeds. As they encounter the slower-moving LV ahead, the FVs automatically change to the time gap mode when joining the platoon.
3. *CACC-only in LV and FVs* – The LV speed is automatically controlled by the speed profile and the FVs are automatically put into time gap mode simultaneously via DSRC command from the LV.

3.9.3.1 Test Setup and Driving Instructions

Initial conditions of all vehicles:

1. Test Conductor initializes the LV speed profile as required for the planned test scenario. who is
2. LV Driver positions the LV between Waypoints heading in the desired CCW direction of travel, centered in the outside lane at a minimum of 300 m before a Waypoint, as illustrated in Figure 6.
3. FV Driver(s) line up behind the LV with a distance of between 2-3 meters (m) to the preceding vehicle, centered in the outside lane, as illustrated in Figure 6.
4. Test Conductor, seated in the back seat of the LV, informs all drivers via hand-held radio of the targeted speed for the Waypoint ahead.

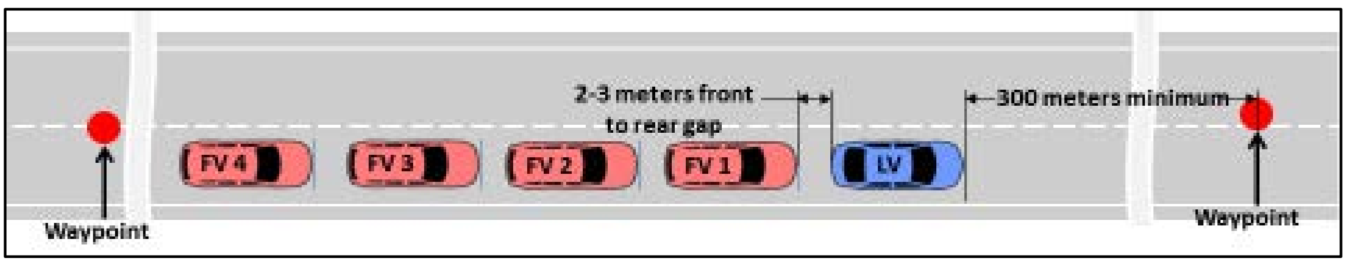

Figure 6. Initial Conditions of LV and 1-4 FVs when Forming the Platoon

LV driving instructions for intermediate and final conditions:

1. On Test Conductor's cue, accelerate at a rate between 2.5-3.5 m/s^2 to ± 6 mph of the targeted speed and turn on the ACC system before reaching the Waypoint, and remain centered in the outside lane.
2. After passing the Waypoint, centered in the outside lane, perform the applicable action, below. (Intermediate conditions are illustrated in Figure 7):
   - In ACC-only type testing, manually set the ACC speed to the target speed.
   - In hybrid or CACC-only type testing, engage CACC.
3. Continue centered in the outside lane under brake and throttle controls as the speed stabilizes and you approach the next Waypoint. (Final conditions are illustrated in Figure 8)

The LV driver shall manually take an evasive action (brake, steer or accelerate) to avoid a potential collision at any time during the test if the driver determines that the test conditions are unsafe. Pressing the brake disengages ACC or CACC, brake or throttle activation overrides any automatic controls, and steering is not automatically controlled at any time.

<u>FV driving instructions for intermediate and final conditions</u>:

1. As the vehicle ahead begins to accelerate, accelerate at a rate to maintain a gap between 20-30 m. After reaching 25 mph, turn on the ACC system.
2. One to three seconds after the LV passes the Waypoint, perform the applicable action below. (Intermediate conditions are illustrated in Figure 7):
    - ACC-only or hybrid, set ACC set speed to 65 mph. Set gap to minimum time-gap setting.
    - CACC-only type testing, engage CACC.
3. Continue centered in the outside lane under brake and throttle controls as the speed stabilizes and you approach the next Waypoint. At this stage, the FVs are in an automatic time-gap control mode as each vehicle follows the preceding vehicle. (Final conditions are illustrated in Figure 8).

The FV drivers shall manually take an evasive action (brake, steer or accelerate) to avoid a potential collision at any time during the test if the driver determines that the test conditions are unsafe. Pressing the brake disengages ACC or CACC, brake or throttle activation overrides any automatic control, and steering is not automatically controlled at any time. The primary evasive maneuver is to swerve to the inside lane and disengage any automatic brake or throttle control by tapping the brake. If more than one FV is simultaneously performing an evasive maneuver, drivers are recommended to swerve alternating to the inside or outside lane in the order of the drivers' position in the platoon.

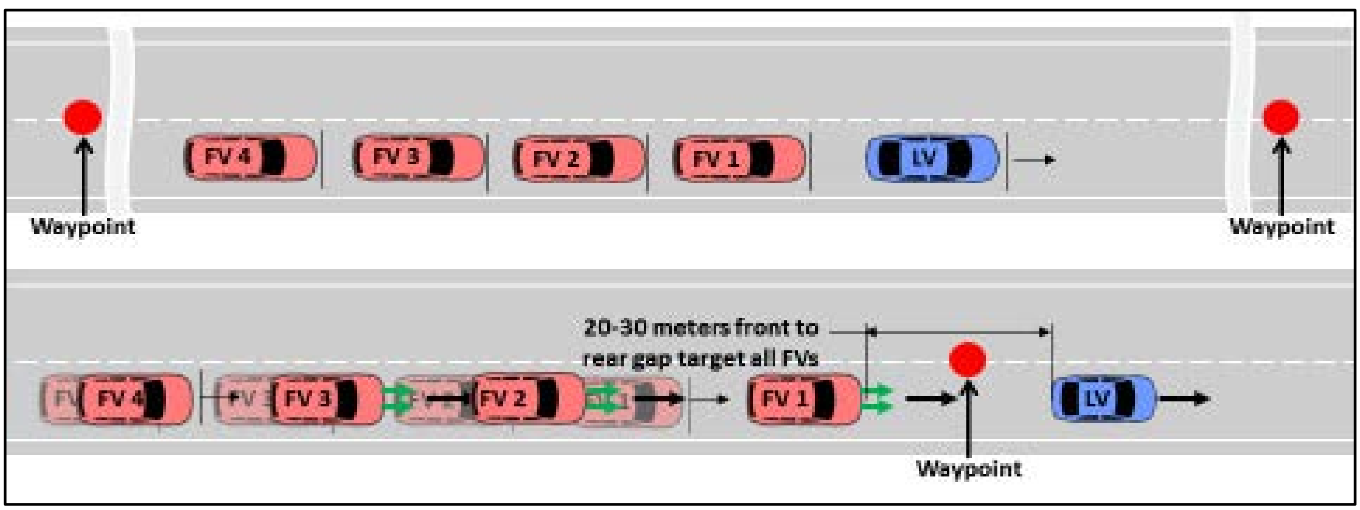

Figure 7. Intermediate Conditions of LV and 1-4 FVs when Forming the Platoon

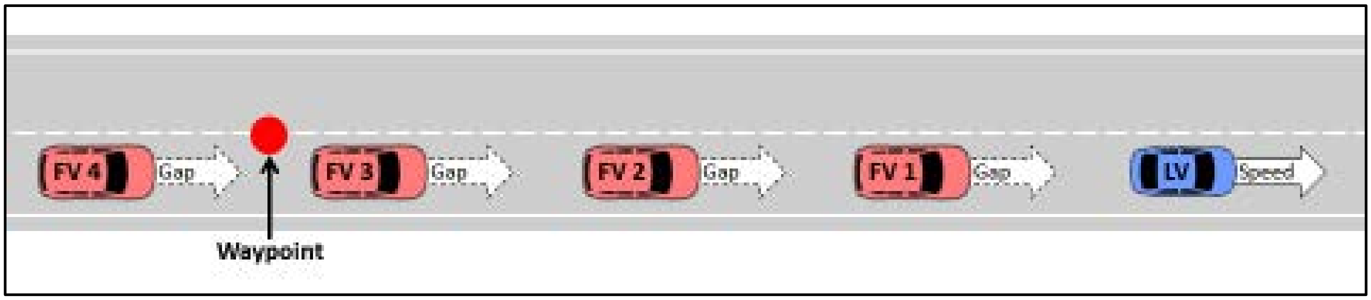

Figure 8. Final Conditions of LV and 1-4 FVs when Forming the Platoon

3.9.4 Constant Time Gap with Varying Speed Procedure

This procedure begins after forming the platoon, using the multiple-use speed profile shown in Table 10.

Table 10. Speed Profile – CCW, Four-Waypoint, Constant Time Gap, and Varying Speed

# Waypoint Label	Speed (mph)	Accel (m/s^2)	Radius (m)	Gap (ms)	Single Use
Point 4 – 230	60	1	6	1200	M
Point 3 – 450	45	0.3	6	1200	M
Point 2 – 620	60	1	6	1200	M
Point 1 – 150	45	0.3	6	1200	M

3.9.4.1 Test Set-up and Driving Instructions

Initial conditions – LV under speed control and 1-4 FVs under time gap control: (As illustrated in Figure 9).

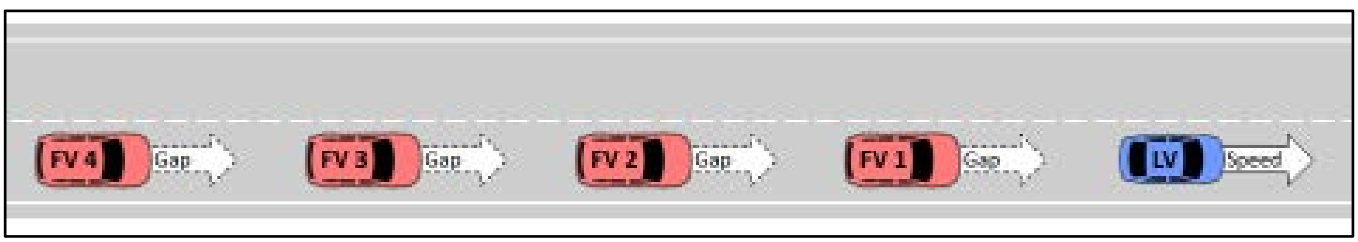

Figure 9. Initial Conditions of LV and 1-4 FVs in "Constant Time Gap with Varying Speed" Procedure

LV Driving Instructions:

1. As you approach the next Waypoint, continue centered in the outside lane under brake and throttle controls.
2. After passing the Waypoint, centered in the outside lane, perform the applicable action, below. (Intermediate conditions are illustrated in Figure 10):
   - ACC-only type testing, manually set the ACC speed to the target speed as advised by the Test Conductor.
   - Hybrid or CACC-only type testing, prepare for a deceleration or acceleration as advised by the Test Conductor.

3. Continue centered in the outside lane under brake and throttle controls as the speed stabilizes and you approach the next Waypoint. (Final conditions are illustrated in Figure 11)
4. Via hand-held radio on the Test Conductor's cue, notify the FV drivers that you are dissolving the platoon.

<u>FV Driving Instructions:</u>

1. As you approach the next Waypoint, continue centered in the outside lane under brake and throttle controls.
2. After the LV passes the Waypoint, prepare for an automatic deceleration or acceleration of your vehicle as advised by the Test Conductor. Continue centered in the outside lane. (Intermediate conditions are illustrated in Figure 10).
3. Continue centered in the outside lane under brake and throttle controls as the speed stabilizes and you approach the next Waypoint. (Final conditions are illustrated in Figure 11).

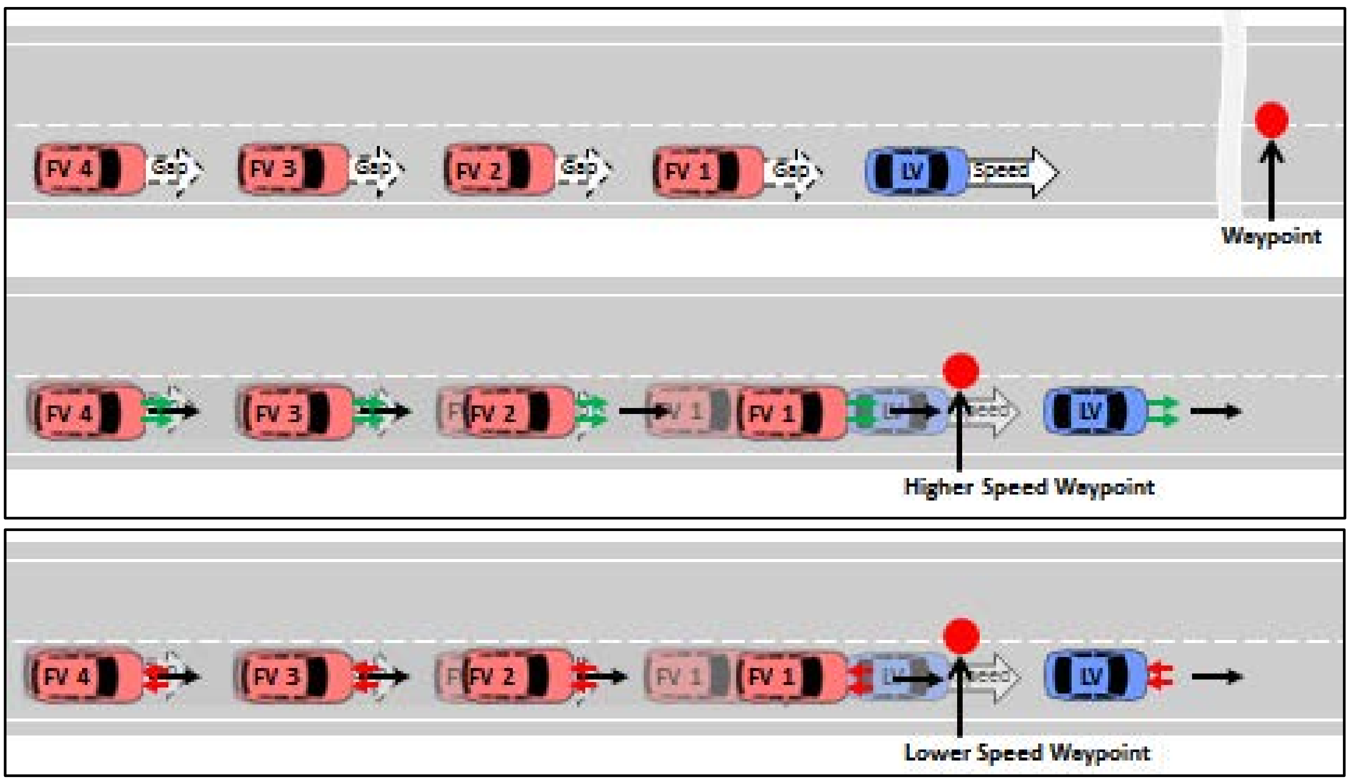

Figure 10. Intermediate Conditions of LV and 1-4 FVs in "Constant Time Gap with Varying Speed" Procedure

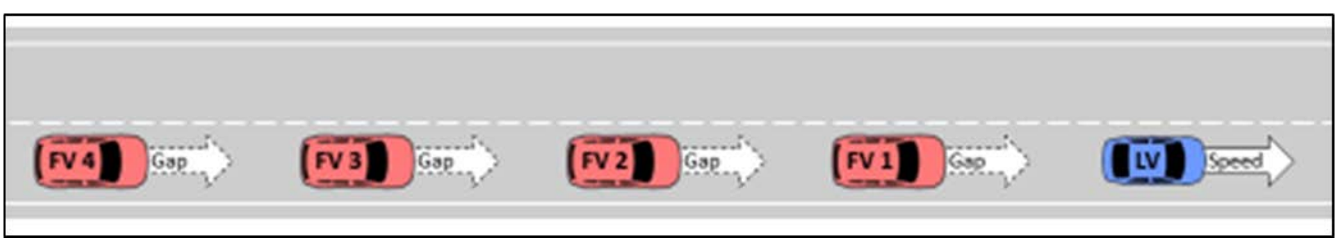

Figure 11. Final Conditions of LV and 1-4 FVs in "Constant Time Gap with Varying Speed" Procedure

Evasive Maneuver Instructions:

All drivers shall manually take an evasive action (brake, steer or accelerate) to avoid a potential collision at any time during the test if the driver determines that the test conditions are unsafe. Pressing the brake disengages ACC or CACC, brake or throttle activation overrides any automatic controls, and steering is not automatically controlled at any time. The primary evasive maneuver is to swerve to the inside lane and disengage any automatic brake or throttle control by tapping the brake. If more than one vehicle is simultaneously performing an evasive maneuver, drivers are recommended to swerve alternating to the inside or outside lane in the order of the drivers' position.

3.9.5 Constant Speed with Varying Time Gap Procedure

This procedure begins after forming the platoon**,** using the multiple-use speed profile shown in Table 11.

Table 11. Speed Profile – CCW, Four-Waypoint, Constant Speed, and Varying Time Gap

# Waypoint Label	Speed (mph)	Accel (m/s^2)	Radius (m)	Gap (ms)	Single Use
Point 4 - 230	55	0.3	6	2000	M
Point 3 - 450	55	0.3	6	1600	M
Point 2 - 620	55	0.3	6	1200	M
Point 1 - 150	55	0.3	6	1000	M

3.9.5.1 Test Set-up and Driving Instructions

Initial conditions – LV under speed control and 1-4 FVs under time gap control: (As illustrated in Figure 12**)**

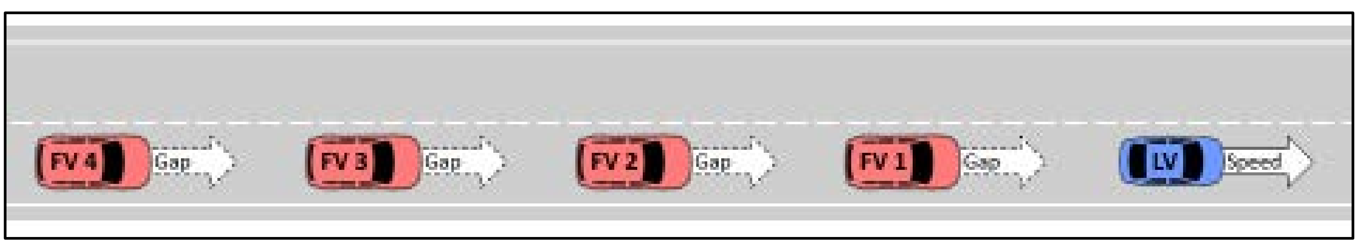

Figure 12. Initial Conditions of LV and 1-4 FVs in "Constant Speed with Varying Time Gap" Procedure

LV Driving Instructions:

1. As you approach the next Waypoint, continue centered in the outside lane under brake and throttle controls.
2. After passing the Waypoint, continue centered in the outside lane. (Intermediate conditions are illustrated in Figure 13).
3. Continue centered in the outside lane under brake and throttle controls as the new platoon gap stabilizes and you approach the next Waypoint. (Final conditions are illustrated in Figure 14).

4. Via hand-held radio on the Test Conductor's cue, notify the FV drivers that you are dissolving the platoon.

<u>FV Driving Instructions:</u>

1. As you approach the next Waypoint, continue centered in the outside lane under brake and throttle controls.
2. After the LV passes the Waypoint lane, perform the applicable action, below. (Intermediate Conditions are illustrated in Figure 13):
   - o Pure ACC or Hybrid type testing set the ACC gap to the "Far," "Medium" or "Near" setting as advised by the Test Conductor.
   - o Hybrid or Pure CACC type prepare for a smaller gap (acceleration) or larger gap (deceleration) as advised by the Test Conductor.

3. Pure CACC type prepare for a smaller gap (acceleration) or larger gap (deceleration) as advised by the Test Conductor.
4. Continue centered in the outside lane under brake and throttle control as the gap stabilizes and you approach the next Waypoint. (Final Conditions are illustrated in Figure 14).

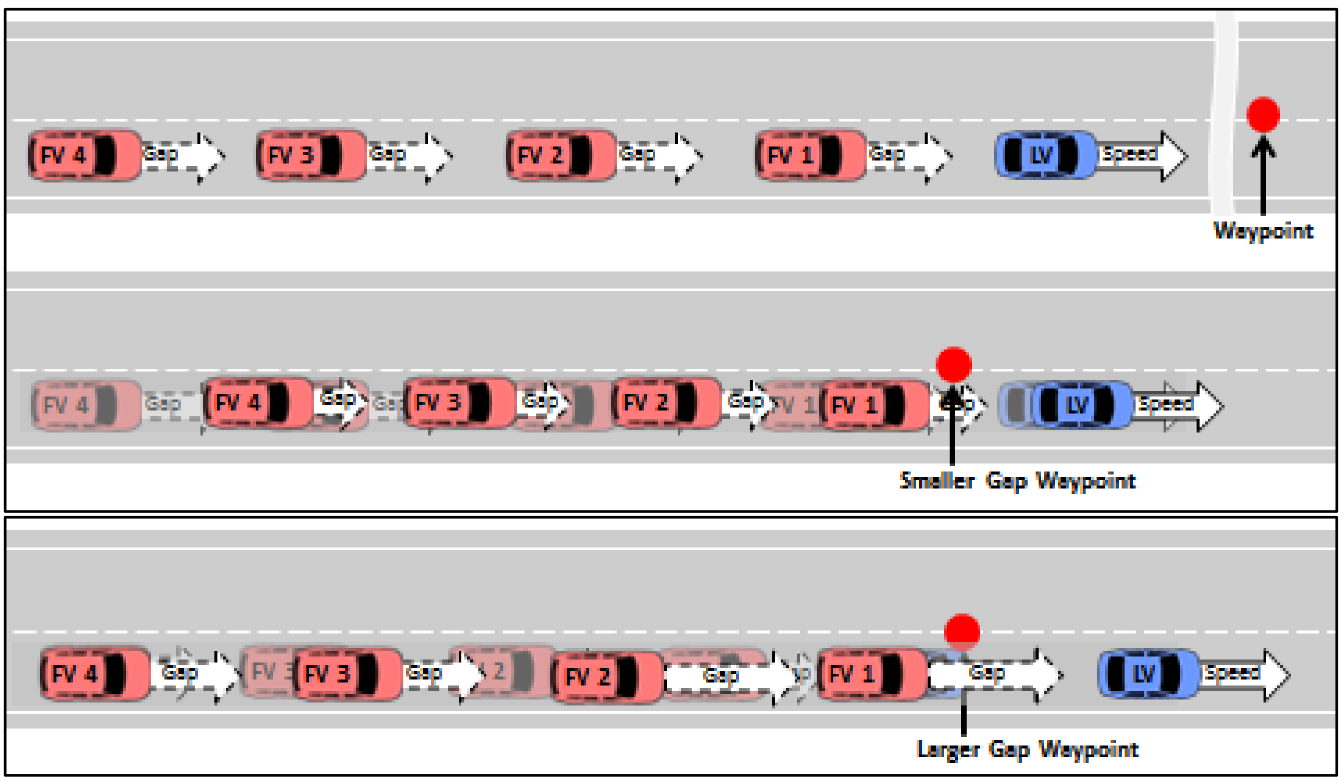

Figure 13. Intermediate Conditions of LV and 1-4 FVs in "Constant Speed with Varying Time Gap" Procedure

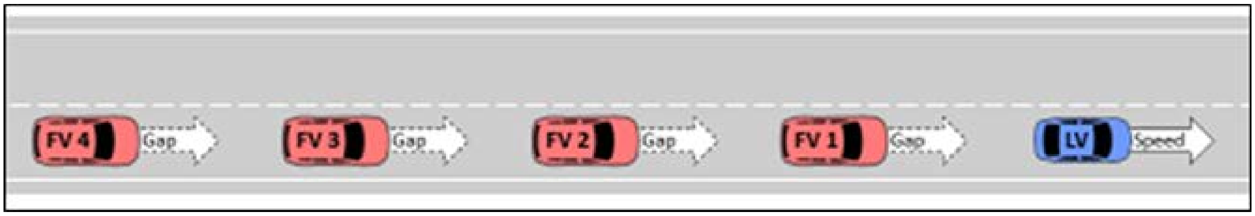

Figure 14. Final Conditions of LV and 1-4 FVs in “Constant Speed with Varying Time Gap” Procedure

Evasive Maneuver Instructions:

See section 3.9.4.1.

3.9.6 Platoon Dissolution

This procedure is used for dissolving the platoon with the LV and one to four FVs for all “normal driving” test procedures. As indicated in the “Platoon Formation” section, three types of platoons are formed: ACC-only in LV and FVs, Hybrid CACC in LV and ACC in FVs, and CACC-only in LV and FVs. A common procedure is used for dissolving the platoon for all three types since tapping the brake disables both ACC and CACC.

3.9.6.1 Test Setup and Driving Instructions

Initial conditions of all vehicles – LV and 1-4 FVs platooning centered in the outside lane: (As illustrated in Figure 15).

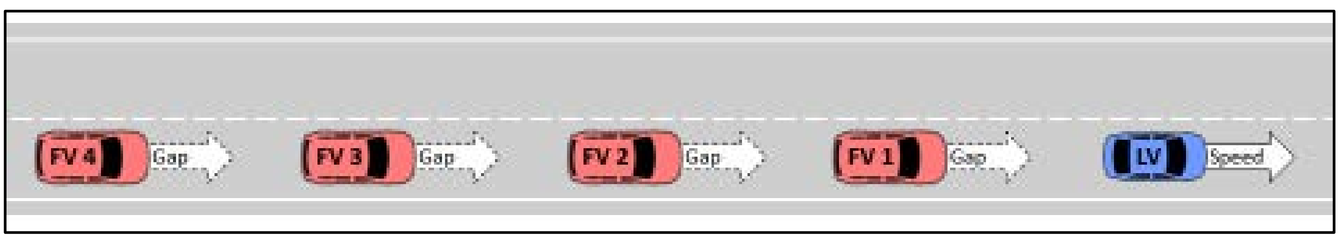

Figure 15. Initial Conditions of LV and 1-4 FVs when Dissolving the Platoon

LV Driving Instructions:

1. Continue driving centered in the outside lane.
2. Via hand-held radio on the Test Conductor’s cue, notify the FV drivers that you are dissolving the platoon.
3. Tap the brake pedal taking manual control of the brake and throttle, continue driving in the center of the outside lane at a light to moderate deceleration. (Intermediate Condition are illustrated in Figure 16).
4. After all FVs in the platoon have taken manual control or at the Test Conductor’s cue, slow to a stop one lane to the outside onto the shoulder of the track-paved surface, and leave the engine

running with the transmission in Park. (Final Conditions are illustrated in Figure 17).

<u>FV Driving Instructions:</u>

1. Continue driving centered in the outside lane.
2. After radio notification and observing brake light activation of the vehicle immediately ahead, tap the brake pedal taking manual control of the brake and throttle, continue driving in the center of the outside lane at a light to moderate deceleration. (Intermediate Condition are illustrated in Figure 16).
3. Following the vehicle immediately ahead, slow to a stop one lane to the outside onto the shoulder of the track-paved surface, and leave the engine running with the transmission in Park. (Final Conditions are illustrated in Figure 17).

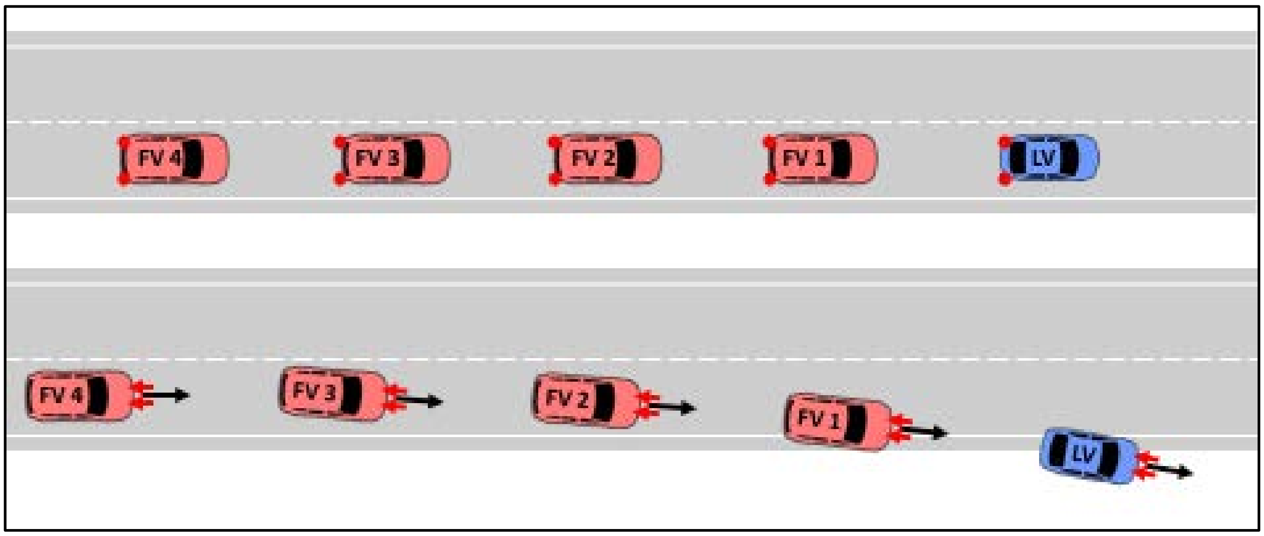

Figure 16. Intermediate Conditions of LV and 1-4 FVs when Dissolving the Platoon

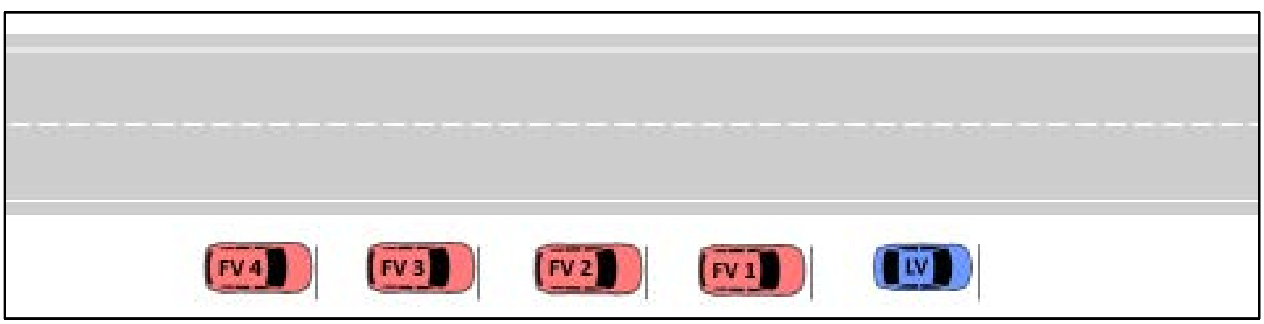

Figure 17. Final Conditions of LV and 1-4 FVs when Dissolving the Platoon

<u>Evasive Maneuver Instructions</u>:

See Section 3.9.4.1.

4. Proof-of-Concept Test Scenarios

The Volpe Center evaluated a proof-of-concept, CACC-based, vehicle platooning system based on data collected from objective engineering tests performed between July 25 -28, 2016 on a test track at the ATC. The tests involved five passenger vehicles (2013 Cadillac SRX) that were equipped with CACC and supplied by TFHRC. The TFHRC's Saxton Transportation Operations Laboratory developed and built the CACC system and the CACC-based vehicle platooning proof-of-concept. Under an agreement with TFHRC, the U.S. Army provided the test track, acquired and installed the DAS, executed the test procedures with professional drivers, and collected and transferred the data to the Volpe Center for analysis. Appendix C provides a detailed description and discussion of the DAS data elements.

The vehicle platooning proof-of-concept utilizes a constant time gap car-following approach, which results in the distance between an FV and the preceding vehicle (PV) being directly proportional to the speed of the FV. Moreover, this proof-of-concept:

- Controls the longitudinal motion of the vehicles (acceleration and braking commands), with professional drivers responsible for lane maintenance and evasive maneuvers, if needed.
- Uses DSRC to broadcast the current speed and other information from the LV to every FV within the DSRC range. As a result, every FV within range receives information about the LV's current state and intent at about the same time.

4.1 Proof-of-Concept Test Objectives

The July 2016 test scenarios were designed with the following three objectives:

1. Assess the performance of the custom LV speed controller and compare it to the production ACC at constant set speed performance.
2. Assess the performance of the CACC onboard the FVs and compare them to the production ACC performance.
3. Assess the performance of car platooning by gradually increasing the length of the platoon (i.e., begin with a single FV and add other FVs as soon as the test team was confident they could be safely added.)

To meet the above objectives, the Volpe Center evaluated different test configurations of the LV and FVs:

1. *ACC* – Production controllers for LV and FVs: Collect basic performance data for the LV being controlled by the production ACC, and for the FVs being controlled by the production ACC.
2. *Hybrid* – Production controllers for FVs and custom speed controller for the LV: The benefit of using the custom speed controller for the LV is that it resulted in ACC FVs that could be directly compared to CACC FVs, as the timing and characteristics of the LV speed changes were similar.

3. *CACC* – Custom controllers for LV and FVs: Collect performance data on the proof-of-concept system in all FVs.

In addition to the three objectives above, the Volpe Center also observed the undisturbed performance of the production and CACC-specific sensor suites in the vehicles while at rest by collecting basic navigation sensor data. While it can be performed at any time, this step was the first to be conducted in the assessment.

4.2 Test Scenario Summary

The as-designed test procedures are outlined below. Any deviations from the procedures that occurred during the July 2016 runs are identified in *italics*.

4.2.1 Scenario 0.0: Sensor-at-Rest

The objective of this test is to characterize the performance of the production CACC-specific sensor suites while the vehicles are at rest. For future tests, it is recommended that the data be collected for an extended period of time (hours to days) to gain a statistically-significant sample and to see representative variations in GPS performance due to the ever-changing constellation geometry. It is also recommended that there are no disturbing events during the data collection period (i.e., opening/ closing doors, gear selection, steering, etc.) The results are used to understand sensor noise and bias.

4.2.2 Scenarios 1.0: Production CC and ACC Performance

Initially, this set consisted of four different scenarios (i.e., Scenarios 1.1-1.4.) However, only Scenarios 1.1 and 1.4 were conducted during the July 2016 tests:

- **Scenario 1.1**: <u>Speed Control – LV only set to varying speeds</u>: The objective of this test is to characterize the performance of the production ACC speed controller by manually commanding acceleration and deceleration between 45 and 60 mph. This will be used as a baseline for the CACC speed controller and will also provide insight into vehicle-vehicle performance variations in ACC mode.
- **Scenario 1.2**: <u>Gap Control – LV CC set to 55 mph and single FV with minimum time gap (1.1 s)</u>: The objective of this test is to characterize the performance of the production ACC controller in each FV while following the LV which is moving at a constant speed and is using the production ACC speed controller. There is only one FV at a time, and it is rotated out to provide insight into vehicle-vehicle performance variations. The FV's ACC performance behind a production ACC speed controller will be compared to Scenario 2.2 to determine the impact of the CACC LV performance on FV performance. *This scenario was not executed during the July 2016 tests because it was determined that the CACC performance was adequate to proceed directly to Scenario 1.4*.

- **Scenario 1.3**: Gap Control – LV CC set to varying speeds and single FV with minimum time gap (1.1 s): This is similar to Scenario 1.2, but speed variations are introduced where the LV moves at a defined speed profile that accelerates and decelerates between 45 and 60 mph using the production CC speed controller. Each FV's ACC performance in this scenario will be compared to its performance in Scenario 2.3 to determine the impact the FV of the LV using CC or CACC. The FVs are rotated out to provide insight into vehicle-vehicle performance variations. *This scenario was not executed during the July 2016 tests because it was determined that the ACC performance was adequate to proceed directly to Scenario 1.4*.
- **Scenario 1.4**: Gap Control – LV CC set to 55 mph and 4 FVs with minimum time gap (1.1 s): This is similar to Scenario 1.2, but there is a string of four FVs at a time and two sequences are tested to provide limited insight into vehicle-vehicle performance variations. The results will be indirectly compared to Scenario 2.4 to determine the impact of the LV's CC versus CACC performance on FV performance.[5]

4.2.3 Scenarios 2.0: Hybrid – LV CACC Speed Profile and FV ACC Performance

Initially, this set consisted of four different scenarios (i.e., Scenarios 2.1-2.4.) However, only Scenarios 2.3 and 2.4 were conducted during the July 2016 tests:

- **Scenario 2.1**: Not Applicable.
- **Scenario 2.2**: Gap Control – LV CACC speed profile set to 55 mph and single FV with minimum time gap (1.1 s): The objective of this test is to characterize the performance of the production ACC controller while following the LV, which is using the CACC LV speed controller to move at a constant speed. There is only one FV at a time, and it is rotated out to provide insight into vehicle-vehicle performance variations. The results of this scenario will be compared to Scenario 1.2. The results of this scenario will also be compared to the results of Scenario 3.2 to assess the improvements in FV stability when in CACC vs ACC. *This scenario was not run during the July 2016 tests*.
- **Scenario 2.3**: Gap Control – LV CACC speed profile with 3 speed changes and single FV with minimum time gap (1.1 s): This is similar to Scenario 2.2, but speed variations are introduced. The results of this scenario will be compared to Scenario 1.3. The results will also be used as a baseline for assessing the improvements in the FV stability when in CACC versus ACC by comparing the results of this scenario to Scenario 3.3.
- **Scenario 2.4**: Gap Control – LV CACC with 2 speed changes and 4 FVs with minimum time gap (1.1 s): This is similar to Scenario 2.3, but there is a string of four FVs at a time and two sequences are tested to provide limited insight into vehicle-vehicle performance variations. The results will be compared to the results of Scenario 3.4 and used as a baseline for assessing the improvements in the FV stability when in CACC versus ACC.

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[5] A direct comparison to Scenario 2.4 is not possible because Scenario 1.4 uses a constant speed of 55 mph and Scenario 2.4 uses varying speeds of 60-45-60-…

4.2.4 Scenarios 3.0 CACC – LV CACC Speed Profile and FV CACC Performance

Initially, this set consisted of four different scenarios (i.e., Scenarios 3.1-3.4.) However, only Scenarios 3.3 and 3.4 were conducted during the July 2016 tests:

- **Scenario 3.1**: Not Applicable.
- **Scenario 3.2**: Gap Control – LV New CACC speed profile set to 55 mph and single FV with minimum time gap (1.2 s): The objective of this test is to characterize the performance of the CACC controller while following the LV moving at a constant speed using the CACC LV speed controller. There is only one FV at a time. It is rotated out to provide insight into vehicle-vehicle performance variations. The results of this scenario will be compared to Scenario 2.2. *This scenario was not executed during the July 2016 tests because it was determined that the CACC performance was adequate to proceed directly to Scenario 3.3*.
- **Scenario 3.3**: Gap Control – LV CACC speed profile with 3 speed changes and single FV with minimum time gap (1.2 s): This is similar to Scenario 3.2, but speed variations are introduced. The results of this scenario will be compared to Scenario 2.3. *While this scenario was executed during the July 2016 tests, a detailed assessment is not necessary because this is a subset of Scenario 3.4 that was executed and assessed*.
- **Scenario 3.4**: Gap Control – LV CACC speed profile with 2 speed changes and 4 FVs with minimum time gap (1.2 s): This is similar to Scenario 3.3, but there is a string of four FVs at a time. The objective of this test is to characterize the performance of the CACC controller while following the LV moving at a speed profile with pre-defined accelerations and decelerations. The results of this procedure will be compared to Scenario 2.4.

4.2.5 Hybrid and CACC Scenario Differences

While the CACC Scenarios 3.0 are intended to be compared to the Hybrid Scenarios 2.0, there are two important differences that will be addressed in Section 5:

1. *Time Gap Settings*: While the minimum production time gap for ACC is 1.1 s, the CACC runs were executed with a set time gap of 1.2 s. This had a small impact on the assessment, which is addressed in Section 5.
2. *LV Acceleration and Deceleration Limits*: The LV for the Hybrid runs had lower acceleration and deceleration limits of 0.25 m/s^2.[6] The LV for the CACC runs had higher acceleration and deceleration limits of 1.0 m/s^2 and 0.3 m/s^2, respectively. This had a small impact on the assessment, which is also addressed in Section 5.

[6] The LV limits were lowered because the FVs in ACC mode could not maintain a stable platoon at higher limits.

4.2.6 Analyzed Test Scenarios

Table 12 identifies the July 2016 test runs, vehicle sequences, and scenarios that were partially or fully assessed. The run titles that are in **bold** were fully assessed and the results are presented in Section 5. As the objective of the analysis is to assess the nominal CACC performance of the vehicles operated to design intent, a number of runs were excluded from the analysis because one or more CACC vehicles exhibited clear system failures (e.g., Basic Safety Message (BSM) dropouts that prevented one or more FVs from reacting as expected to LV changes).

Table 12. July 2016 Test Scenarios and Runs

Run Title	LV	FV Sequence	Scen #	Scen Mode	Accel Limits	Decel Limits	Description
02160725 1712	BLACK	n/a	1.1	ACC	n/a	n/a	60-45-60-45-60-45 mph for 10 min
02160725 1740	WHITE	n/a	1.1	ACC	n/a	n/a	n/a
20160726 1536	BLACK	GREEN-SILVER-GREY-WHITE	1.4	ACC	n/a	n/a	55 mph for 4+ min
20160726 1546	BLACK	GREEN-SILVER-GREY-WHITE	1.4	ACC	n/a	n/a	55-60-45-60-45-60-45 mph for 6 min
20160726 1558	**BLACK**	**WHITE-GREY-GREEN-SILVER**	**1.4**	**ACC**	**n/a**	**n/a**	**55-60-45-60-45 mph for 10 min**
20160726 1738	BLACK	n/a	1.1	ACC	n/a	n/a	60-45-60 mph for 15 min
20160727 1319	BLACK	n/a	2.2	Hybrid	0.25	0.25	55 mph for 10 min
20160727 1337	n/a	n/a	2.2	Hybrid	0.25	0.25	55 mph for 10 min
20160727 1507	BLACK	GREEN-WHITE-SILVER-GREY	2.4	Hybrid	0.25	0.25	60-45-60 mph for 5 min
20160727 1516	**BLACK**	**WHITE-GREY-GREEN-SILVER**	**2.4**	**Hybrid**	**0.25**	**0.25**	**60-45-60 for 4 min**
20160727 1627	**BLACK**	**GREY-GREEN-SILVER-WHITE**	**2.4**	**Hybrid**	**0.25**	**0.25**	**60-45-60 for 4 min**
20160727 1634	**BLACK**	**GREEN-SILVER-WHITE-GREY**	**2.4**	**Hybrid**	**0.25**	**0.25**	**60-45-60 for 4 min**
20160727 1641	**BLACK**	**SILVER-WHITE-GREY-GREEN**	**2.4**	**Hybrid**	**0.25**	**0.25**	**60-45-60 for 4 min**
20160727 1834	BLACK	WHITE	3.3	CACC	0.3	0.3	60-45-60-45-60-45 mph for 15 min
20160728 1226	BLACK	WHITE	3.3	CACC	1	0.3	55-60-45-60 mph for 11 min
20160728 1330	BLACK	WHITE	3.3	CACC	1	0.3	55-60-45-60 mph for 13 min
20160728 1445	BLACK	GREEN-WHITE-SILVER-GREY	3.4	CACC	1	0.3	60-45-60 mph for 5 min
20160728 1456	**BLACK**	**WHITE-SILVER-GREY-GREEN**	**3.4**	**CACC**	**1**	**0.3**	**60-45-60 mph for 5 min**
20160728 1504	**BLACK**	**SILVER-GREY-GREEN-WHITE**	**3.4**	**CACC**	**1**	**0.3**	**60-45-60 mph for 5 min**
20160728 1515	**BLACK**	**GREY-GREEN-WHITE-SILVER**	**3.4**	**CACC**	**1**	**0.3**	**60-45-60 mph for 5 min**
20160728 1522	**BLACK**	**GREEN-WHITE-SILVER-GREY**	**3.4**	**CACC**	**1**	**0.3**	**60-45-60 mph for 5 min**

4.3 Performance Measures

This section describes the primary performance measures and identifies the associated data elements and metrics. The intent is for these performance measures to be assessed for the ACC and CACC scenarios. In general, the CACC system should exhibit less variation and more consistency between vehicles than ACC. It is important to note that the majority of these measures is not independent. For example, an initial response delay may lead to increased acceleration levels to reach the LV speed and may result in increased transient settling times. A critical aspect of a CACC-based platoon's performance is string stability. The Volpe Center addressed both the oscillation for a given position in the platoon and whether the magnitude of the oscillations grows towards the tail of the platoon [9].

4.3.1 Time Gap Accuracy/Stability

The objective for both ACC and CACC systems is to consistently maintain the commanded time gap. In the event that there are variations in the time gap, increasing gaps are preferred over decreasing gaps because decreasing gaps pose potential safety concerns due to a decreased time to perform crash avoidance maneuvers. In this report, time gap was calculated as the radar-based separation divided by the GPS-derived CACC speed:

$$Time\ Gap\ [s] = \frac{Radar\ Range}{GPS\ Speed}$$

As the ACC commanded a time gap of 0.1 s lower than the CACC commanded time gap setting (1.1 s for ACC vs. 1.2 s for CACC), the time gap error was used to facilitate the comparison between the Hybrid scenarios (ACC FVs) and the CACC scenarios. Specifically:

$$Time\ Gap\ Error\ [s] = [Time\ Gap] - \ [Commanded\ Time\ Gap]$$

To assess the variation for a given vehicle, the minimum, maximum, mean, and standard deviation values were assessed against the commanded time gap. Ideally, there is little variation over the course of a run for each vehicle.

To assess the variation within the platoon, the same metrics were compared for the various vehicle positions. Ideally, there is little or no degradation in the time gap towards the tail of the platoon. It would be beneficial to address the overall string length over time in future assessments, as this reflects the cumulative effects of time gap variations.

4.3.2 Speed Accuracy/Stability

The objective for CACC systems is to closely parallel the speed of the preceding vehicles via the DSRC transmittal of the LV and/or preceding vehicle's (PV's) speed and acceleration. As ACC vehicles do not receive any data from PVs, the expectation is that the DRSC transmission will allow CACC systems to respond to speed changes more accurately than ACC systems. In addition, as the LV's speed and acceleration changes are broadcast to all FVs in the platoon, the expectation is that speed errors will not propagate towards the tail of the platoon.

For this assessment, there are several potential sources of speed measurements, including the production wheel speed, the PinPoint GPS speed, the internal CACC GPS speed, and the GPS speed from the Advanced Distributed Modular Acquisition System (ADMAS). The Volpe Center decided to use the internal CACC speed[7] for the following reasons:

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[7] During the ACC and Hybrid runs, the `speed_CACC` measurement for the white vehicle exhibited a lag of ~16 s. As a result, the `velocity_fwd_PINPOINT` was used in place of `speed_CACC` for all ACC and Hybrid white vehicle speed calculations. This was deemed an acceptable substitute because during the CACC runs the white

1. The internal CACC speed is based on GPS, and is therefore not affected by variations in tire pressure, etc.
2. The internal CACC speed is assumed to be the input for the CACC controller, and therefore directly reflects the intent of the controller.

To assess the variation for a given vehicle, the minimum, maximum, mean, and standard deviation values were assessed against the LV speed. Ideally, there is little variation over the course of a run for each vehicle.

To assess the variation within the platoon, the same metrics were compared for the various vehicle positions. Ideally, there is little or no deviation in the speed toward the tail of the platoon.

For more mature CACC prototypes, it will be preferable to assess the relative speed between both each FV and LV, and between each FV and its immediate PV. This is because the minimum and maximum of the absolute speeds of the LV and FVs are likely not synchronous (this is masked when just looking at the absolute speeds.) However, the Volpe Center determined that the absolute speed was adequate for demonstrating the speed stability issues in this assessment.

4.3.3 Acceleration Accuracy/Stability

As the objective for CACC systems is to closely parallel the speed of the PVs, the acceleration between the vehicles should follow similar profiles. In addition, the maximum and minimum acceleration should be reasonably low to avoid saturating the controller, and they should not increase significantly towards the tail of the platoon, as this risks saturating the controller for long platoons. In addition, as the LV's speed and acceleration changes are broadcast to all FVs in the platoon, the expectation is that the minimum and maximum accelerations will not grow towards the tail of the platoon.

Due to significant noise and bias in the available acceleration measurements,[8] it was necessary to derive the acceleration from the speed measurements and smooth it by calculating the moving average:

$$a_i\ [m/s^2] = \frac{speed_i - speed_{i-1}}{t_i - t_{i-1}}$$

$$Moving\ Average\ Acceleration\ [m/s^2] = \frac{a_{i-3} + \cdots + a_{i-1} + a_i + a_{i+1} + \cdots + a_{i+5}}{9}$$

While this method provided reasonable acceleration measurements, it has two notable limitations:

1. There is a slight delay between a given acceleration condition and observing the condition. This is considered acceptable due to the short duration between the time of the moving average and the furthest point included in the average.

vehicle's `velocity_fwd_PINPOINT` is generally just slightly higher than the `speed_CACC` (0 to 0.3 mph greater).

[8] More details on the acceleration measurement issues are provided in Section 5.3.3.

2. Very short duration minimum and maximum are smoothed. This is considered preferable to including the potential noise from a single measurement in the metrics.

To assess the variation for a given vehicle, the minimum, maximum, mean, and standard deviation values were assessed and compared to the LV acceleration. Ideally, there is little variation during periods of constant speed for each vehicle, and the mean remains near zero. During periods of changing speed, the two criteria assessed for individual vehicles were that the acceleration levels were not saturated and that they remained within the specified limits, if any.

To assess the variation within the platoon, the same metrics were compared for the various vehicle positions. Ideally, there is little or no deviation in the acceleration towards the tail of the platoon.

4.3.4 Initial Response Delay

The objective for CACC systems is for FVs to respond to LV speed changes as quickly as possible. As ACC vehicles do not receive any data from PVs and rely on relative navigation sensors (RADAR, LIDAR, etc.), the expectation is that the DRSC transmission will allow CACC systems to respond to speed changes more rapidly than ACC systems. As the LV's speed and acceleration changes are broadcast to all FVs in the platoon, the expectation is that response delay will not grow toward the tail of the platoon.

The ideal response delay is zero, but actual response delays are unavoidable due to system and sensor latency. This latency includes:

- Duration for the LV bus to transmit the speed change commands to the DSRC
- Duration to broadcast the signal to the FV
- Duration for the FV bus to transmit the speed change commands from the DSRC to the CACC controller
- Duration for the CACC controller to command a speed change
- Duration for the commanded speed change to be affected on the system (i.e., mechanical delay)

While this activity was not intended to assess the system latency, the initial response delay was observable in the period immediately after the commanded LV deceleration and acceleration in the speed profile. It should be inclusive of the latency effects.

For this activity, the method for defining the initial response delay was to perform the following for the initiation of each LV speed change:

1. Calculate the initial response time for the LV ($t_{initial\ response.LV}$) and each FV ($t_{initial\ response.FV}$), where the initial response time is defined as the first time when there is at least a magnitude of 0.2 m/s^2 (sustained for at least 0.4 s) in the moving average of the acceleration.
2. Calculate the initial response delay:

$$Initial\ Response\ Delay_{\ FV_i}[s] = t_{initial\ response,FV_i} - t_{initial\ response,LV}$$

The same metric was compared for the various vehicle positions to assess the variation within the platoon. Ideally, there is little or no increase in the initial response delay toward the tail of the platoon.

4.3.5 Transient Settling Durations

While the Initial Response Delay is a reflection of how quick an FV responds to the initiation of a speed change, the transient settling durations reflect how quickly an FV is able to complete the speed change. For this assessment, two metrics are assessed:

- *5% Following Speed Duration*: The time between the initial response time for the LV ($t_{initial\ response,LV}$) and the moment that the vehicle is first within ±5% of the speed of the immediate PV when the immediate PV has reached a steady speed.
- *0% Following Speed Duration*: The time between the initial response time for the LV ($t_{initial\ response,LV}$) and the moment that the vehicle first reaches the speed of the immediate PV when the immediate PV has reached a steady speed.

The same metric was compared for the various vehicle positions to assess the variation within the platoon. Ideally, there is little or no increase in the transient settling durations toward the tail of the platoon.

4.4 LV Speed Controller Assessment

The performance of the LV speed profile controller has a significant impact on this activity:

- As the goal of the CACC FVs is to mirror the speed of the LV, sudden significant changes in the LV acceleration may cause instability in the platoon due to system delays (e.g., initial response time, etc.)
- Test scenarios are designed for repeatability between runs to allow for straightforward comparisons. Inconsistency in the LV speed profile complicates the comparison between different runs.

For this reason, the Volpe Center assessed the performance of the LV speed profile to identify potential impacts on the test results. The results are briefly summarized in Section 5.2.

4.5 CACC Subsystem Assessment

While assessing the CACC subsystem performance is not an objective of this test, it is necessary to perform a limited characterization of the sensors and speed controller to have confidence in the sensor measurements.

This is intended to provide confidence in the sensor suite and controllers and to identify any periods of poor performance that would have a negative impact on the stability evaluation. This is a very limited, high-level assessment and it does not provide enough information to verify the performance or to troubleshoot poor performance. For example, the assessment of the PinPoint sensor only assesses whether the filtered states appear smooth, and does not independently confirm the filter performance nor evaluate the underlying GPS, accelerometer, and gyrometer measurements.

This assessment includes a limited characterization of:

- The production wheel speed noise and bias for a vehicle-at-rest and in-motion.
- The PinPoint position noise and bias for a vehicle-at-rest.
- The PinPoint and CACC speed noise and bias for a vehicle-at-rest and in-motion.
- The PinPoint and CACC acceleration noise and bias for a vehicle-at-rest and in-motion.
- The custom controller that is used to command speed changes, with the specific focus on the commanded torque, brake commands, and gear changes.

The results are briefly summarized in Section 5.3.

5. Proof-of-Concept Performance Results

This section presents the results of analyzing the nine test scenarios (Table 12) for the CACC-based car platooning proof-of-concept. The following notes apply to the majority of the results presented in this section:

- *Deceleration, Acceleration, and Constant Speed Periods*: As significant variations were observed between the different periods in the speed profile (deceleration, acceleration, and constant speed), performance measures and results are presented for the individual periods. This avoids the duration of and performance during a specific period from biasing the overall results. For example, during periods of constant speed, the ACC and CACC time gap errors are generally quite small, whereas during periods of changing speed, the time gap errors are considerably larger. If they were calculated for a set of individual periods, the time gap errors would be weighted by the ratio of the duration of constant speed versus the duration of changing speed. The constant speed, deceleration, and acceleration results are presented separately to avoid this effect.
- *Plot Colors*: The following plot conventions are used throughout this report:
    - The ACC results are displayed in orange squares (■), the Hybrid results are displayed in green circles (●), and the CACC results are displayed with blue diamonds (◆).
    - In general, the Hybrid and CACC plots show the results for each for the four runs that were analyzed to illustrate the variability for the same operating mode.
        - For simplicity, the colors are the same for all runs of a given mode.
        - When it is important to differentiate between runs within a given mode, the color schemes are retained. The LV is the darkest shade of a color and the traces become lighter toward the tail of the platoon.
- *Representative Reference Plots*: For simplicity, when plotting the time-series of a set of data for a scenario, only one representative run is presented for each mode. The complete set of plots for every run is provided in Appendix D.
- *Summary Tables*: Each subsection includes a table that summarizes the results. When applicable, the stability of each performance measure includes the following for each assessed period:
    - Evaluation of the *oscillation* of the metric. This is applicable to parameters that should remain steady for a given vehicle position, such as the Constant Time Gap or a vehicle's speed during steady state periods. This is generally represented as a coefficient of variation (CV) to allow comparisons between values of different magnitudes. When there is a single commanded value (e.g., time gap) the commanded value is used in place of the mean. For values that oscillate about zero, such as the acceleration during constant speed, oscillation is represented by the standard deviation.
    - Evaluation of the *trend* of the metric. This is applicable to parameters that should remain steady throughout the platoon, such as the Constant Time Gap or the settling durations. This is generally represented as the absolute and/or percentage change in a parameter between adjacent vehicles.

In addition, a simple red/yellow/green color scheme is used to provide a quick comparison between Hybrid and CACC performance. While the color code is useful for highlighting relative differences, this approach is both coarse and subjective. For example, all green would not necessarily represent acceptable performance.

5.1 Performance Evaluation

This section presents and discusses the test results of the car platooning proof-of-concept for each of the performance measures in sin Section 44. Figure 18 illustrates the difference in FV speed performance for Hybrid (FVs in ACC) and CACC (FVs in CACC) reference scenarios. Figure 18 shows speeds only from a single Hybrid run and a single CACC run. Observations of interest are:

- Deceleration:
    - At the start of the deceleration, the FVs in ACC (green traces) begin decelerating much more gradually than in the CACC (blue traces).
    - At the end of the deceleration, every FV in ACC significantly overshoots the LV, whereas this only happens for FV1 and FV3 in CACC.
    - In the transient at the end of the deceleration, the FVs in CACC stabilize more rapidly than in ACC mode.

- Acceleration:
    - The Hybrid LV acceleration profile (darkest green trace) is not as aggressive as the CACC LV profile that occurs between 95 and 125 s.[9] This is likely due to the different LV acceleration settings between these scenarios (for Hybrid runs, the LV acceleration limit is set to 0.25 m/s^2, while it is set to 1.0 m/s^2 for the CACC runs).[10] In this case, the lower acceleration limits on the LV should have enabled the ACC FVs to match the LV speed more easily; however, they still drop behind.
    - At the start of the acceleration, the FVs in ACC slow while the LV accelerates.
    - Throughout the acceleration, the FVs in CACC follow the LV acceleration profile much more closely than in ACC mode.
    - In the transient at the end of the acceleration, the FVs in ACC and CACC take similar durations to stabilize.

Figure 19 shows the corresponding time gaps for the reference scenarios. Observations of interest are:

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[9] Note that these times differ from the elapsed times in Appendix D. This is because the time scale for the traces in in Figure 18 and Figure 19 was adjusted to synchronize the ACC and CACC events.
[10] The performance of the LV is further discussed in Section 5.2.

- During the deceleration, the CACC time gaps generally grow, with the significant exception of FV1, in which the time gaps generally shrink. This is due to the very fast and aggressive response of the CACC FVs to the LV deceleration. In contrast, the ACC FV responses are delayed which results in decreased time gaps throughout the platoon.
- During the acceleration, the inverse occurs due to the quick CACC response and acceleration, which results in the FVs keeping up with the PVs and eventually closing the gap. The delay in the ACC response results in the time gap growing slightly.

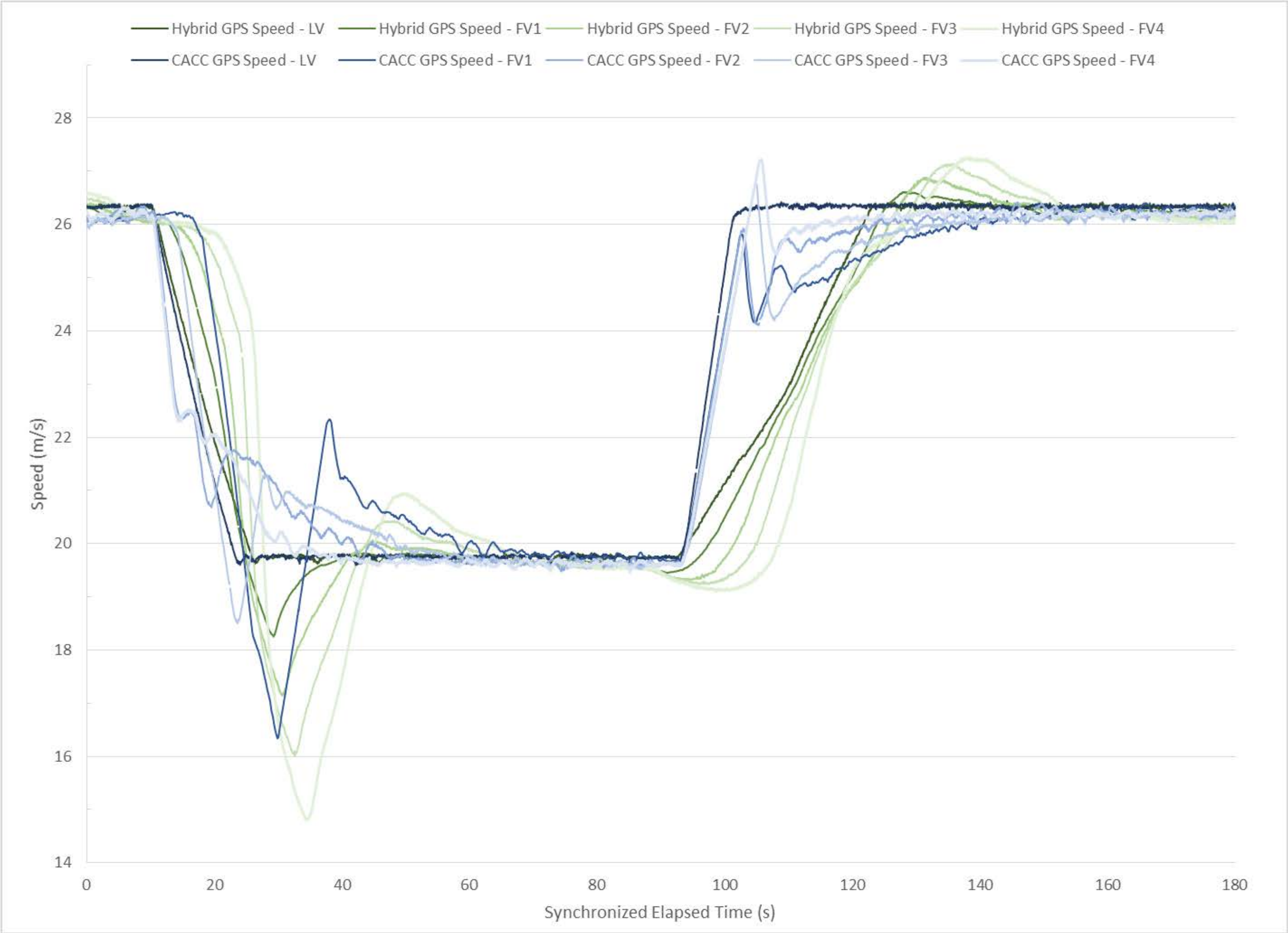

Figure 18. Hybrid versus CACC Speed Performance

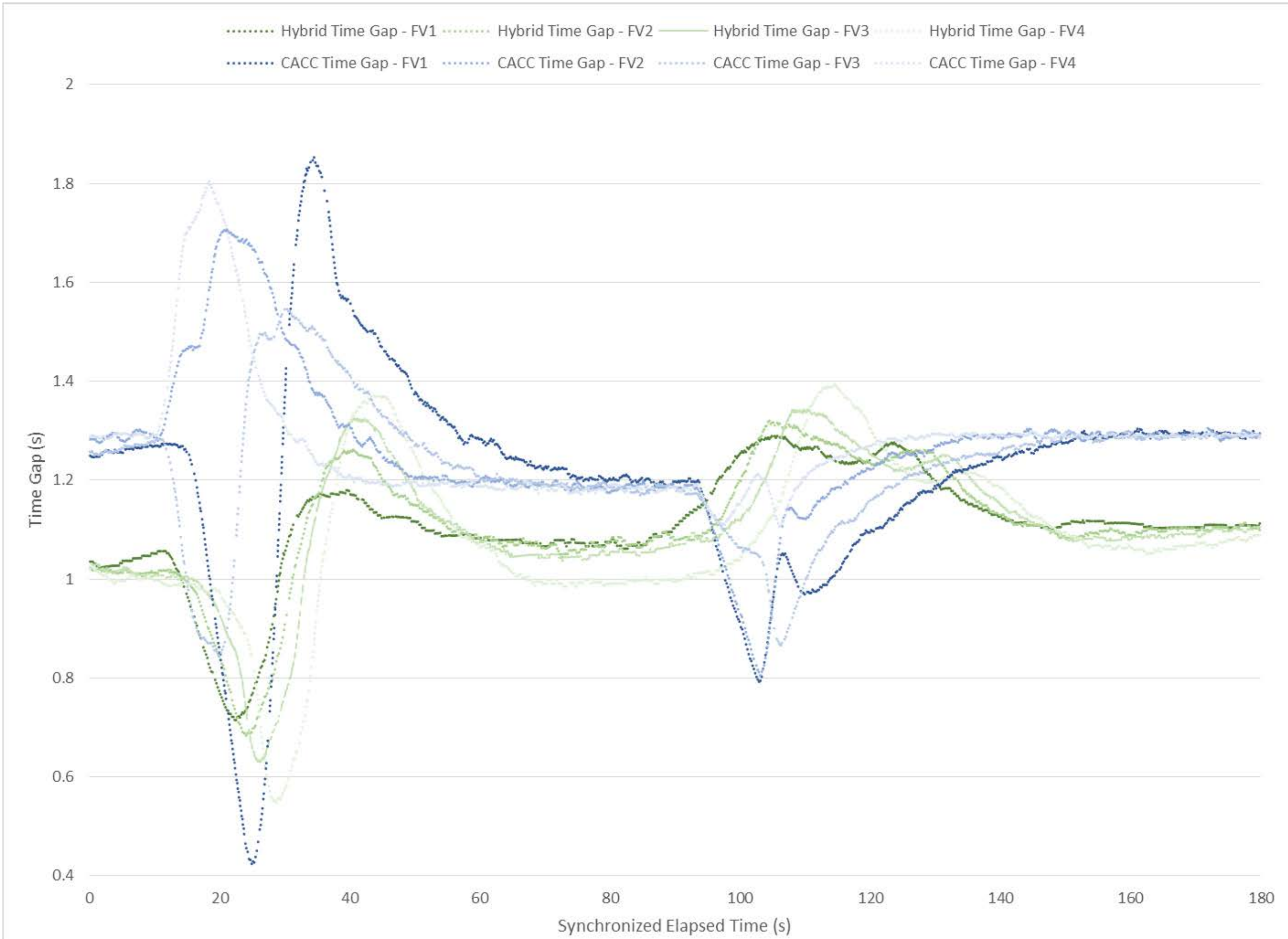

Figure 19. Hybrid versus CACC Time Gap Performance[11]

[11] Note that, while the CACC time gap was set to be at 1.2 s, a time gap of 1.2 s was observed while at 45 mph and a time gap of 1.3 s was observed while at 60 mph. These observed time gaps apply to every following vehicle in every CACC test run.

5.1.1 Time Gap Accuracy/Stability

Figure 20 presents the minimum and maximum time gap errors for the four periods in the scenarios (i.e., 1 deceleration, 1 acceleration, and 2 steady-state periods). Note that:

- Positive errors indicate time gaps are larger than desired, which is safe but less stable.
- Negative errors indicate time gaps are lower than expected, which is a potential safety concern and also less stable.

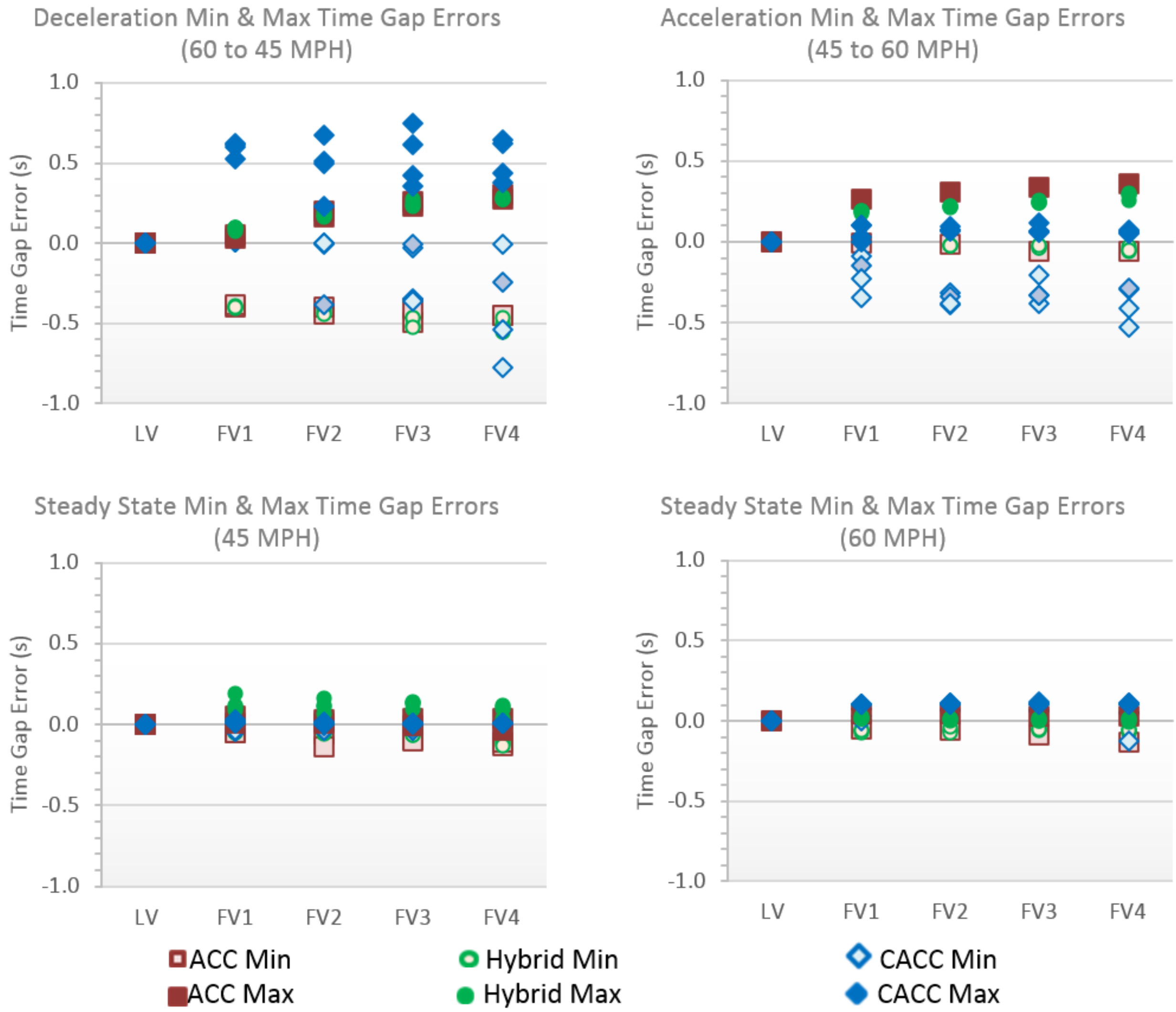

Figure 20. Hybrid versus CACC Time Gap Errors

Table 13 describes the time gap oscillations for a given vehicle position and the trend from the front to the tail of the platoon. In summary, FVs in ACC and CACC modes maintain stable time gaps while at constant speed, but they are less stable during speed changes.

Table 13. Summary of Time Gap Errors

Period	Criteria	Hybrid (ACC FVs)	CACC
Deceleration from 60 to 45 mph	Oscillation *Mean CV*	17.4%	15.5%
Deceleration from 60 to 45 mph	Trend *Mean % Change*	Min: (-3.3%) Max: (5.9%)	Min: (-11.3%) Max: (-1.9%)
Constant Speed at 45 mph	Oscillation *Mean CV*	4.2%	0.5%
Constant Speed at 45 mph	Trend *Mean % Change*	Min: (-2.1%) Max: (-1.1%)	Min: (0.3%) Max: (-0.3%)
Acceleration from 45 to 60 mph	Oscillation *Mean CV*	7.0%	10.3%
Acceleration from 45 to 60 mph	Trend *Mean % Change*	Min: (-1.9%) Max: (3.0%)	Min: (-4.9%) Max: (0.2%)
Constant Speed at 60 mph	Oscillation *Mean CV*	1.2%	0.67%
Constant Speed at 60 mph	Trend *Mean % Change*	Min: (0.1%) Max: (-0.4%)	Min: (-1.2%) Max: (0.1%)

5.1.2 Speed Accuracy/Stability

Figure 21 presents the individual speed maximum and minimum for the four periods in the scenarios.

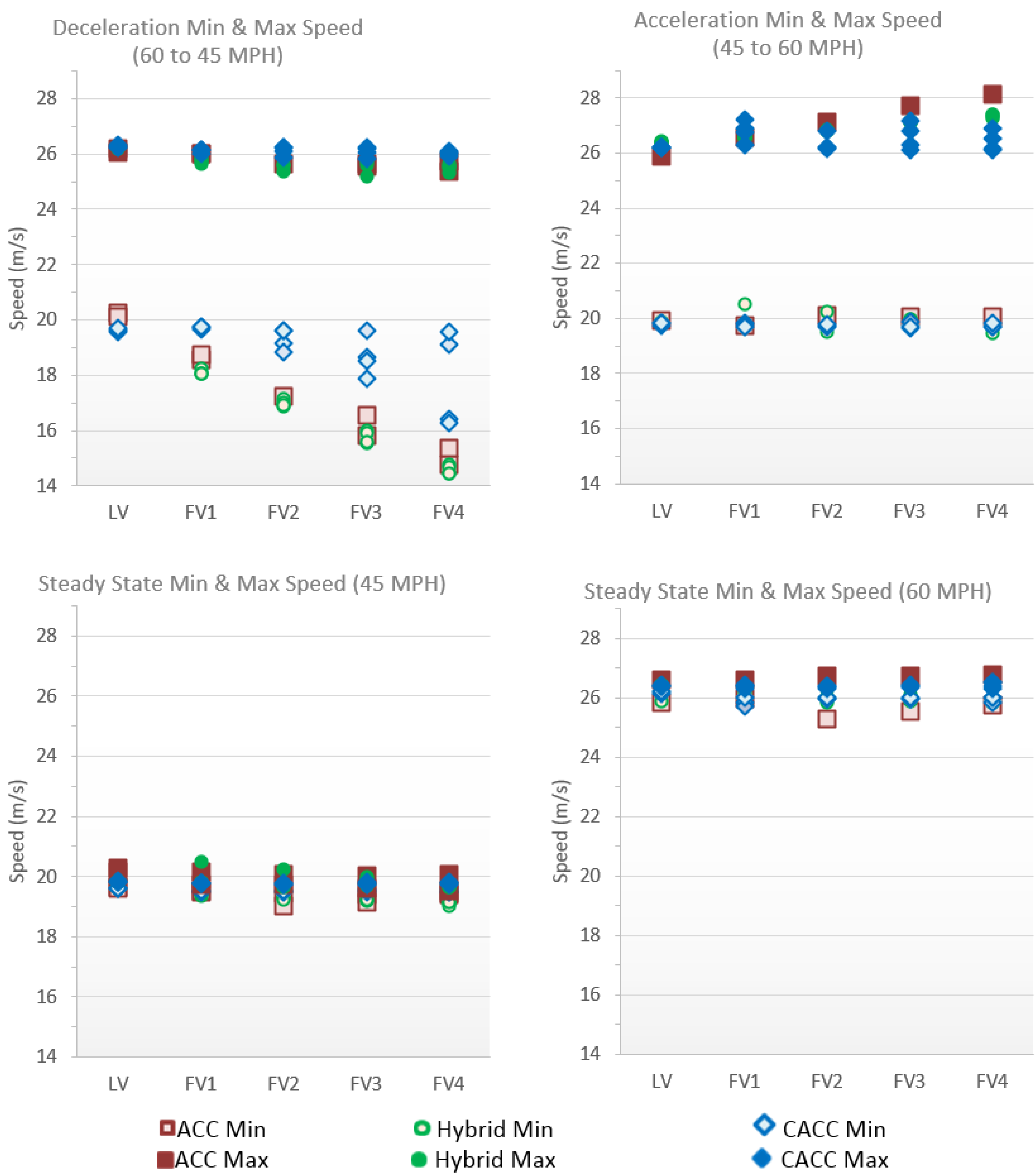

Figure 21. Hybrid versus CACC Speed

Table 14 describes the Hybrid and CACC speed oscillations and trends from the front to the tail of the platoon.

Table 14. Summary of Speed Stability

Period	Criteria	Hybrid (ACC FVs)	CACC
Deceleration from 60 to 45 mph	Oscillation	N/A	N/A
Deceleration from 60 to 45 mph	Trend *Mean Change*	Min: (-1.26 m/s) Max: (-0.18 m/s)	Min: (-0.45 m/s) Max: (-0.07 m/s)
Constant Speed at 45 mph	Oscillation *Mean CV*	LV: (0.2%) FVs: (0.7%)	LV: (0.2%) FVs: (0.2%)
Constant Speed at 45 mph	Trend *Mean Change*	Min: (-0.12 m/s) Max: (-0.03 m/s)	Min: (-0.03 m/s) Max: (0.01 m/s)
Acceleration from 45 to 60 mph	Oscillation	N/A	N/A
Acceleration from 45 to 60 mph	Trend *Mean Change*	Min: (-0.04 m/s) Max: (0.23 m/s)	Min: (-0.01 m/s) Max: (0.05 m/s)
Constant Speed at 60 mph	Oscillation *Mean CV*	LV: (0.1%) FVs: (0.3%)	LV: (0.1%) FVs: (0.3%)
Constant Speed at 60 mph	Trend *Mean Change*	Min: (-0.06 m/s) Max: (-0.01 m/s)	Min: (-0.06 m/s) Max: (0.00 m/s)

To summarize, FVs in ACC and CACC modes maintain stable speeds while at constant speed. During deceleration, the difference between the LV's and each FV's speeds generally increases toward the end of the platoon, as shown in Figure 21. During acceleration, the speed of the FVs in CACC mode appears stable while it is slightly less stable in ACC mode. The difference between the LV's and each FV's maximum speeds increases toward the end of the platoon, as shown in Figure 22. While CACC is generally more stable during deceleration and acceleration, there is more variation between the minimum and maximum CACC speeds, as opposed to ACC where the minimum and maximum are quite close.

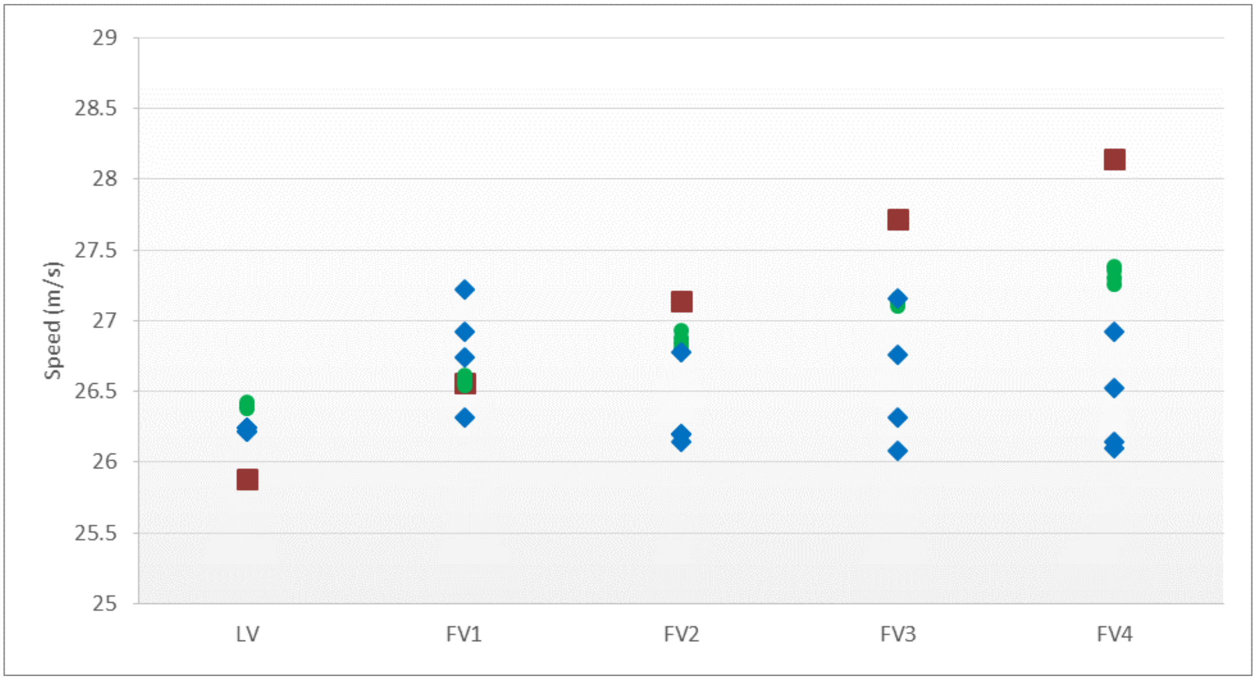

Figure 22. Hybrid versus CACC Maximum Speed during Acceleration

5.1.3 Acceleration Accuracy/Stability

Figure 23 presents the minimum and maximum acceleration values for each of the four periods in the scenarios.

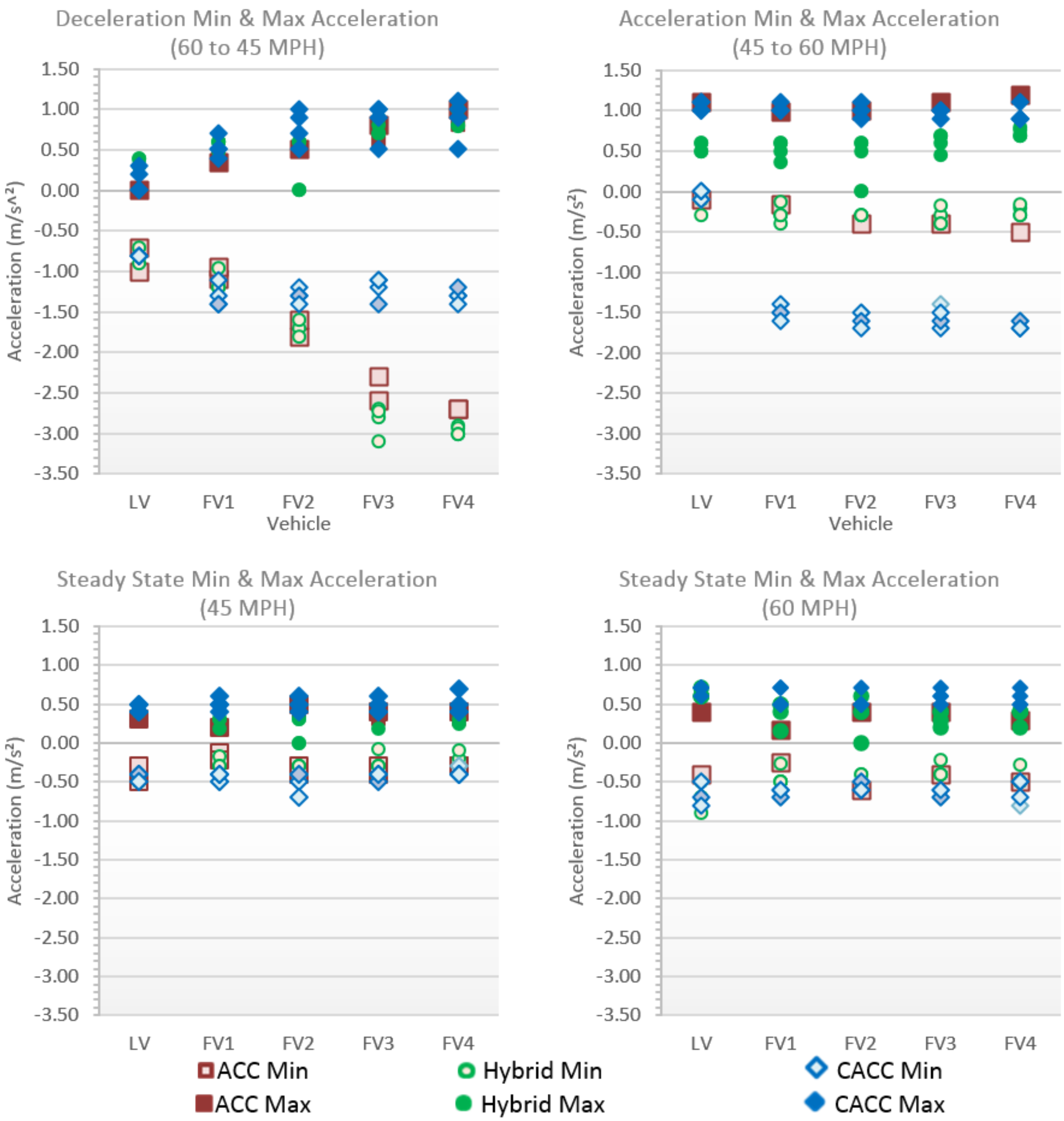

Figure 23. Hybrid versus CACC Acceleration

Note that the Hybrid LV acceleration and deceleration limits were lower than the CACC LV limits, which may impact the results as follows:

- The Hybrid LV maximum acceleration is lower than CACC during the acceleration period. While this may be due to the lower Hybrid LV acceleration limit of 0.25 m/s^2 versus the CACC LV limit of 1 m/s^2, the LV max acceleration exceeds the 0.25 m/s^2 limit in each run (the mean of the LV maxima is 0.55 m/s^2 for the Hybrid runs, whereas it is 1.05 m/s^2 for the CACC runs). This lower LV acceleration for the Hybrid runs may explain the lower acceleration values that are observed for the ACC FVs.
- There is no observable difference in the Hybrid and CACC LV deceleration periods during the deceleration period. While the Hybrid LV limit was -0.25 m/s^2 versus the CACC LV limit of -1 m/s^2, the LV acceleration minimum exceeds 0.25 m/s^2 in each run (the mean of the LV minimum is -0.80 m/s^2 for both Hybrid and CACC runs). This may be due to limitations in the acceleration limits, or it may be due to errors in the moving average acceleration measurements.
- It is important to note that the absence of an accurate acceleration measurement in the data means that the moving average acceleration values shown above may not accurately reflect the internal acceleration value used by the CACC LV controller.

Table 15 describes the Hybrid and CACC acceleration oscillations and trends from the front to the tail of the platoon.

Table 15. Summary of Acceleration Stability

Period	Criteria	Hybrid (ACC FVs)	CACC
Deceleration from 60 to 45 mph	Oscillation	N/A	N/A
Deceleration from 60 to 45 mph	Trend *Mean Change*	Min: (-0.54 m/s^2) Max: (0.14 m/s^2)	Min between FVs: (0.00 m/s^2) Max between FVs: (0.12 m/s^2)* **All FVs exhibit significantly larger rates than LV; statistics exclude LV-FV1 trend*
Constant Speed at 45 mph	Oscillation *Mean Std Dev*	LV: (0.13 m/s^2) FVs: (0.09 m/s^2)	LV: (0.13 m/s^2) FVs: (0.14 m/s^2)
Constant Speed at 45 mph	Trend *Mean Change*	Min: (0.06 m/s^2) Max: (-0.02 m/s^2)	Min: (0.01 m/s^2) Max: (0.01 m/s^2)
Acceleration from 45 to 60 mph	Oscillation	N/A	N/A
Acceleration from 45 to 60 mph	Trend *Mean Change*	Min: (-0.03 m/s^2) Max: (0.05 m/s^2)	Min between FVs: (-0.05 m/s^2)* Max between FVs: (-0.03 m/s^2) **All FVs exhibit significantly larger deceleration rate than LV; statistics exclude LV-FV1 trend*
Constant Speed at 60 mph	Oscillation *Mean Std Dev*	LV: (0.18 m/s^2) FVs: (0.11 m/s^2)	LV: (0.17 m/s^2) FVs: (0.18 m/s^2)
Constant Speed at 60 mph	Trend *Mean Change*	Min: (0.06 m/s^2) Max: (-0.07 m/s^2)	Min: (0.00 m/s^2) Max: (-0.03 m/s^2)

FVs in ACC and CACC modes maintain stable acceleration while at constant speed. During deceleration and acceleration periods, FVs in ACC mode exhibit a clear growth trend between the LV and FV minimum and maximum toward the tail of the platoon. This was pronounced for FVs in ACC mode during deceleration, with the maximum rates growing rapidly and reaching -3.0 m/s^2 for the final FVs.

In contrast, while CACC runs exhibited large increases between the LV and FV1, there were only small increases between FVs. During deceleration periods, the CACC minima appear to be stable between FVs, with growing maxima. The inverse occurs during acceleration periods.

5.1.4 Initial Response Delay

Figure 24 presents the initial response delay durations for the deceleration and acceleration periods.

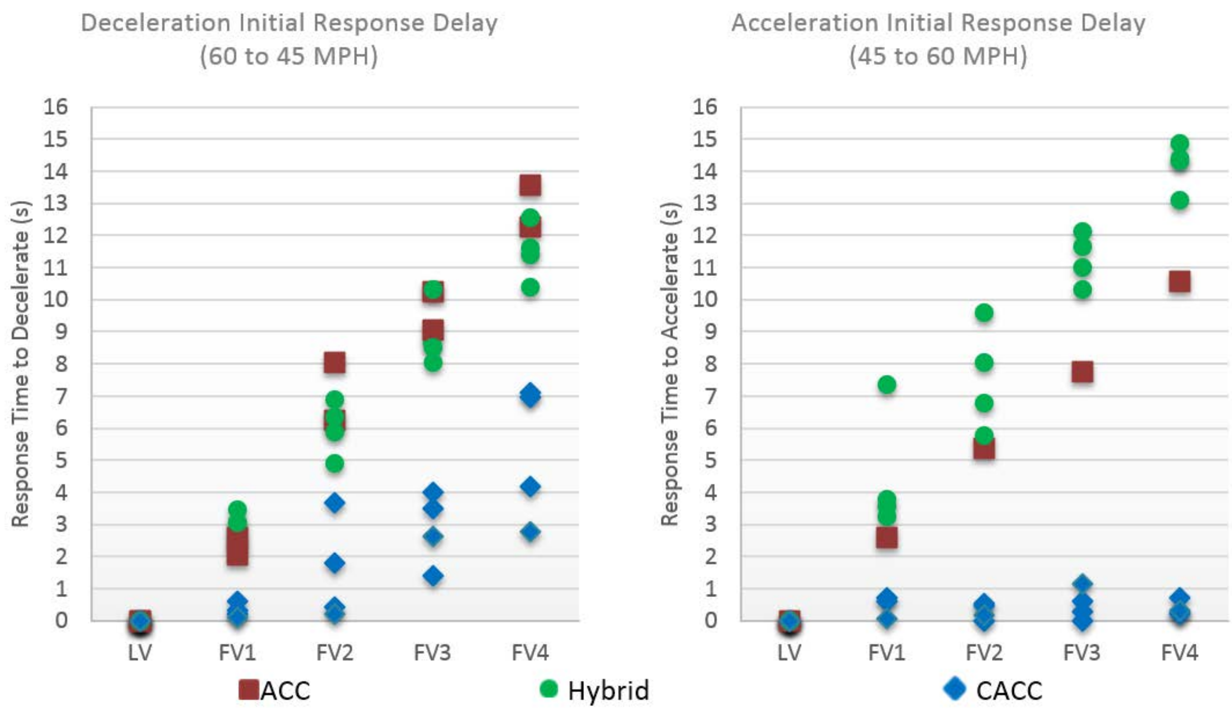

Figure 24. Hybrid versus CACC Initial Response Delay

Table 16 describes the Hybrid and CACC initial response delay duration trends from the front to the tail of the platoon. The oscillation is not relevant because the initial response delay is a single value, and not a continuous measure.

Table 16. Summary of Initial Response Delay Stability

Period	Criteria	Hybrid (ACC FVs)	CACC
Deceleration from 60 to 45 mph	Trend *Mean Change*	2.81 s	1.65 s
Acceleration from 45 to 60 mph	Trend *Mean Change*	3.23 s	0.02 s

FVs in neither ACC nor CACC mode maintain stable initial response delays during deceleration. FVs in ACC mode are similarly unstable during acceleration; but FVs in CACC mode appear stable, with short initial response delays.

5.1.5 Transient Settling Durations

Figure 25 presents the transient settling durations for the deceleration and acceleration periods.

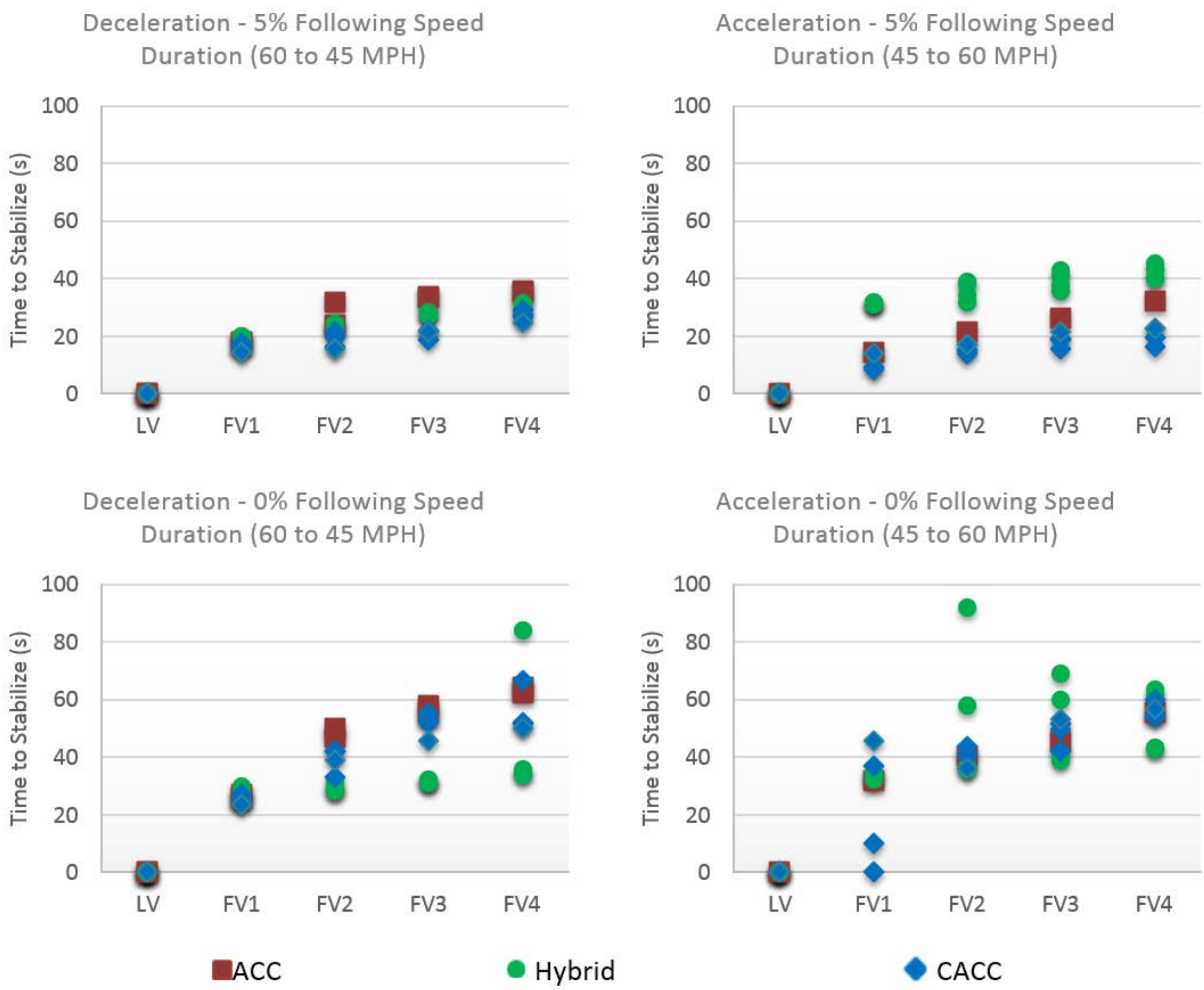

Figure 25. Hybrid versus CACC Transient Settling Delays

Table 17 describes the Hybrid and CACC transient settling trends from the front to the tail of the platoon. The oscillation is not relevant because these settling durations represent a single values, and not continuous measures.

Table 17. Summary of Transient Settling Stability

Period	Criteria	Hybrid (ACC FVs)	CACC
Deceleration from 60 to 45 mph	5% Following Speed Trend *Mean Change*	12.40 s	3.73 s
Deceleration from 60 to 45 mph	0% Following Speed Trend *Mean Change*	6.33 s	10.00 s
Acceleration from 45 to 60 mph	5% Following Speed Trend *Mean Change*	3.62 s	3.00 s
Acceleration from 45 to 60 mph	0% Following Speed Trend *Mean Change*	6.42 s	7.98 s

FVs in ACC and CACC modes exhibit similarly poor settling durations following transient periods. FVs in CACC achieve the 5% following speed trend sooner that FVs in ACC, while FVs in CACC take longer to achieve the 0% following speed trend.

5.2 Lead Vehicle Speed Controller Assessment

The performance of the LV speed profile controller has a significant impact on the evaluation of the vehicle platooning proof-of-concept because sudden significant changes in the LV acceleration may cause instability in the platoon. Thus, the LV speed profile performance was assessed to identify potential impacts on the test results, with the production CC used as a baseline for the evaluation.

To illustrate the LV performance, two representative LV runs are discussed in this section:

1. Production CC controller (20160726 1558 ACC)
2. Custom CACC speed controller (20160728 1456 CACC)

5.2.1 LV Speed Transitions

The most significant observation is that the custom CACC LV controller maintained the prescribed speed profiles very accurately. However, a potential concern is that the CACC controller had much more abrupt speed transitions than the production ACC controller.

Figure 26 shows the LV in production ACC mode following a commanded speed profile that was very similar to the commanded profile of the LV in CACC mode, as shown in Figure 27. The most significant observation is that the custom CACC LV controller maintained the commanded speed profiles very accurately. However, a potential concern is that the CACC controller had much more abrupt speed transitions than the production ACC controller, which likely contributes to the instability that is observed in the FVs' speed transitions in CACC.

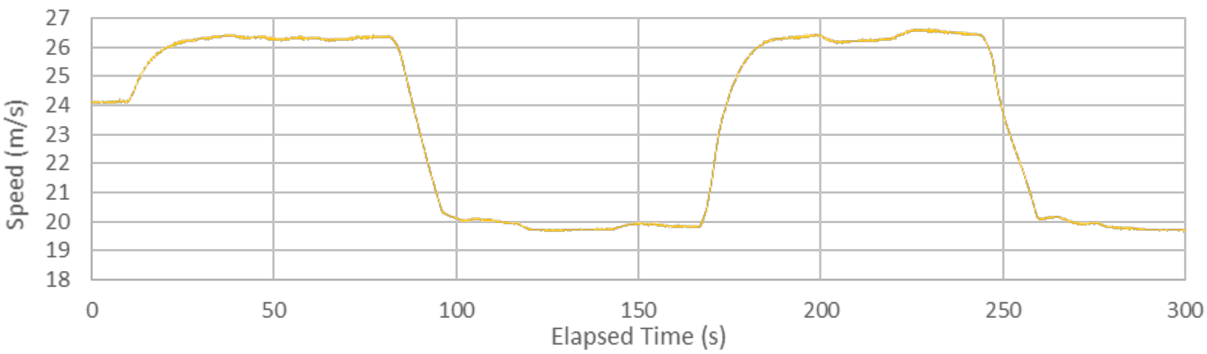

Figure 26. Production ACC LV GPS Speed (60-45-60 mph)

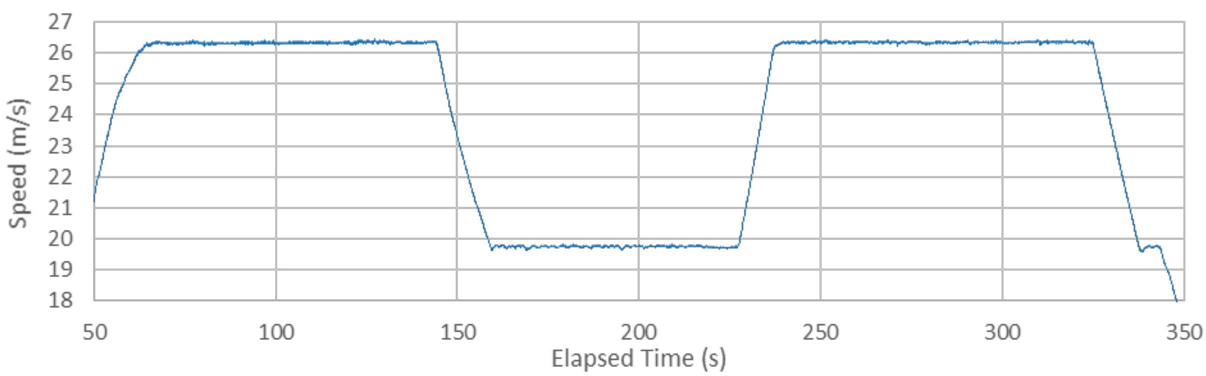

Figure 27. Custom CACC LV GPS Speed (60-45-60 mph)

5.2.2 LV Speed Deadbands

During periods of constant speed, the LV in CACC mode consistently maintained tighter deadbands than in the production ACC mode. While this results in more accurate speed control, it is less precise and may contribute to the FVs' instability due to the more frequent speed adjustments that must be commanded. In addition, this characteristic is likely correlated with the frequent torque modulation that is discussed in section 5.3.4.

Figure 28 shows the LV speed under the production ACC control for the final period of constant speed at 60 mph (26.8 m/s). Figure 29 shows the corresponding period for CACC. Note the tighter deadband but increased noise/decreased precision in CACC vs production ACC control.

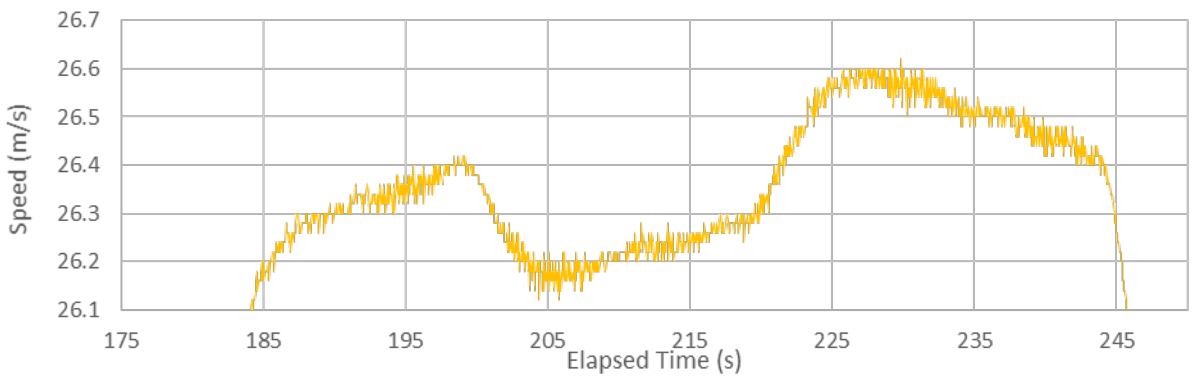

Figure 28. Production ACC LV GPS Speed (60 mph)

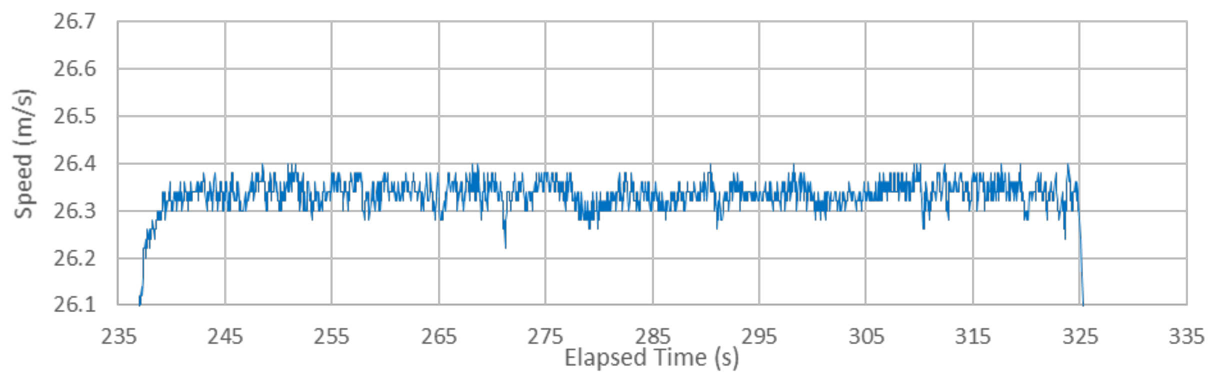

Figure 29. Custom CACC LV GPS Speed (60 mph)

5.3 Subsystem Assessment

While assessing the CACC subsystem performance is not a primary objective of this activity, it was necessary to perform a limited characterization of the sensors and speed controller to have confidence in the sensor measurements.

This assessment was conducted using:

- Data from each assessed run to confirm that the measurements were reasonable.
- A very small duration (5 min) of data that were collected while the vehicles were sitting in the track parking lot with the data collection system running. While the data confirmed that the vehicles were not moving (the vehicle transmissions were in park, the engines were idling, and the steering wheels were stationary), it is possible that the vehicle doors were opened/closed and that occupants entered/exited during the collection. This may explain several short spikes in acceleration measurements. It is highly recommended that future evaluations collect a significantly longer sample (preferably at a surveyed datum) and ensure that the vehicles are not disturbed.

5.3.1 Position Data Assessment

Overall, the PinPoint position data appear to be very accurate and stable. While the vehicles were at rest, the PinPoint position remained tightly clustered, as shown in Table 18. Note that no PinPoint data was collected for the grey and silver vehicles during this period. While the vehicles were in motion, the PinPoint position measurements appeared relatively close to a survey map of the track for each of the assessed data runs, with the notable exception of the grey vehicle. For an unknown reason during the CACC runs, the grey PinPoint local position data appeared to rotate clockwise in the local frame, as shown in Figure 30 (grey PinPoint data were not available for comparison in the ACC or Hybrid runs). No observable effects on CACC performance have been correlated with this behavior.

Table 18. Summary of At-Rest Position Data

Vehicle	Range [max – min] East (m)	Range [max – min] North (m)	Standard Deviation East (m)	Standard Deviation North (m)
Black	0.151	0.116	0.025	0.018
Green	0.161	0.102	0.016	0.058
White	0.165	0.155	0.037	0.032

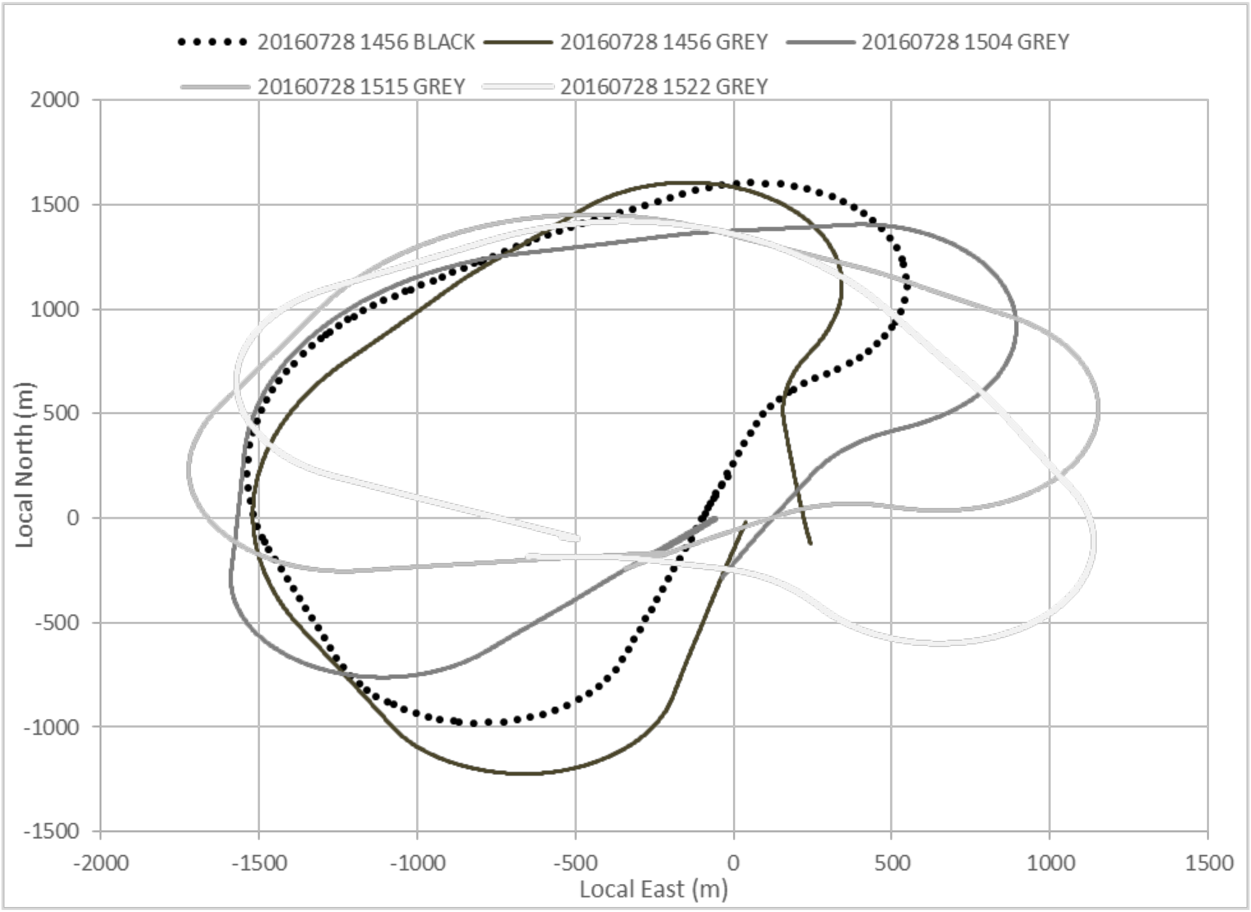

Figure 30. Rotating Grey PinPoint Position Measurements

5.3.2 Speed Data Assessment

5.3.2.1 At-Rest Speed: Wheel Sensors

The production wheel speed data remained zero while the vehicles were at rest.

5.3.2.2 At-Rest Speed: PinPoint

PinPoint provided the only non-zero speed measurements while the vehicles were at rest. The measurements exhibited very little noise (< 0.03 m/s) and no significant bias, as summarized in Table 19 and plotted in Figure 31. Note that no PinPoint data was collected for the grey and silver vehicles during this period.

Table 19. Summary of At-Rest PinPoint Speed

Vehicle	Mean (m/s)	Min (m/s)	Max (m/s)	Std Dev (m/s)
Black	0.000	-0.022	0.017	0.003
Green	0.000	-0.018	0.020	0.003
White	0.000	-0.016	0.022	0.003

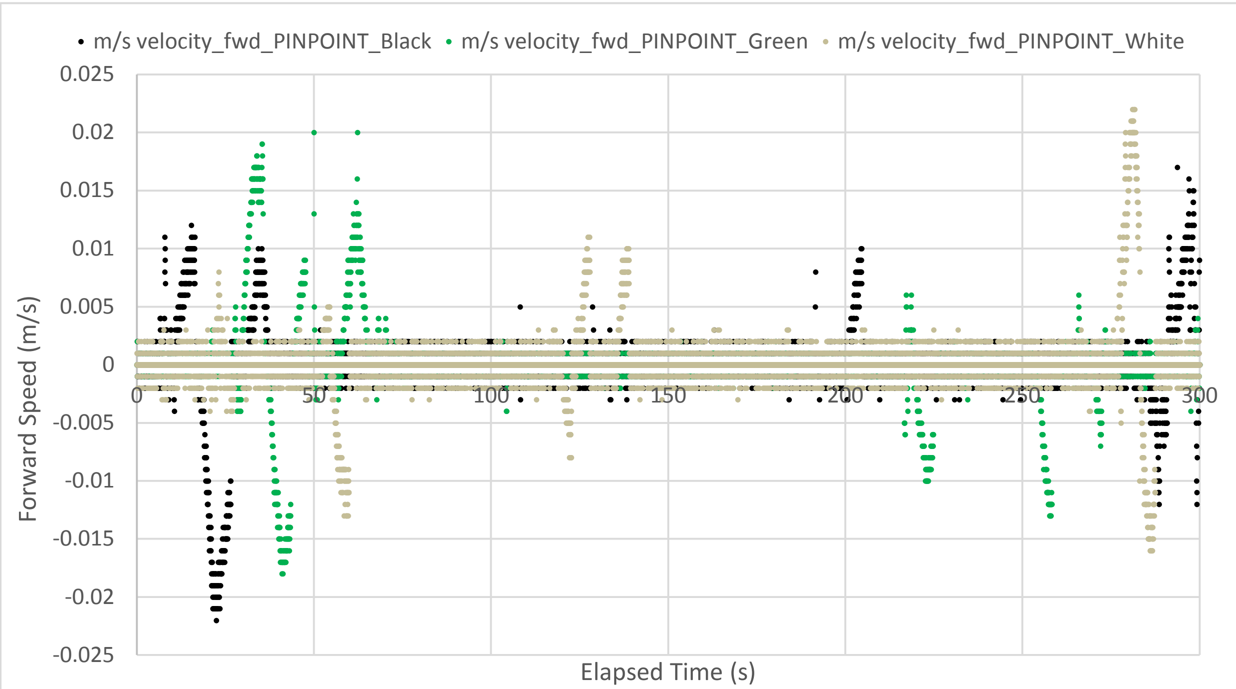

Figure 31. All At-Rest Speed Sources

5.3.2.3 At-Rest Speed: CACC

At rest, the CACC measurement is consistently zero, although it is not known if this reflects the actual measurement or dissimilar processing when the vehicle is not in motion.

5.3.2.4 In-Motion Speed: All

Overall, all speed measurements appeared to be accurate, although the wheel sensors were biased slightly above the PinPoint and CACC measurements.

To illustrate the performance, the Volpe Center selected the LV performance during one of the assessed CACC runs (20170728-1456) as representative of overall performance. Figure 32 shows the three speed measurements over the course of this run. Figure 33 zooms to the final 60 mph constant speed duration, with the metrics for this duration summarized in Table 20. Observations of interest are:

- It is clear that the wheel speed measurements are consistently greater than the measurements from the other sensors, which is not unexpected, and it could be due to sensor errors, tire pressure, tread wear, etc.
- It is less clear why the PinPoint and CACC measurements exhibit similar but slightly different behavior. While few details are available in the CACC documentation regarding how the CACC speed is calculated, the differences could be due to the input data rate, the smoothing algorithm, or different input measurements. Table 20 summarizes the performance in the final 60 mph constant speed duration.

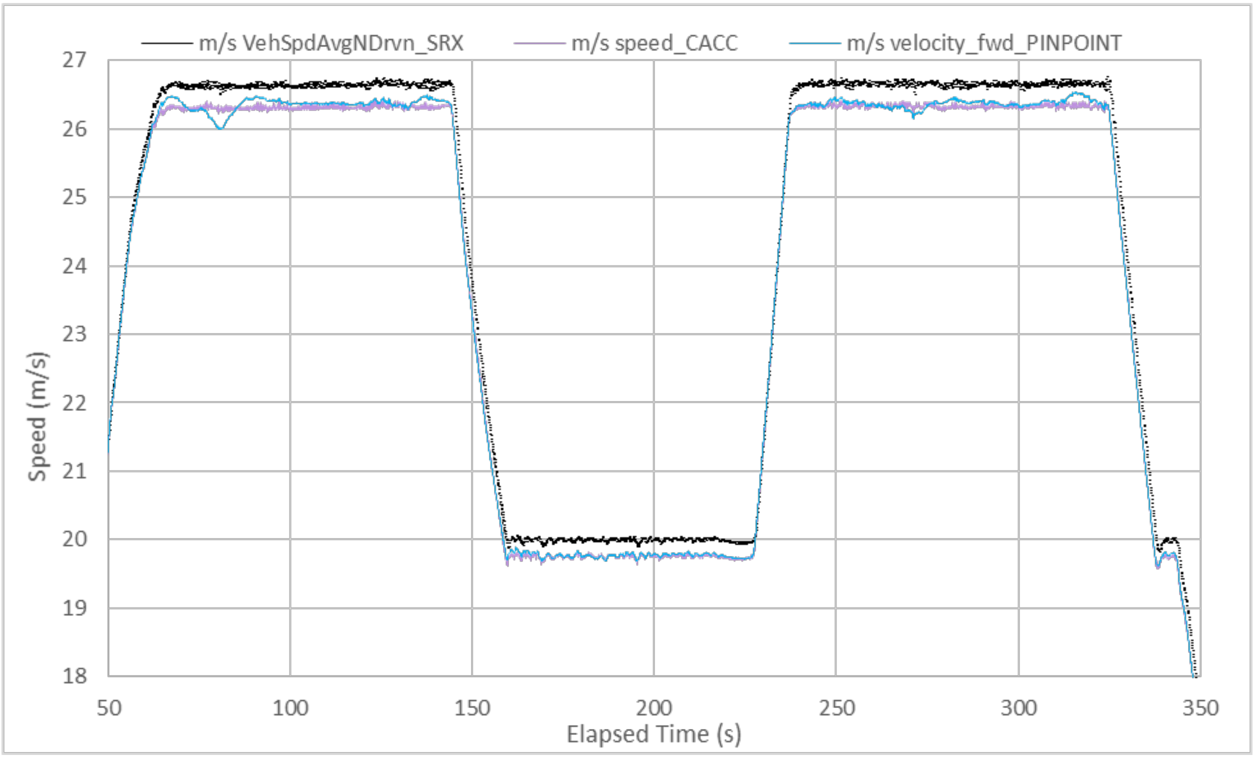

Figure 32. Speed Example (60-45-60 mph)

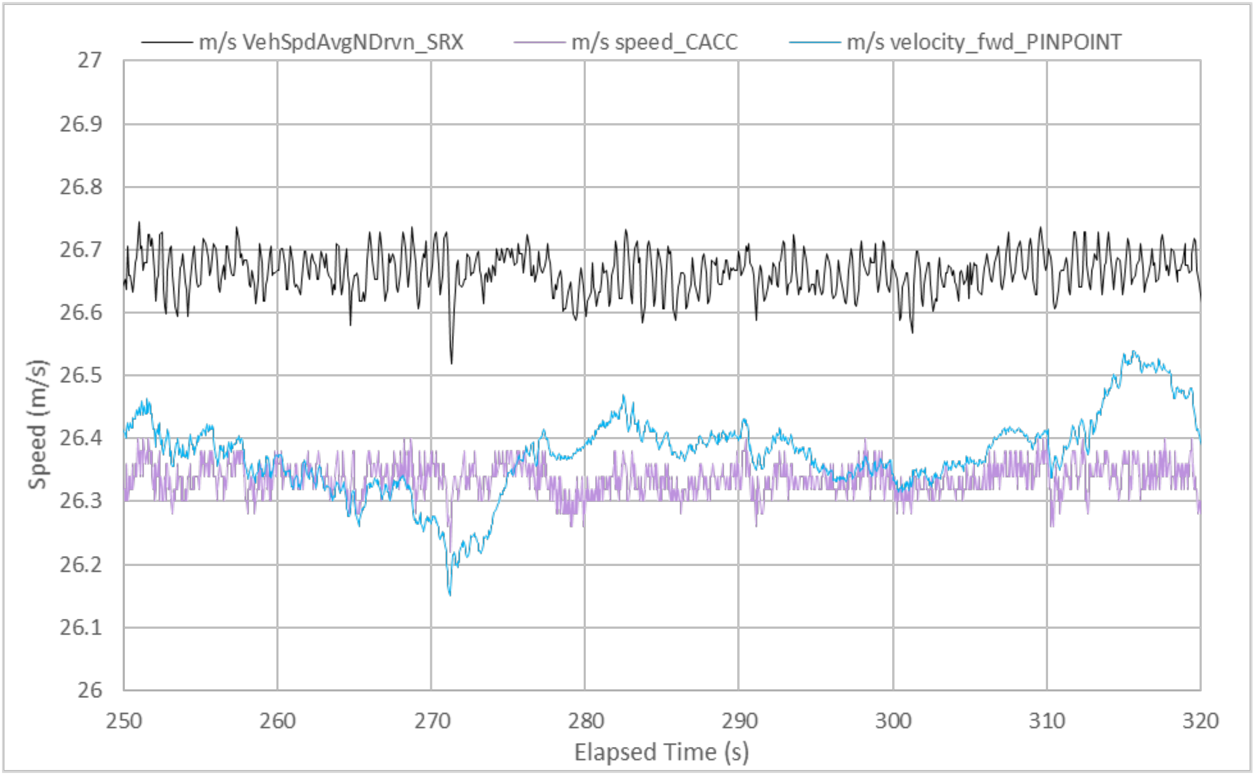

Figure 33. Speed Example (60 mph)

Table 20. Summary of In-Motion Speeds (60 mph)

Sensor	Mean (m/s)	Min (m/s)	Max (m/s)	Std Dev (m/s)
Wheel Sensors	26.66	26.52	26.77	0.03
PinPoint	26.37	26.15	26.54	0.06
CACC	26.34	26.22	26.40	0.03

5.3.3 Acceleration Data Assessment

PinPoint provided the only acceleration measurements that were identified in the available data. However, the measurements exhibited significant noise and bias when the vehicles were both at rest and in motion. Table 21 summarizes the PinPoint forward acceleration performance while at rest, which is plotted in Figure 34. Note that the acceleration measurements have significantly different bias signatures, with the green vehicle showing a time-variant increase in the bias. No PinPoint data was collected for the grey and silver vehicles during this period.

The PinPoint acceleration measurements were considered unusable in the analysis due to the significant unexplained errors. The acceleration moving average was calculated from the GPS-based speed measurements as an alternative. Table 22 provides a comparison of the PinPoint and moving average for the final constant speed period in the reference run, and the comparison is plotted in Figure 35.

Table 21. Summary of At-Rest Acceleration Measurements

Vehicle	Mean (m/s²)	Min (m/s²)	Max (m/s²)	Std Dev (m/s²)
Black	0.202	-0.012	0.924	0.030
Green	0.449	0.165	0.934	0.034
White	0.0359	-0.253	0.180	0.025

Table 22. Summary of In-Motion Acceleration Measurements (60 mph)

Sensor	Mean (m/s²)	Min (m/s²)	Max (m/s²)	Std Dev (m/s²)
PinPoint	0.118	-0.822	0.885	0.228
Moving Average	0.001	-0.500	0.700	0.157

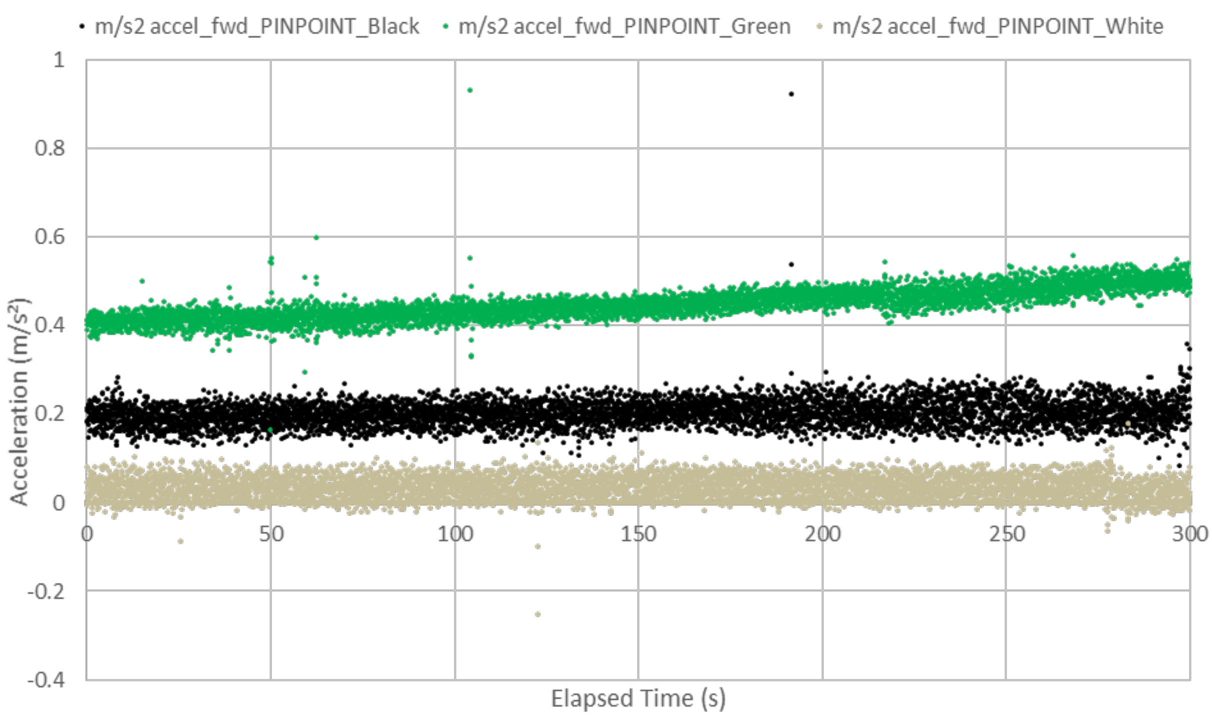

Figure 34. PinPoint At-Rest Acceleration

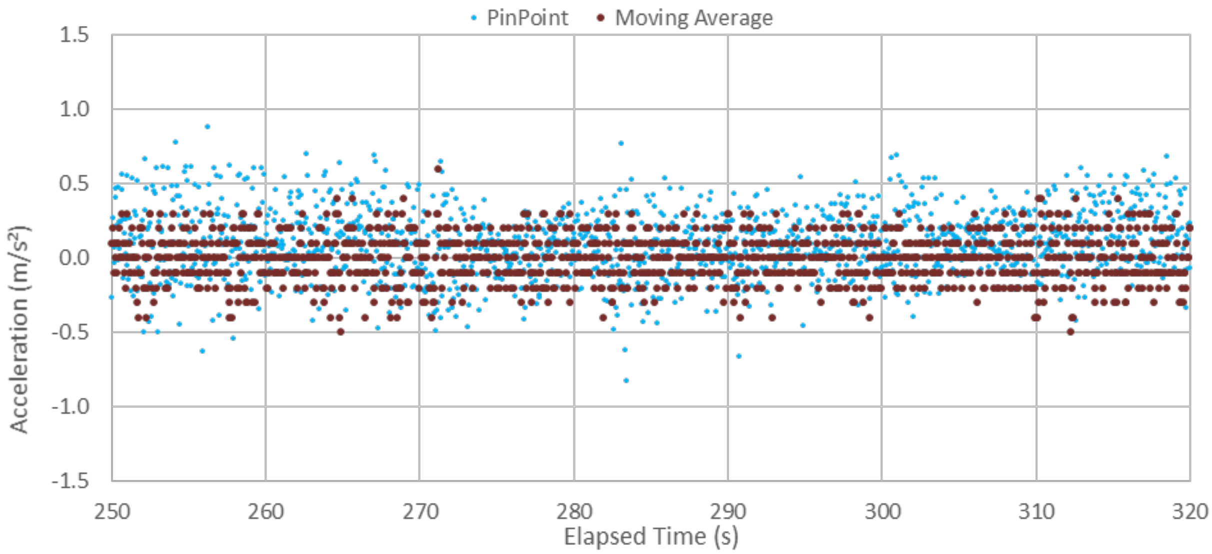

Figure 35. PinPoint In-Motion Acceleration (60 mph)

5.3.4 Torque Controller Assessment

The CACC torque controller frequently exhibited significant jumps in the commanded torque when compared to the production CC and ACC controllers. Figure 36 shows a typical ACC speed profile in black, with the commanded torque in purple. The red dots in the plot mark the vehicle brake light commands. As expected, the torque commands increase at the start of acceleration periods and decrease at the start of deceleration periods. There are fairly consistent torque levels commanded during constant speed periods. When the torque changes significantly, it is generally over a short duration, and is not instantaneous. In addition, the brake lights are only commanded during significant decelerations.

The production system performance contrasts significantly with the CACC performance, which is shown in Figure 37. CACC exhibits significant modulation between positive torque and negative torque (a torque value of -500 Nm indicates the maximum negative torque from the powertrain, after which braking is required to increase the deceleration torque). In addition, brake light commands were observed more frequently during deceleration periods and during periods of constant speed. The frequent braking and jittery motion were also observed by the vehicle occupants.

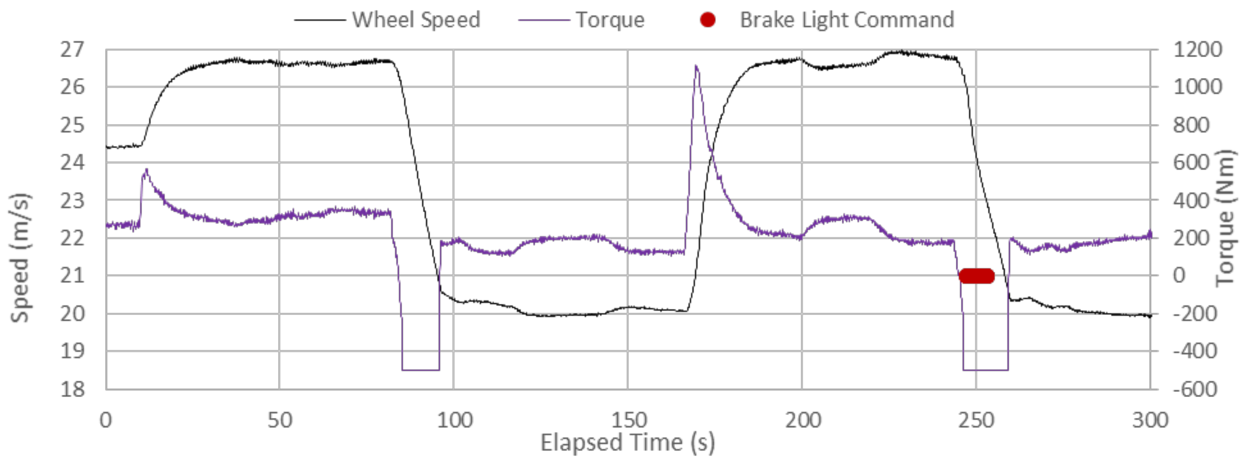

Figure 36. Production ACC LV Torque (60-45-60 mph)

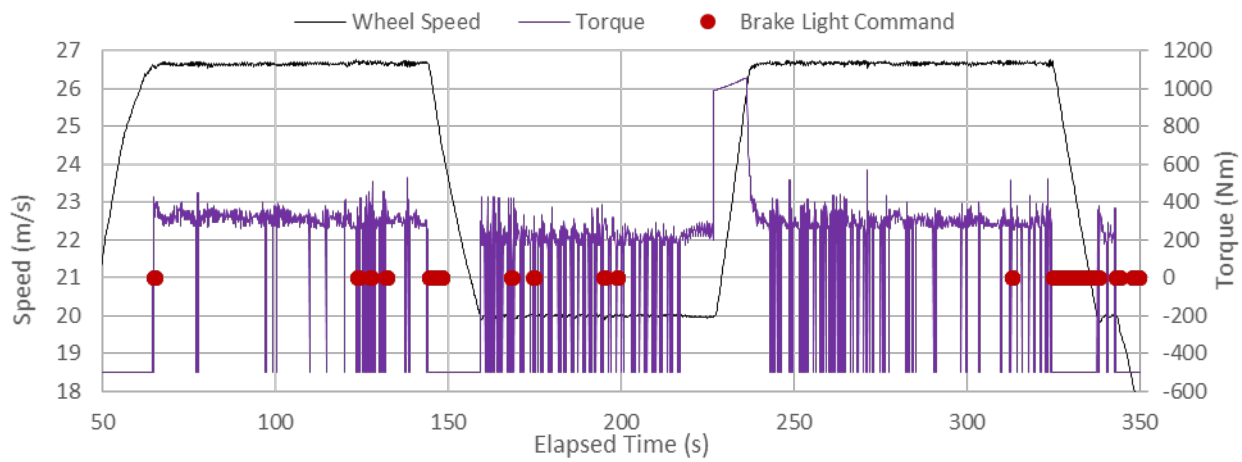

Figure 37. Custom CACC LV Torque (60-45-60 mph)

An example of the frequency of the modulation from positive to negative torque is shown for the production ACC LV controller in Figure 38, and for the CACC LV controller in Figure 39. While the production system only commanded a single change for each deceleration event, the CACC controller frequently commanded positive-to-negative torque changes 2-3 times per second, with the maximum rate in this example reaching 4 changes in a single second. This maximum rate occurred during a period of constant speed, and not during a deceleration period.

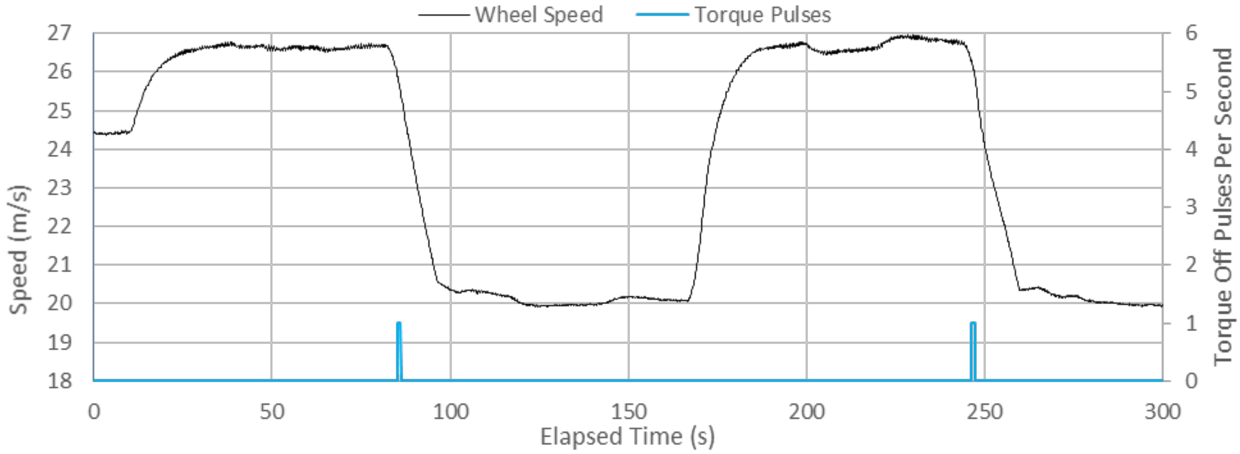

Figure 38. Production ACC LV Torque Modulation Rate (60-45-60 mph)

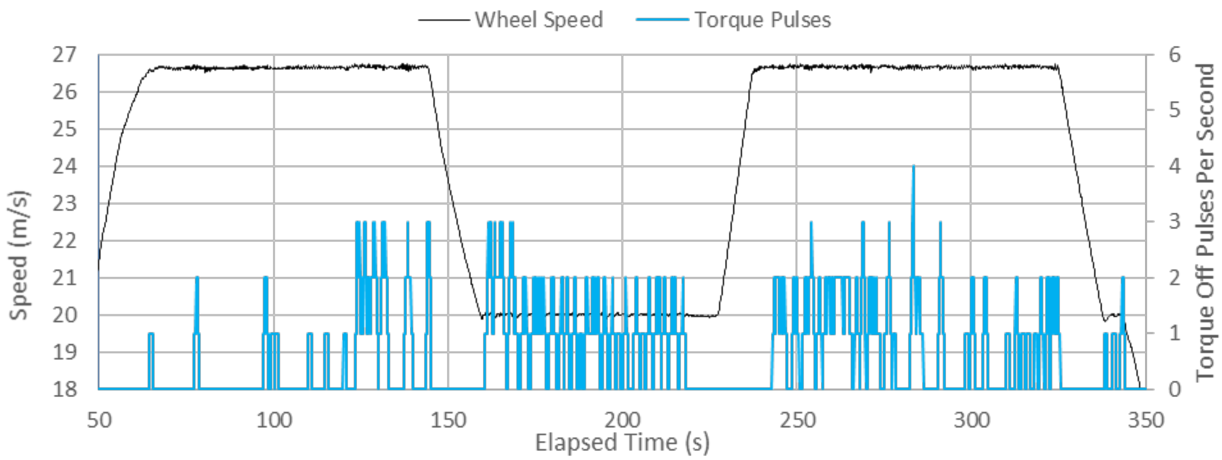

Figure 39. Custom CACC LV Torque Modulation Rate (60-45-60 mph)

The frequent torque modulation discussed above occurred consistently for the LV and FVs in each CACC run. As the abrupt jumps in torque result in abrupt changes in LV acceleration, these may contribute to string instability. As the FVs require a finite duration to respond to changes in LV motion, the more abrupt the change in LV acceleration then the more difficult it will be for FVs to maintain the prescribed time gap, resulting in string instability. In addition, the FVs will need to exceed the acceleration of the LV or continue accelerating as the LV reaches a steady speed to restore the desired gap. CACC systems should avoid excessive torque modulation when taking the comfort of the vehicle occupants into consideration.

5.4 Analysis Summary

The CACC performance assessment outlined in this report provided a consistent method for assessing the CACC proof-of-concept system. While the results identified several shortcomings in the current performance, they provide a baseline by which future systems may be evaluated.

Table 23 provides a high-level summary of the ACC and CACC following vehicle performance for each of the performance measures that were assessed. Although this assessment clearly shows that improvement is needed in the CACC design (particularly during periods when the lead vehicle is changing speeds,) the CACC system generally demonstrated an improvement over ACC. The areas of improvement included more stable speed control and faster initial response times.

Table 23. Consolidated Stability Results

Measure	Period	Criteria	Hybrid	CACC
Time Gap Errors	Deceleration	Oscillation	17.4%	15.5%
Time Gap Errors	Deceleration	Trend	Min -3.3%/Max 5.9%	Min -11.3%/Max -1.9%
Time Gap Errors	Constant Speed at 45 mph	Oscillation	4.2%	0.5%
Time Gap Errors	Constant Speed at 45 mph	Trend	Min -2.0%/Max -1.1%	Min 0.3%/Max -0.3%
Time Gap Errors	Acceleration	Oscillation	6.97%	10.33%
Time Gap Errors	Acceleration	Trend	Min -1.9%/Max 2.95%	Min -4.9%/Max 0.2%
Time Gap Errors	Constant Speed at 60 mph	Oscillation	1.2%	0.7%
Time Gap Errors	Constant Speed at 60 mph	Trend	Min 0.1%/Max -0.4%	Min -1.2%/Max 0.1%
Speed Control	Deceleration	Oscillation	n/a	n/a
Speed Control	Deceleration	Trend (m/s)	Min -1.26/Max -0.18	Min -0.45/Max -0.07
Speed Control	Constant Speed at 45 mph	Oscillation	LV 0.2%/FVs 0.7%	LV 0.2%/FVs 0.2%
Speed Control	Constant Speed at 45 mph	Trend (m/s)	Min -0.12/Max -0.03	Min -0.03/Max 0.01
Speed Control	Acceleration	Oscillation	n/a	n/a
Speed Control	Acceleration	Trend (m/s)	Min -0.04/Max 0.23	Min -0.01/Max 0.05
Speed Control	Constant Speed at 60 mph	Oscillation	LV 0.1%/FVs 0.3%	LV 0.1%/FVs 0.3%
Speed Control	Constant Speed at 60 mph	Trend (m/s)	Min -0.06/Max -0.01	Min -0.06/Max 0.00
Acceleration	Deceleration	Oscillation	n/a	n/a
Acceleration	Deceleration	Trend (m/s^2)	Min -0.54/Max 0.14	Min 0.00/Max 0.12
Acceleration	Constant Speed at 45 mph	Oscillation (m/s^2)	LV 0.13/FVs 0.09	LV 0.13/FVs 0.14
Acceleration	Constant Speed at 45 mph	Trend (m/s^2)	Min 0.06/Max -0.02	Min 0.01/Max 0.01
Acceleration	Acceleration	Oscillation	n/a	n/a
Acceleration	Acceleration	Trend (m/s^2)	Min -0.03/Max 0.05	Min -0.05/Max -0.03
Acceleration	Constant Speed at 60 mph	Oscillation (m/s^2)	LV 0.18/FVs 0.11	LV 0.17/FVs 0.18
Acceleration	Constant Speed at 60 mph	Trend (m/s^2)	Min 0.06/Max -0.07	Min 0.00/Max -0.03
Initial Response Delay	Deceleration	Initial Response Trend	2.81 s	1.65 s

Measure	Period	Criteria	Hybrid	CACC
Initial Response Delay	Acceleration	Initial Response Delay Trend	3.23 s	0.02 s
Transient Settling Durations	Deceleration	5% Following Speed Trend	12.40 s	3.73 s
Transient Settling Durations	Deceleration	0% Following Speed Trend	6.33 s	10.00 s
Transient Settling Durations	Acceleration	5% Following Speed Trend	3.62 s	3.00 s
Transient Settling Durations	Acceleration	0% Following Speed Trend	6.42 s	7.98 s

6. Conclusions and Recommendations

This report presented the results of a top-down analysis for the test and evaluation of CACC-based car platooning proof-of-concept. The goal of this analysis is to advance cooperative driving automation systems from the proof-of-concept stage to product deployment in order to realize their potential benefits in improving mobility, traffic flow stability, and safety. This type of analysis can be applied to other cooperative driving automation systems, such as eco-approach and departure at signalized intersections and speed harmonization. In the following order of the top-down analysis steps, this report:

- Described three concepts of cooperative driving automation systems and a general deployment framework for automotive systems, which points out the need for objective test procedures, performance measures and requirements, and assessment of cost-benefits and user acceptance.
- Illustrated a systems-engineering process to test and evaluate cooperative driving automation systems, which produces test procedures and performance requirements.
- Focused on the test and evaluation of vehicle platooning by delineating:
    - Various vehicle platooning concepts along an evolutionary path of enhanced system functions and capabilities
    - High-level framework for comprehensive test procedures that consist of a progressive series of tests from very basic testing under closed track and normal driving conditions to more complex test scenarios and driving conditions on a test track and public roads.
- Detailed stages of characterization test procedures that evolve from the initial test scenario concepts, first- and second-pass test-the-test procedures, to dry-run and final characterization testing.
- Developed test-the-test characterization test procedures that were used for testing the CACC-based vehicle platooning proof-of-concept to help establish performance objectives for the next-level Phase 1 prototype system. The intent of these test procedures was to provide quantitative measures of how well the CACC-based platooning application under test met its goals or design intent under normal driving conditions that included forming the platoon, vehicle following at constant time gap with varying LV speeds or at constant LV speed with varying time gaps, and dissolving the platoon.
- Specified the test scenarios and concomitant performance measures for the CACC-based five-vehicle platooning proof-of-concept that was tested on July 25 -28, 2016 on a test track at the U.S. Army's ATC in Maryland to assess the performance of the LV speed controller, CACC onboard the FVs, and car platooning. Three different vehicle test configurations were evaluated:
    - ACC– Production controllers for LV and FVs
    - Hybrid– Production controllers for FVs and custom speed controller for the LV
    - CACC– Custom controllers for LV and FVs
- Provided and discussed the results of the July 2016 tests.

Based on the results of the July 2016 test data analysis, the Volpe Center identified several issues and made associated recommendations to advance the design of the vehicle platooning proof-of-concept, improve the test and evaluation procedures, and identify the appropriate performance measures and related data elements.

6.1 Design of Vehicle Platooning Proof-of-Concept

The Volpe Center identified the following recommendations for the CACC controller capabilities, which should be considered for improving the performance and string stability in future iterations of the CACC-based vehicle platooning application:

1. When not required for safety, command smoother acceleration changes in order to reduce the extreme torque modulation, shifting, and braking events that occur in both the LV and FVs. This may include each FV easing its acceleration/deceleration as it nears the specified time gap to avoid an over/undershoot.
2. Base the LV speed profile on the concept of operations for the overall CACC system, which may include:
    - Easing the profile at the start and end of speed changes, which should contribute to smoother acceleration changes and better FV stability.
    - Relaxing the deadband when maintaining a constant speed, which should decrease the frequency of acceleration changes and contribute to better FV stability.
3. While the FV performance must still be safe during contingency braking events, overall string stability may not be a priority in these situations.
4. Make more LV and FV information available to the FVs to improve FV's independent threat assessments.

6.2 Test and Evaluation Procedures

None of the test procedures in this effort advanced past the first-pass, test-the-test level, and will require future development before being ready for more general use. Specific recommendations for moving the procedures forward are provided below for system documentation, testing safety plan, test validity criteria, and test procedures:

1. *System Documentation*: Clearly document the vehicle subsystems and controller design prior to finalizing the test and evaluation plan. This will allow the test and evaluation to be tailored to the specific control objectives.
2. *Testing Safety Plan*: There are challenges in ensuring driver safety when testing and validating the performance of the cooperative driving automation systems from under normal driving to conflict driving conditions. The following steps are recommended to address these challenges:
    - Have high confidence that the application under test can appropriately respond to pre-crash scenarios commonly encountered on the road.
    - Use simulation, such as software- and hardware-in-the-loop simulations, to advance system/subsystem performance in challenging conditions.

- Formalize the software and hardware development process of the application to include traceability and functional validation to safe level requirements following system and functional safety standards such as the International Organization for Standardization (ISO) 26262 standard[12].

3. *Test Validity Criteria*:
    - Establishing validity criteria is critical to updating the test procedures from test-the-test stages toward the dry- or final-run testing stages. The challenge is to set the test run validity criteria that account for a combination of expected system performance, test repeatability, and ability to discern whether the observed performance anomalies are caused by the failure of the application to perform to its design intent or by how the test procedures were conducted.
    - Establish and test validity criteria for V2V and V2I DSRC radio performance using some combination of packet error rates, received signal strength, and received signal delay.
    - Establish and test validity criteria for platoon stability, and adjust the number and positioning of waypoints to allow adequate time for the platoon to stabilize while balancing for testing efficiency.
4. *Test Procedures*:
    - Repeat the same vehicle sequences when comparing the ACC versus CACC controller performance. For example, the 1.4, 2.4, and 3.4 runs should maintain the same vehicle sequences in order to remove inter-vehicle performance variation from the comparison of the different controllers. Performing multiple runs with different vehicle sequences for each procedure would still permit assessing the inter-vehicle performance variations.
    - Have at least one CACC time gap set to the ACC minimum to provide a direct comparison, since ACC is limited to three production time gap options.
    - Increase the duration between speed changes to provide a larger steady-state duration. This will provide a better data set for assessing the steady-state performance. This may require iteration to determine the stabilization times.
    - Collect at least 24 hours of data with the vehicles at rest for assessment of GPS measurements (i.e., noise and bias in position, velocity, and acceleration).
    - Validate FV threat assessment capabilities and the data elements used and available from over-the-air and in-vehicle sensors.

6.3 Performance Measures and Data Elements

Finally, the following recommendations are made for performance measures and data elements:

1. Identify the detailed analysis plan (i.e., objectives, performance metrics, and criteria) and

[12] ISO 26262, titled "Road vehicles – Functional safety," is an international standard for the functional safety of electrical and/or electronic systems in production motor vehicles.

associated data elements prior to finalizing the vehicle and system design to ensure the required data elements are available.

2. Confirm that all data elements that are inputs or outputs to the controller are available for data collection. In addition, include outputs of internal data filters (e.g., smoothed acceleration) to avoid unnecessary post-processing.
3. Identify and validate fuel economy performance measures for comparison between the cooperative driving automation systems and baseline vehicle systems.
4. Ensure that the quality (e.g., noise, bias, frequency, etc.) of the data elements supports the analysis objectives. This will likely require laboratory or limited field verification of the system performance.
5. Establish procedures to verify the quality of the data collection in near-real time. Ideally, this would be performed on at least a daily basis and while there is adequate time remaining in the test campaign to repeat tests in the event critical data are not available.

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Appendix A. Detailed CACC Start-up Procedures

Vehicle Startup:

1. Turn on the CARMA platform and wait 30 s for system to boot.
2. Start the engine.
3. Unplug the AC shore power connection in the trunk.

CACC Startup:

4. Plug in to Microtik router or join the vehicle wireless network (verify color and plate number).
5. Use Putty to SSH (log in) to Secondary PC (192.168.88.10): username is stol and password is das.

Lead Vehicle:

6. Navigate (use cd command) to the /opt/leadvehicle folder(directory).
7. Run the lead vehicle script . /run.sh (Speed profile/(s) used previously will be restarted from the beginning)

Following Vehicles:

6. Navigate to the /opt/v2i folder.
7. Run the lead vehicle script ./runv2i

8. Navigate to the logs folder.
9. Verify that a new log file is generated in the logs folder and the size of the log is increasing (use the command ls –l).
10. Verify the DSRC entries in the log file (use the command tail –f [filename]. If 2 or more vehicles are connected, DSRC-O (OBU messages) and DSRC-M (MAB messages) entries will be logged.

To run previously-loaded speed profiles that have been "commented out" from presently running, the # must be removed from in front of the name in the leadvehicle.properties configuration file using the vi editor.

To load new speed profile/(s) to the secondary computer using a Windows-based machine, use the WinSCP application as follows:

1. Set File protocol: SCP Host name: 192.168.88.10 Port Number: 22 (Same username and password as above).
2. File directories are shown for the Windows PC on the left and Secondary Linux PC on the right.
3. Copy and paste (or drag and drop) the speed profiles to the Secondary PC opt/leadvehicle folder (directory).
4. End the WinSCP session.

Before the new profiles can be run, the names must be added to the speed profile section of the leadvehicle.properties configuration file using the vi editor.

Vehicle Shutdown:

1. Plug in to AC shore power connector in trunk.
2. Stop the engine.
3. Turn off the CARMA platform.

Appendix B. Concept-Phase Procedures

Table 24. Concept-Phase Test Framework

Driving Mode	Driving State	Sub & Sub_sub Category	Name of Test	Test Purpose/Action Required	Notes/Comments/Quotes	Test Number	Framework Ref.
0 - Pre-test			Profile Verification	LV prove-out of profile for use in testing with FVs. From Profile "start" LV manual then "Profile Control".	For any given Profile verify that the LV can meet the commanded speed at each and within 1 loop of the track. Without driver braking multiple loops possible/design intent.		
1.0 - Normal Driving	**1.0 - Steady State - Stability**	Constant speed and range of gap settings	Constant speed following with various gaps.	Verify platoon stability-LV speed profile set at 1st waypoint. 1-4 FV match LV speed with 4 manual gap settings.	The algorithm must maintain string stability while adjusting distance gaps. The LV speed will determine all other vehicles' speeds within the string.	1.1.1	1ai
1.0 - Normal Driving	**1.0 - Steady State - Stability**	Constant gaps and range of higher speeds - Delta V_{LV} <- 15 mph	Speed Ramp-Various predetermined gaps with 1.5 m/s^2 acceleration.	Verify platoon stability - Manually set 4 gaps from 2.0 - 0.6 seconds. LV commands 4 speeds from 30-70 mph @ 1.5 m/s^2 via profile. Initiate FV CACC mode for automatic acceleration(s) and 1-4 FVs.	The algorithm must maintain string stability during acceleration/ deceleration to reach the desired speed. After reaching profile speed, the lead vehicle transitioned into a standard ACC mode.	1.1.2	1ai
1.0 - Normal Driving	**1.0 - Steady State - Stability**	Constant gaps and range of higher speeds - with higher acceleration and Delta V_{LV} = 20 mph	Speed Ramp-Various predetermined gap with 2.5 m/s^2 acceleration and higher delta V_{LV}.	Verify platoon stability - similar to 1.1.2. Vary in 2 steps 30-60-70 and 1-4 FV. Cancel CACC w/FV brake. Vary gap from 1.0 to 0.6 for next run. 1-4 FVs.	The algorithm must maintain string stability at 2 Delta V_{LV} X 2 gaps. Observe stability with smaller gaps and larger speed changes.	1.1.2.1	1ai
1.0 - Normal Driving	**1.0 - Steady State - Stability**	Constant gaps and range of higher speeds - with higher acceleration and Delta V_{LV} = 40 mph	Speed Ramp-Various predetermined gap with 2.5 m/s^2 acceleration and higher delta V_{LV}.	Verify platoon stability - similar to 1.1.2. Vary in 1 steps 30-70 and 1-4 FV. Cancel CACC w/FV brake. Vary gap from 1.0 to 0.6 for next run. 1-4 FVs.		1.1.2.2	1ai
1.0 - Normal Driving	**1.0 - Steady State - Stability**			Level 2 capability for higher range of the accel rate for next Sub_sub level needed.		1.1.2.3	Design Level 2

Driving Mode	Driving State	Sub & Sub_sub Category	Name of Test	Test Purpose/Action Required	Notes/Comments/Quotes	Test Number	Framework Ref.
1.0 - Normal Driving	**1.0 - Steady State - Stability**	Constant gaps and range of lower speeds - Delta V_{LV} <- 15 mph	Speed Ramp- Various predetermined gaps with 1.5 m/s^2 deceleration.	Verify platoon stability - Manual set gaps from 2.0 - 0.6 seconds, LV commands speeds from 70-30 mph, initiate CACC mode, automatic deceleration(s) and 1-4 FVs	The algorithm must maintain string stability during acceleration/deceleration to reach the desired speed. After reaching profile speed, the lead vehicle transitioned into a standard ACC mode.	1.1.3	1ai
1.0 - Normal Driving	**1.0 - Steady State - Stability**	Constant gaps and range of lower speeds - with higher deceleration and Delta V_{LV} = 20 mph	Speed Ramp- 2 predetermined gap with 2.0 m/s^2 deceleration.	Verify stable deceleration. Similar to 1.1.3 start profile at high speed and decrease from 70-50-30 mph with higher automatic deceleration and higher Delta V_{LV}. Vary gap from 1.0 to 0.6 for next run. 1-4 FVs.	The algorithm must maintain string stability at 2 Delta V_{LV} X 2 gaps. Observe stability with smaller gaps and larger speed changes.	1.1.3.1	1ai
1.0 - Normal Driving	**1.0 - Steady State - Stability**	Constant gaps and range of lower speeds - with higher deceleration and Delta V_{LV} = 40 mph	Speed Ramp- 2 predetermined gap with 2.0 m/s^2 deceleration.	Verify stable deceleration. Similar to 1.1.3.1 start profile at high speed and decrease from 70-30 mph. Vary gap from 1.0 to 0.6 for next run. 1-4 FVs.	The algorithm must maintain string stability at 1 Delta V_{LV} X 2 gaps. Observe stability with smaller gaps and larger speed changes.	1.1.3.2	1ai
1.0 - Normal Driving	**1.0 - Steady State - Stability**			Design test capability for Level 2 higher range of decel rates.		1.1.3.3	Design Level 2
1.0 - Normal Driving	**1.0 - Steady State - Stability**			Design test capability for Level 2 algorithm modeling/simulation data needs		1.1.4	Design Level 2
1.0 - Normal Driving	**1.0 - Steady State - Stability**			Design test capability to study or verify need for better engine versus requested torque to avoid downshifting other jerk factors.		1.1.4.1	Design Level 2

Driving Mode	Driving State	Sub & Sub_sub Category	Name of Test	Test Purpose/Action Required	Notes/Comments/Quotes	Test Number	Framework Ref.
1.0 - Normal Driving	**2.0 - Transient State - Platoon Forming and Leaving**	Platoon formation - 4 constant speeds various gaps from back	CACC Formation - from back	Verify platoon stability during formation of a 4 FV platoon with more than 1 FV joining that platoon at 4 constant speeds and various gaps. 1-3 FVs joining at the rear of an already formed platoon. All FVs approaching in the same lane as existing FV.	COO: 1-3 FVs would join an existing 3-1 FV platoon operating at a CACC controlled constant target speed and gap. The existing platoon is at speeds and gaps from 1.1.1. Joining FV would be between ± 5 mph and ± 0.5 second gaps but not less than a 0.6 second gap or over 70 mph.	1.2.1	1ai
1.0 - Normal Driving	**2.0 - Transient State - Platoon Forming and Leaving**	Platoon formation - 4 constant speeds various gaps in middle of string	CACC Formation - from side	Verify platoon stability during formation of a 4 FV platoon with 1 FV joining that platoon at the 2nd or 3rd platoon locations from the right adjacent lane of an already formed 3 FV platoon. FV_{ahead} and $FV_{entering}$ drivers via radio confirm that blind zone detection (BZD) is not activated, $FV_{entering}$ moves into CACC lane and commands CACC on.	COO: If blind zone detection of FV_{ahead} (verifying gap behind it) and $FV_{entering}$ (verifying gap behind it) are both "off," then okay to enter. $FV_{entering}$ moves into CACC lane and commands "CACC on". The existing platoon is at speeds and gaps from 1.1.1. For "test-the-test," gaps will be limited 2.0 and 1.5 seconds and speed to 45 mph. BZD requirement expected to be in the range of 12 - 14 m.	1.2.1.1	1ai
1.0 - Normal Driving	**2.0 - Transient State - Platoon Forming and Leaving**	Platoon leaving - 4 constant speeds various gaps from back	CACC Leaving - from back	Verify platoon stability during FV leaving a 4 FV platoon. One to four FVs are instructed by the LV driver via radio to leaving the platoon at the same time by depressing the brake and moving into the right adjacent lane.	Speeds, gaps and "bail" maneuvers from 1.1.1. For "test-the-test," gaps will be limited 2.0 and 1.5 seconds and speed to 45 mph. Multiple formations around the track to be studied.	1.2.2	1ai
1.0 - Normal Driving	**2.0 - Transient State - Platoon Forming and Leaving**	Platoon leaving - 4 constant speeds various gaps in middle of string	CACC Leaving - from side	Verify platoon stability during FV leaving a 4 FV platoon. One FV leaving the platoon from the 1st then 2nd then 3rd platoon position. The FV changes lanes into the right adjacent lane and then depresses the brake.	Speeds, gaps and "bail" maneuvers from 1.1.1. For "test-the-test," gaps will be limited 2.0 and 1.5 seconds and speed to 45 mph. Multiple formations around the track to be studied.	1.2.2.1	1ai

Driving Mode	Driving State	Sub & Sub_sub Category	Name of Test	Test Purpose/Action Required	Notes/Comments/Quotes	Test Number	Framework Ref.
2.0 - Conflict Driving	**1.0 - Lead Vehicle Conflict**	Forward Threat	AV Stopped - 4 constant speeds various gaps	Verify platoon stability-LV speed profile set at 1st waypoint. 1-4 FV match LV speed with 4 manual gap settings. The AV is parked in the right hand lane 100 m forward of the 1st waypoint and not visible to the LV's radar. At the 1st way point the platoon is also in the right hand lane. The LV should start to slow the platoon before the required deceleration exceeds the 2.5 m/s^2 limit of the ACC system.	The algorithm must maintain string stability while adjusting distance gaps. The LV speed will determine all other vehicles' speeds within the string. Speeds and gaps from 1.1.1. For "test-the-test," gaps will be limited 2.0 and 1.5 seconds and speed to 45 mph.	2.1.1.1	1aii
2.0 - Conflict Driving	**1.0 - Lead Vehicle Conflict**	Forward Threat	AV Moving at a slower speed - 4 constant speeds various gaps	Verify platoon stability-LV speed profile set at 1st waypoint. 1-4 FV match LV speed with 4 manual gap settings. The AV is moving 20 mph slower in the right hand lane 100 m forward of LV. At the 1st waypoint the platoon is also in the right hand lane. **The LV should start to slow the platoon before the required deceleration exceeds the 2.5 m/s^2 limit of the ACC system.**	The algorithm must maintain string stability while adjusting distance gaps. The LV speed will determine all other vehicles' speeds within the string. Speeds and gaps from 1.1.1. For "test-the-test," gaps will be limited 2.0 and 1.5 seconds and speed to 45 mph.	2.1.1.2	1aii
2.0 - Conflict Driving	**1.0 - Lead Vehicle Conflict**	Forward Threat	AV Decelerating - 4 constant speeds various gaps			2.1.1.3	1aii
2.0 - Conflict Driving	**1.0 - Lead Vehicle Conflict**	Lateral Threat	Cut in-DSRC Equipped			2.1.2.1	1aii
2.0 - Conflict Driving	**1.0 - Lead Vehicle Conflict**	Lateral Threat	Cut in- Not DSRC Equipped			2.1.2.2	1aii

Table 25. Concept-Phase Safety Mitigation Procedures

Location	Sub Test	Name of Test	Test Purpose/Action Required	LV	FV1	FV2	FV3	FV4	Comments/Notes	Test Number
Garage or Parking Lot	1	Red Button Continuity Check	Verify with an ohm meter that CACC components are not connected to SRX CAN buses "when pushed".	X	X	X	X	X	Required once per vehicle.	0.1.1.1
Garage or Parking Lot	2	Air Bag and Curtain Deployment Area Obstruction	Visually inspect that the area in front of all air bags or curtains are not obstructed by installed components.	X	X	X	X	X	All CACC equipment and test instrumentation should be installed in its intended location before this test is conducted.	0.1.1.2
Garage or Parking Lot	3	Installed Component Secure mounting Verification - cargo area	Visually inspect that all components installed in the cargo area are securely attached to the vehicle.	X	X	X	X	X	Conceptualize a 35 mph crash or roll-over to assess acceptable method of attachment	0.1.1.3
Garage or Parking Lot	4	Installed Component Secure mounting and clearance to control functions verification - driver and passenger areas.	Visually inspect that all components installed in the passenger areas are securely attached to the vehicle and do not interfere with controls for CACC, ACC, brakes, transmission, or steering.	X	X	X	X	X	Required daily if vehicle in use.	0.1.1.4
Garage or Parking Lot	5	Vehicle tire pressure, wear and liquids safety checks	Verify the tire pressure is to vehicle manufacturers recommended setting, that no liquids of spills are around the vehicle and that tire tread height is above wear bars and even across tread width.	X	X	X	X	X	Required daily if vehicle in use.	0.1.1.5
Low Speed Track Testing	1.0	Red Button CACC Disable functional Verification	While the vehicle under test (VUT) is going a stead speed of 40 mph with a 2 second gap in CACC mode. Verify that the CACC system is disabled and the vehicle is returned to driver factory controls when the Red Button is pushed.	X	X	X	X	X	Required once per vehicle. Not done daily, due to difficulty in clearing error codes generated.	0.1.2.1.0
Low Speed Track Testing	2.0	ACC System - ISO Disable functional verification	While the vehicle under test is going a stead speed of 40 mph with a 2 second gap in ACC, verify that the following actions disable the ACC system and notifies the driver: Depressing the brake pedal, switching the steering wheel on/off switch to off.	X	X	X	X	X	ISO requirement to disable ACC with brake or steering wheel switch.	0.1.2.2.0
Low Speed Track Testing	2.1	ACC System - GM ACC response to stopped/stationary vehicle verification	While the vehicle under test is going a stead speed of 40 mph with a 2 second gap in ACC, verify the system response to a stopped (never seen moving) AV in the same lane. Be prepared to swerve out of the lane if the ACC system does not respond in time to bring the vehicle to a stop.	X	X	X	X	X	ISO does not require an ACC system to respond to a stationary target. Verify the GM system capability.	0.1.2.2.1

Location	Sub Test	Name of Test	Test Purpose/Action Required	LV	FV1	FV2	FV3	FV4	Comments/Notes	Test Number
Low Speed Track Testing	2.2	ACC System - ISO driver commanded throttle will override ACC automatic control	While the vehicle under test (VUT) is going a stead speed of 40 mph with a 2 second gap in ACC and an AV < 2 seconds ahead, verify the system response to the VUT driver accelerating by depressing the throttle as if to pass the AV. Be prepared to swerve out of the lane of the AV irrespective of any control system attempts to control the VUT.	X	X	X	X	X	ISO requirement to gives the driver authority to override the ACC system engine power control. If the power demand of the driver is greater than that of the ACC system automatic braking shall be disengaged with an immediate brake force release. A driver intervention on the accelerator pedal shall not lead to a significant delay of response to driver's input.	0.1.2.2.2
Low Speed Track Testing	2.3	ACC gap and accel/decel verification	VUT with ACC set to 40 mph approaches AV in the same lane the AV is moving at 35 mph. VUT gap setting at low setting. After VUT stabilizes behind AV, AV then W.O.T. accels to 50 mph. When VUT stabilizes at 40 mph run is complete. Repeat test at gap settings of middle and high.						Verify range of gaps, accels and decels allowed by standard ACC.	0.1.2.2.3
Low Speed Track Testing	2.4	ACC "in-lane", "out-of-lane" specification/verification	Some "test-the-test" experience required to develop concept-of-operation.						Verify how much a vehicle must be in the lane of the VUT as it comes into and departs a lane. Expected value coming in of 1.0 meters inside lane marking of a 3.6 m lane with VUT on centerline of lane.	0.1.2.2.4
Low Speed Track Testing	3.0	CACC/TORC Disable functional verification	Repeat ACC (0.1.2.2.0) test while in CACC mode	X	X	X	X	X	ISO requirement for brake and steering wheel switch deactivation.	0.1.2.3.0
Low Speed Track Testing	3.1	CACC/TORC gap and accel/decel verification	Some "test-the-test" experience required to develop concept-of-operation (COO)	X	X	X	X	X	Verify range of gaps, accels and decels allowed.	0.1.2.3.1
Low Speed Track Testing	3.2	CACC not capable of meeting commanded profile parameters	Some "test-the-test" experience required to develop COO	X	X	X	X	X		0.1.2.3.2
Low Speed Track Testing	4.0	Forward Collision Alert - performance and capability	Verify braking authority and speeds	X	X	X	X	X	Reference owner's manual details.	
Low Speed Track Testing	5.0	Lane Departure Warning - performance and capability	Verify warning zones, speeds and headings	X	X	X	X	X	Reference ISO standards for zone definitions.	

Table 26. Concept-Phase Mini-Design Verification Procedures

Function Number	Function Description	Mini CACC Design Verification: Description	Mini CACC Design Verification: Test Number (i)	Mini CACC Design Verification: Test Number (ii)	Mini CACC Design Verification: Time (minutes)	CACC Design Verification: Description	CACC Design Verification: Time (minutes)
1	Speed profiles from 29-70 mph.	30 & 45 mph	0.2.1.3	0.2.1.5	20	60 & 70 mph	20
2	Acceleration and deceleration rate in speed profile, 1 per Waypoint. Gap 1200 ms	30-45-30-45 and 1.5 & 2.5 m/s^2	0.2.1.9	0.2.2.9	20	30 -45-60-70 and 1.5 & 2.5 m/s^2	20
3	Once started on a test run, the lead vehicle shall be able to run continuously around the track for multiple laps at 45 mph	Multi-lap: Run clockwise and counter clockwise	0.2.1.5		15		
4	The lead vehicle shall be able to start or terminate a test run anywhere on the track. Do multiple laps at 30 mph	Use brake disable and restart at next waypoint? or previous waypoint?	0.2.1.3		30		
5	Single use waypoints	Combine DV_LV1 & 2			25		
6	From a stop - 0 speed					Design level 2	
7	Millisecond gaps from 500-64999	1.1.1b - 45 2.0, 1.5, 1, 0.6			20	1.1.1c - 60 2.0, 1.5, 1, 0.6	20
8	Millisecond gaps for factory ACC switch = 65000: Verify Gaps low, med, high at FV CACC initiation only. Verify using steady state 45 mph.	Multiple starts with low, med., high gap settings manually	0.2.1.5		20		
9	Red Button CACC Disable functional Verification @ 30 mph	0.1.2.1.0	0.2.2.0		10		
10	ACC System - ISO Disable functional verification @ 45 mph	0.1.2.2.0			10		
11	ACC System - GM ACC response to stopped/stationary vehicle verification					0.1.2.2.2	15
12	ACC System - ISO driver commanded throttle will override ACC automatic control					0.1.2.2.3	15
13	Modified M_DV_ LV2 Test-Acceleration and deceleration rate in speed profile, 1 per Waypoint. Gap 3000 ms	30-45-30-45 and 2.5 & 4.5 m/s^2			20		
14	ACC "in-lane", "out-of-lane" specification/ verification. Recommend dropping test-no ISO required specification.					0.1.2.2.5	
				Total for sequence:	190		90

Appendix C: Data Elements

C.1. Data Binning Approach

The raw CACC and SRX data present three challenges:

- At the point-of-collection, the data is asynchronous, both within individual vehicles and between vehicles.
- At the point-of-collection, the nominal data frequencies are between 10 and 100 Hz (observed frequencies were 1, 10, 15, 20, 25, 50, 80, and 100 Hz).
- The CANBUS data is not precisely metered to the nominal frequencies (e.g., for the 20 Hz data, in a given one second period slightly more or less than 20 measurements could occur).

To perform the analysis, it was necessary to synchronize the data to allow direct comparison between all measurements. The following sections provide a brief overview of the approach that was used to synchronize the data.

C.1.1. Interpolating Values or Rounding Timestamps

Two methods were identified for synchronizing the data: interpolating the measurements to a common time bin, and rounding the timestamps to common time bins without modifying the values. As the majority of the data was available at a relatively high frequency (20 Hz), it was determined that the second approach was sufficient for the analysis outlined in this report. As a result, all data was binned into 20 Hz intervals (0.00 s, 0.05 s, 0.10 s, 0.15 s, etc.) by rounding the UTC timestamp associated with each element. A limitation of this method is that the time of the bin should not be used when high precision is required; for this reason, the original timestamps are retained in the dataset.

C.1.2. Truncation or Rounding

For the sake of consistency, all timestamps were rounded to the nearest time bin. This ensures that any measurement in a time bin is without ± 0.025 s of the original timestamp. It should be noted that this approach results in bins containing 'future data.' For the analysis outlined in this report this presents no issues, but this approach may not be ideal for some simulation applications.

C.1.3. Binning Non-Uniform Data Rates

As the CANBUS data can be collected at rates slightly below or above the nominal rate, the following rules were applied for the time bins:

- **Lower-frequency data results in blank fields.**[13] Examples:
  - If CAN messages are nominally 20 Hz but only 19 are received in a given second, one bin will be empty.
  - If CAN messages are nominally 10 Hz, generally every other bin will be empty.

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[13] An exception is the 1 Hz brake light data, for which each message is repeated until the next message arrives. This generally results in a single brake light value being repeated 20 times.

- **Higher-frequency data was discarded when two values rounded to the same time bin. In this case, the nearest value was retained.** For example, if CAN messages are nominally 20 Hz but 21 elements are received in a given second, for the two elements that rounded to a single bin the furthest measurement from the bin time was discarded. Note that this can occur even when there are 20 or fewer elements in a given second because the imprecise metering of CANBUS data can result in two messages rounding to a single bin time.

C.1.4. Binning BSM Data with More Than One Associated Timestamp

Every element has at least one UTC timestamp that can be used as the basis for the binning. Some elements, such as those derived from the Basic Safety Message (BSM), can have two sources (primary is the ADMAS network observation, secondary is the PRISM Radio Log files (PCAPS)). In almost every case, the ADMAS UTC timestamp was used. Only in cases where the ADMAS data was not available do is PRISM the chosen source of time for binning purposes. In addition, the BSM fields (columns from setSpeed_CACC thru elevation_CACC) have multiple observation times (one that is the sent time used for binning, and multiple receive times; one for each receiving vehicle). For example, if BLACK is the sender, the BLACK_ADMAS_TOO (BLACK Time of Observation by ADMAS) is used to bin the BSM data.

C.1.5. Blank Data Elements

In the event that a data element was determined to be unavailable for any reason, it will appear as a blank cell (the associated timestamp should also be blank). If the data element was available but zero, it will correctly appear as a zero (in this case, the associated timestamp is populated).

C.2. Data Elements

This section lists the elements that are included in the primary dataset that was collected and used for the analysis in this report (the 'CACCcoredata' files). The elements are sorted in the order that they appear in the dataset.

Table 27. CACCcoredata File Data Elements

Element	Units	Codes	Original Frequency	Description
veh_color	n/a	n/a	n/a	The color of the vehicle
bin_utc_time_s	s	n/a	n/a	The bin time is the nearest 20 Hz interval to the timestamp associated with the element. This is in Unix time (UTC seconds since January 1, 1970)
setSpeed_CACC	m/s	n/a	20	Set speed for the ACC system
throtPos_CACC	%	n/a	20	Percentage throttle application
grpMode_CACC	n/a	n/a	20	Mode of CACC group
grpManDes_CACC	n/a	n/a	20	Desired maneuver of CACC group
grpManID_CACC	n/a	n/a	20	Current maneuver of CACC group
longitude_CACC	deg	n/a		The longitude of the vehicle from the CACC system
vehID_CACC	n/a	n/a	20	Unique ID of vehicle, Corresponds to last 3 digits of license plate by default
frntCutIn_CACC	n/a	n/a	20	If there is a non-CACC vehicle cut into the platoon in front of the vehicle
vehGrpPos_CACC	n/a	n/a	20	Vehicle's position in its group
vehFltMode_CACC	n/a	n/a	20	Vehicle's fault mode
vehManDes_CACC	n/a	n/a	20	Vehicle's desired maneuver
vehManID_CACC	n/a	n/a	20	Vehicle's current maneuver
distToPVeh_CACC	m	n/a	20	Distance to preceding vehicle
relSpdPVeh_CACC	m/s	n/a	20	Relative speed to preceding vehicle
distToLVeh_CACC	m	n/a	20	Distance to lead vehicle
relSpdLVeh_CACC	m/s	n/a	20	Relative speed to lead vehicle
desTGapPVeh_CACC	s	n/a	20	Desired time-gap to preceding vehicle
desTGapLVeh_CACC	s	n/a	20	Desired time-gap to lead vehicle
estDisPVeh_CACC	m	n/a	20	Estimated distance gap to preceding vehicle

Element	Units	Codes	Original Frequency	Description
estDisLVeh_CACC	m	n/a	20	Estimated distance gap to lead vehicle
desSpeed_CACC	m/s	n/a	20	Desired speed of vehicle
secMark_CACC	ms	n/a	20	Milliseconds elapsed in current minute
speed_CACC	m/s	n/a	20	The speed of the vehicle from the CACC system
heading_CACC	deg	n/a	20	The heading of the vehicle from the CACC system
yaw_rate_CACC	deg/s	n/a	20	The yaw rate of the vehicle from the CACC system
latitude_CACC	deg	n/a	20	The latitude of the vehicle from the CACC system
elevation_CACC	m	n/a	20	The elevation of the vehicle from the CACC system
black_prism_too	s	n/a	20	Black vehicle Time Of Observation at the PRISM logger
black_admas_too	s	n/a	20	Black vehicle Time Of Observation at the ADMAS logger
black_prism_rssi	-	n/a	20	Black vehicle Received Signal Strength reported in the PRISM log entries. These appear with each incoming BSM
black_prism_sos	s	n/a	20	Black vehicle Speed of Service (latency) as measured between PRISM log observations
black_admas_sos	s	n/a	20	Black vehicle Speed of Service (latency) as measured between ADMAS observations
white_prism_too	s	n/a	20	White vehicle Time Of Observation at the PRISM logger
white_admas_too	s	n/a	20	White vehicle Time Of Observation at the ADMAS logger
white_prism_rssi	-	n/a	20	White vehicle Received Signal Strength reported in the PRISM log entries. These appear with each incoming BSM.
white_prism_sos	s	n/a	20	White vehicle Speed of Service (latency) as measured between PRISM log observations
white_admas_sos	s	n/a	20	White vehicle Speed of Service (latency) as measured between ADMAS observations
silver_prism_too	s	n/a	20	Silver vehicle Time of Observation at the PRISM logger

Element	Units	Codes	Original Frequency	Description
silver_admas_too	s	n/a	20	Silver vehicle Time of Observation at the ADMAS logger
silver_prism_rssi	-	n/a	20	Silver vehicle Received Signal Strength reported in the PRISM log entries. These appear with each incoming BSM
silver_prism_sos	s	n/a	20	Silver vehicle Speed of Service (latency) as measured between PRISM log observations
silver_admas_sos	s	n/a	20	Silver vehicle Speed of Service (latency) as measured between ADMAS observations
grey_prism_too	s	n/a	20	Grey vehicle Time of Observation at the PRISM logger
grey_admas_too	s	n/a	20	Grey vehicle Time of Observation at the ADMAS logger
grey_prism_rssi	-	n/a	20	Grey vehicle Received Signal Strength reported in the PRISM log entries. These appear with each incoming BSM
grey_prism_sos	s	n/a	20	Grey vehicle Speed of Service (latency) as measured between PRISM log observations
grey_admas_sos	s	n/a	20	Grey vehicle Speed of Service (latency) as measured between ADMAS observations
green_prism_too	s	n/a	20	Green vehicle Time of Observation at the PRISM logger
green_admas_too	s	n/a	20	Green vehicle Time of Observation at the ADMAS logger
green_prism_rssi	-	n/a	20	Green vehicle Received Signal Strength reported in the PRISM log entries. These appear with each incoming BSM
green_prism_sos	s	n/a	20	Green vehicle Speed of Service (latency) as measured between PRISM log observations
green_admas_sos	s	n/a	20	Green vehicle Speed of Service (latency) as measured between ADMAS observations

Element	Units	Codes	Original Frequency	Description
throttle_ovr_flag_CACC_MAB	n/a	True: Throttle pedal overriding ACC False: Throttle pedal not overriding ACC	50	Flag indicating whether the ACC throttle command is being overridden by the throttle pedal
accelmodulefeedback_utc	s	n/a	50	The UTC for the throttle_ovr_flag_CACC_MAB element, this is in Unix time (UTC seconds since January 1, 1970)
max_accel_CACC	m/s^2	n/a	50	The maximum acceleration allowed to achieve the desired speed
command_mode_CACC	n/a	0: Disable ACC system (including base vehicle ACC) 1: robotic “wrench effort” control 2: robotic speed control	50	Enumeration used to dictate how control should be applied
override_enabled_CACC	n/a	True: Enable robotic override, False: Disable robotic override	50	Flag to enable robotic override of the ACC system
speed_command_CACC	m/s	n/a	50	The desired speed for the vehicle. This will be used when the command_mode is 2
accelcontrol_utc	s	n/a	50	The UTC for the max_accel, command_mode, override_enabled, and speed_command elements, this is in Unix time (UTC seconds since January 1, 1970)
VehSpdAvgNDrvn_SRX	m/s	n/a	10	The speed of the vehicle
ppei_vehicle_speed_and_distance_utc	s	n/a	10	The UTC for the VehSpdAvgNDrvn element, this is in Unix time (UTC seconds since January 1, 1970)
FLRRTrk1Range_SRX	m	n/a	15	The range, as measured by radar, to the preceding vehicle
FLRRTrk1RangeRate_SRX	m/s	n/a	15	The range rate, as measured by radar, to the preceding vehicle

Element	Units	Codes	Original Frequency	Description
FLRRTrk1Azimuth_SRX	deg	n/a	15	The angle, as measured by radar, to the preceding vehicle, if available
f_lrr_obj_track_1_utc	s	n/a		The UTC for the forward long range radar elements, this is in Unix time (UTC seconds since January 1, 1970)
ACCDrvrSeltdSpd_PreCACC_SRX	m/s	n/a	25	ACC driver set speed from the SRX CAN Bus prior to being modified by the CACC
ACCHdwyStg_PreCACC_SRX	n/a	3 = Headway Setting 3 (Far) 2 = Headway Setting 2 (Medium) 1 = Headway Setting 1 (Near)	25	Driver ACC/FCA gap setting (near, medium, far)
ACCAct370_PreCACC_SRX	n/a	1 = true 0 = false	25	ACC active status
adaptive_cruise_disp_stat_hs_utc	s	n/a	25	The UTC for the ACC display elements, this is in Unix time (UTC seconds since January 1, 1970)
AcActPos_PreCACC_SRX	%	n/a	100	Accelerator pedal position from the SRX data prior to being modified by the CACC
Engine_RPM_SRX	RPM	n/a	100	The angular rate of the vehicle engine, in revolutions per minute (RPM)
ppei_engine_general_status_1_utc	s	n/a	100	The UTC for the Engine RPM element, this is in Unix time (UTC seconds since January 1, 1970)
BrkPdlPos_PreCACC_SRX	%	n/a	80	Brake pedal position from the SRX CAN Bus prior to being modified by the CACC
ptei_brake_apply_status_utc	s	n/a	80	The UTC for the brake pedal element, this is in Unix time (UTC seconds since January 1, 1970)
BrkLightFlag_SRX	n/a	1 = on 0 = off	1	A flag indicating whether the vehicle brakes are being applied (either manually or via automation)
exterior_lighting_hs_utc	s	n/a	1	The UTC for the brake light element, this is in Unix time (UTC seconds since January 1, 1970)
StrWhAng_SRX	+/- 180 deg	n/a	100	Steering wheel angle from the SRX data

Element	Units	Codes	Original Frequency	Description
ppei_steering_wheel_angle_utc	s	n/a		The UTC for the steering wheel element, this is in Unix time (UTC seconds since January 1, 1970)
TransGear_SRX	n/a	n/a	40	The current gear of the transmission from the SRX data. This is useful because the vehicle performance may appear momentarily unstable when the vehicle is changing gears
proprietary_501_utc	s	n/a	40	The UTC for the transmission gear elements, this is in Unix time (UTC seconds since January 1, 1970)
global_lat_PINPOINT	deg	n/a	20	Latitude of the vehicle's origin
global_long_PINPOINT	deg	n/a	20	Longitude of the vehicle's origin
global_yaw_PINPOINT	deg	n/a	20	Rotation about the Down axis of the vehicle. Note this will be identical to the local_yaw_deg
local_north_PINPOINT	m	n/a	20	Location of the vehicle's origin in the North direction relative to the arbitrary local frame origin
local_east_PINPOINT	m	n/a	20	Location of the vehicle's origin in the East direction relative to the arbitrary local frame origin
horizontal_pos_accuracy_PINPOINT	m	n/a	20	Horizontal position accuracy of the navigation solution. This is computed as the magnitude of the norm of the North and East accuracy vectors. The true position should lie within a circle centered on the current position value whose radius is equal to this horizontal accuracy
velocity_fwd_PINPOINT	m/s	n/a	20	Velocity of the vehicle in the Forward direction (vehicle's frame)
velocity_right_PINPOINT	m/s	n/a	20	Velocity of the vehicle in the Right direction (vehicle's frame)
velocity_accuracy_PINPOINT	m/s	n/a	20	Accuracy of the velocity solution. This is computed as the magnitude of the norm of the Forward, Right, and Down accuracy vectors
accel_fwd_PINPOINT	m/s^2	n/a	20	Acceleration of the vehicle in the Forward direction (vehicle's frame)

Element	Units	Codes	Original Frequency	Description
accel_right_PINPOINT	m/s^2	n/a	20	Acceleration of the vehicle in the Right direction (vehicle's frame)
global_pose_pinpoint_utc	s	n/a	20	The UTC for the PinPoint global frame data, this is in Unix time (UTC seconds since January 1, 1970)
global_pose_admas_utc	s	n/a	20	The UTC for the ADMAS global frame data, this is in Unix time (UTC seconds since January 1, 1970)
local_pose_pinpoint_utc	s	n/a	20	The UTC for the PinPoint local frame data, this is in Unix time (UTC seconds since January 1, 1970)
local_pose_admas_utc	s	n/a	20	The UTC for the ADMAS local frame data, this is in Unix time (UTC seconds since January 1, 1970)
acc_pinpoint_utc	s	n/a	20	The UTC for the PinPoint acceleration elements, this is in Unix time (UTC seconds since January 1, 1970)
acc_admas_utc	s	n/a	20	The UTC for the ADMAS acceleration elements, this is in Unix time (UTC seconds since January 1, 1970)
filt_pinpoint_utc	s	n/a	20	The UTC for the PinPoint filter data, this is in Unix time (UTC seconds since January 1, 1970)
filt_admas_utc	s	n/a	20	The UTC for the ADMAS filter data, this is in Unix time (UTC seconds since January 1, 1970)
admas_avg_lat_acc	g	n/a	20	The average lateral acceleration from ADMAS
admas_avg_long_acc	g	n/a	20	The average longitudinal acceleration from ADMAS
admas_avg_vert_acc	g	n/a	20	The average vertical acceleration from ADMAS
research_bus_injected_torque_CACC_MAB	-	n/a	20	The CACC injected torque command. To convert to Nm: T [Nm] = 0.125 * [research_bus_injected_torque_CACC_MAB] – 22534
acc_axle_torque_cmd_axle_torque_request	Nm	n/a	20	The commanded torque command
ppei_adaptive_cruise_axl_trq_req_utc	s	n/a	20	The UTC for the torque data, this is in Unix time (UTC seconds since January 1, 1970)

C.3. Additional Data Elements for Future Analysis

The following is a short list of additional data elements that are recommended for future assessments.

Table 28. Additional Data Elements for Future Analysis

Element	Rationale
CACC Commanded Acceleration	The CACC commanded acceleration. This should reflect both the commands for the powertrain and the braking system
CACC Commanded Torque	If the acceleration is achieved via torque commands, this should be included. It should reflect both the commands for the powertrain and the braking system
Acceleration	A more accurate forward acceleration measurement is required for detailed analysis due to the significant noise and bias in the current PinPoint element
Battery Current	Improved diagnostics of system performance
Battery Voltage	Improved diagnostics of system performance
Air Conditioner Compressor Status	A/C switching on/off can affect the engine load
Instantaneous Fuel Economy	Insight into the efficiency of the CACC controller
Odometer	Additional information for assessment
Throttle Plate Position	Insight into the engine response to commands
Accelerator Effective Position	Insight into the engine response to commands
Brake Axle Torque Command	Insight into CACC controller performance during braking
Road Load Nominal Axle Torque	Insight into CACC controller performance
Position in Platoon	Will assist with automating analysis
Packet Error Rate (BSM Completion Rate-%)	Will assist with diagnosing BSM issues

C.4. Observed Data Element Issues

The following is a list of the issues that were observed with the data elements in the July 2016 test data analysis. For each issue, a non-exhaustive list of examples is provided.

1. **Data elements were unavailable in the CANBUS data.**
   - Loss of data from full sub-system(s) (e.g., PinPoint, CACC, SRX)
     - Mid-run
       - 20160726 1738 BLACK: The PinPoint data stops after 310s. Note that the related CACC elements freeze at this time, which implies a PinPoint system issue, and not a data logging issue. The test team confirmed that this is not an ADMAS issue because ADMAS continued to record network traffic past the point when PinPoint traffic drops out (17:43:10). The related carmadatalog elements also freeze at this time, which supports that this is not a data logging issue, but the MAB continued to output its log data at 20 Hz to the Host after the event occurred.
       - 20160727 1319 BLACK: The PinPoint data stops after 238s and exhibits the same behavior as the previous issue.
     - Full run
       - 02160725 1740 WHITE: No SRX data was available. The testing team confirmed that the ADMAS was on during this time period; however there is no CANBUS data from this ADMAS. The test team suspects that there was a cabling issue in the vehicle between the ADMAS and the CANBUS interface.

- 20160727 1337 BLACK: No PinPoint and limited CACC data was available. The test team suspects this was due to an issue with either the Pinpoint or the host controller.
- 20160728 1445 SILVER: No PinPoint data was available. The test team confirmed that the SILVER PinPoint module was outputting nothing but zeros during this time window, with the exception of altitude, which was consistently -0.46 meters.

- Loss of data for specific elements
  - 20160725 1712 BLACK: No gear data (TransGear_SRX and TransEstGear_SRX). This was due to an issue in the CANBUS reduction software and it has been resolved.

2. **Incorrect units**
   - research_bus_injected_torque_CACC_MAB was not in useable units. Conversion to Nm was confirmed using the following equation:
     T [Nm] = 0.125 * [research_bus_injected_torque_CACC_MAB] – 22534

   This calculation will be performed for future datasets.

3. **Many CACC elements are integers in the CANBUS data, and this occurs in every data set**
   - 20160728 1504 ALL: desSpeed_CACC, distToPVeh_CACC, and distToLVeh_CACC are integers. The test team confirmed that these are integer values in the specification for the CACC messages.

4. **The distance to the previous vehicle is often not populated, and the distance to the lead vehicle appears to be the distance to the previous vehicle in every run.**
   - 20160728 1522 GREEN, GREY, SILVER, WHITE: distToPVeh_CACC and distToLVeh_CACC show the same values. The carmadatalog shows the same behavior. The test team confirmed that this is an issue with the raw CACC data, and not the collection system.

5. **Some runs have incorrect CACC GPS data.**
   - 20160728 1445 SILVER: heading_CACC, yaw_rate_CACC, latitude_CACC, and longitude_CACC, elevation_CACC are populated with all zeros or constant values (9.00E-07 for longitude, -6554.100098 for elevation). The PinPoint data is also missing for this run, and the carmadatalog shows the same behavior. The test team suspects that this was due to a PinPoint issue, and confirmed that the SILVER PinPoint module was outputting nothing but zeros during this time window, with the exception of altitude, which was consistently -0.46 meters.

6. **Several of the CACC data elements are incorrect in every run.**
   - 20160728 1522 GREEN, GREY, SILVER, WHITE: vehGrpPos_CACC is the same value (‘2’) for each vehicle. The corresponding carmadatalog element (veh_pos_in_grp) shows the same behavior (all ‘2’), which suggests a CACC issue, and not data collection. The test team confirmed that this is the format of the raw CACC data.

7. **The WHITE vehicle has ~16 s delay in the speed_CACC element for the Hybrid runs. This element appears to have no delay during the ACC and CACC runs.**
   - 20170727 1516 WHITE: Occurs throughout the run
   - 20170727 1627 WHITE: Occurs throughout the run
   - 20170727 1634 WHITE: Occurs throughout the run
   - 20170727 1641 WHITE: Occurs throughout the run

8. The GREY PinPoint local frame appears to rotate counter clockwise.

- 20160728 1456 GREY: No impact on system performance was observed
- 20160728 1504 GREY: No impact on system performance was observed
- 20160728 1515 GREY: No impact on system performance was observed
- 20160728 1522 GREY: No impact on system performance was observed

Appendix D: July 2016 Proof-of-Concept Performance Plots

This section contains plots of GPS Speed and Time Gap for all five vehicles (LV, FV1, etc.) on each ACC, Hybrid, and CACC run assessed during the July, 2016 testing.

Figure 40. ACC 20170727 1558 Speed and Time Gap

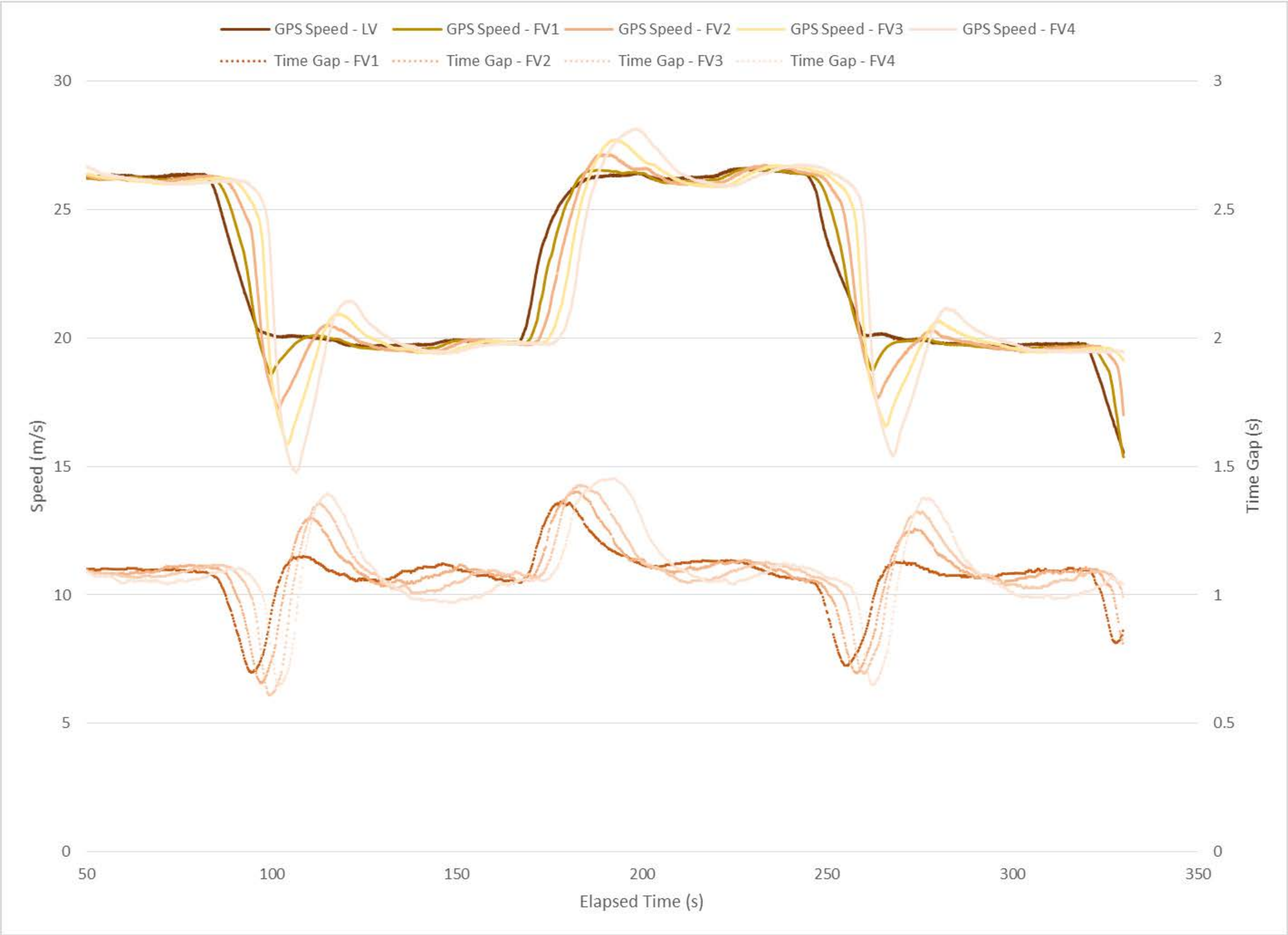


Figure 41. Hybrid 20170727 1516 Speed and Time Gap

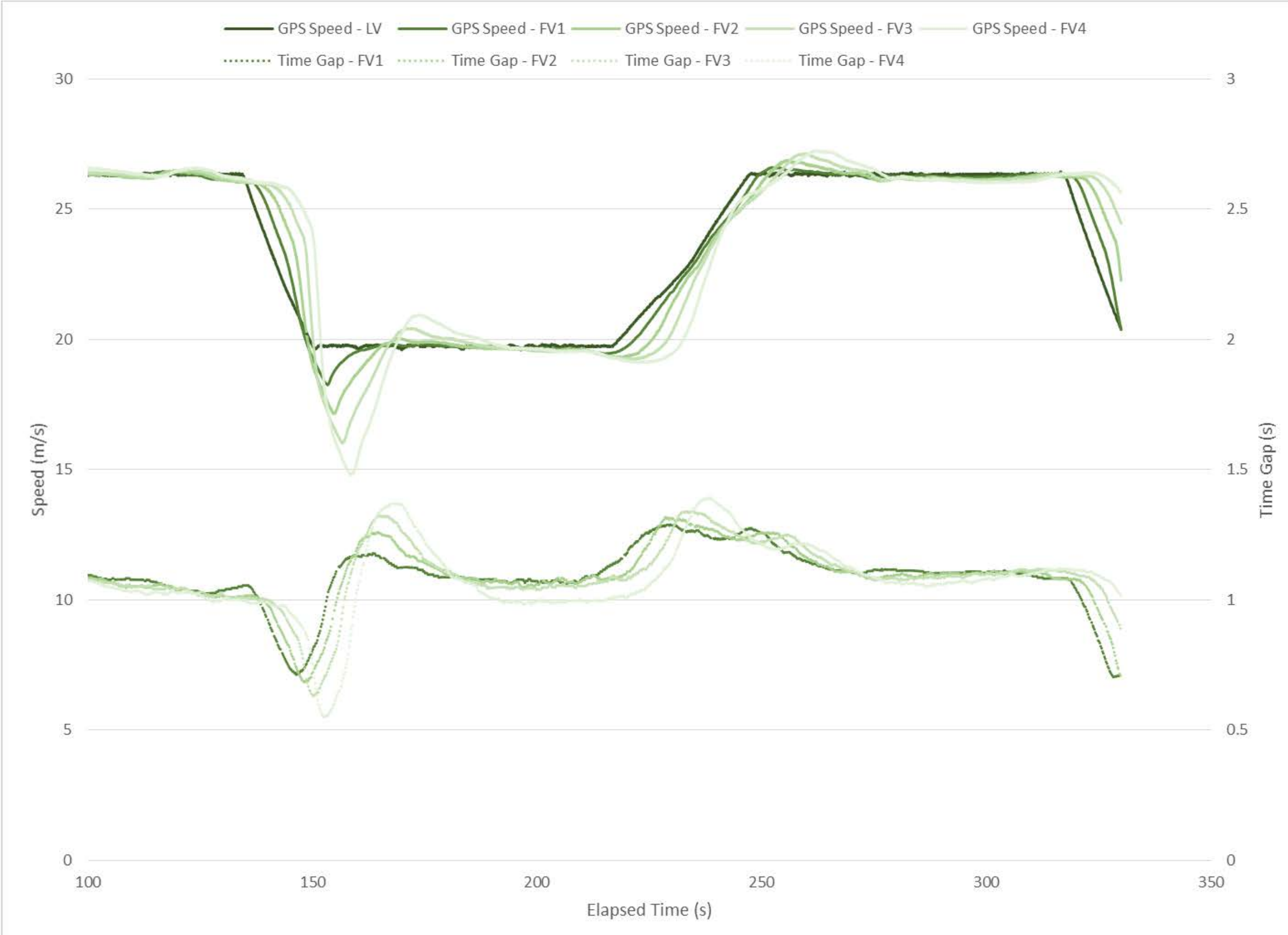


Figure 42. Hybrid 20170727 1627 Speed and Time Gap

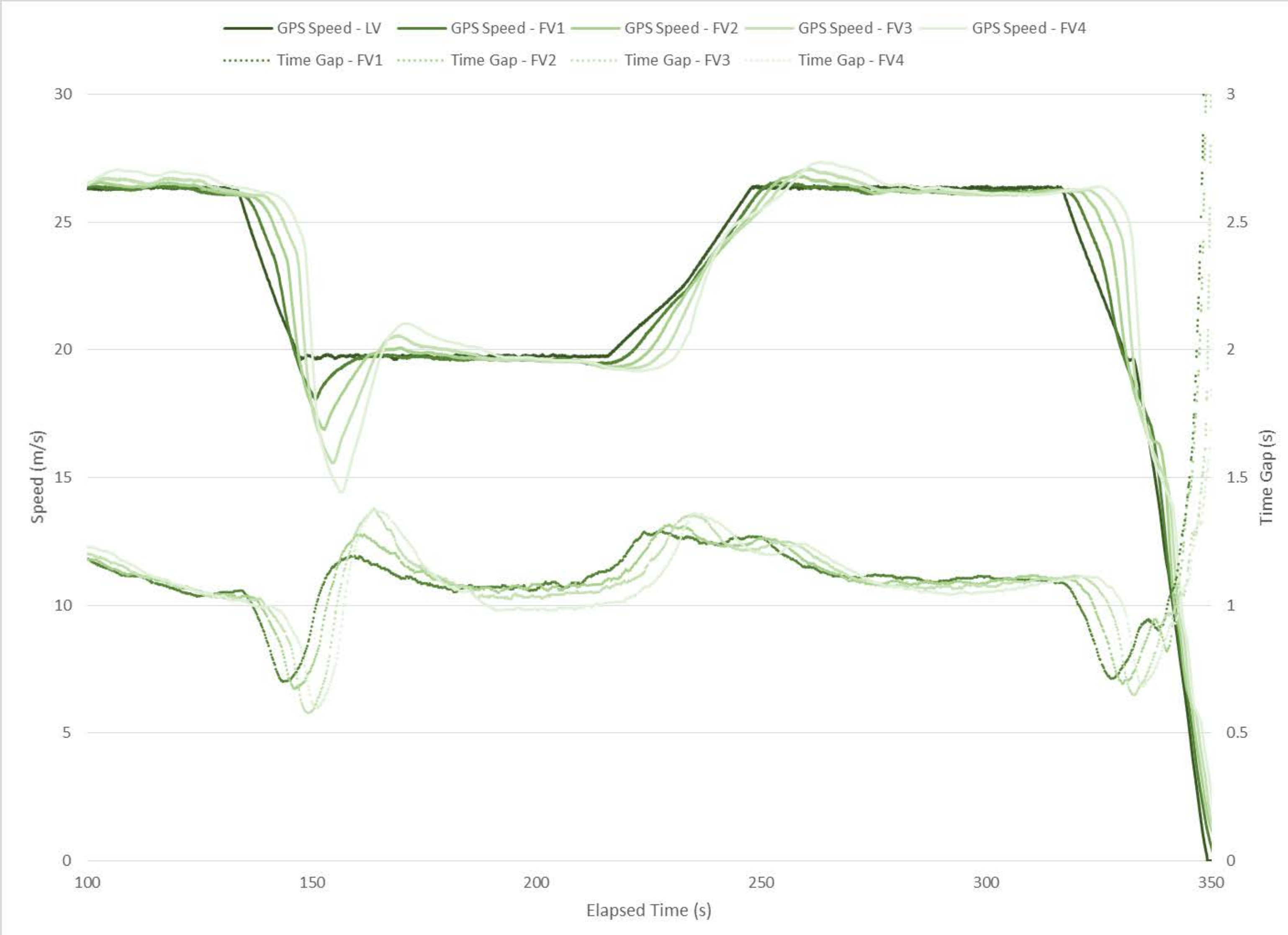


Figure 43. Hybrid 20170727 1634 Speed and Time Gap

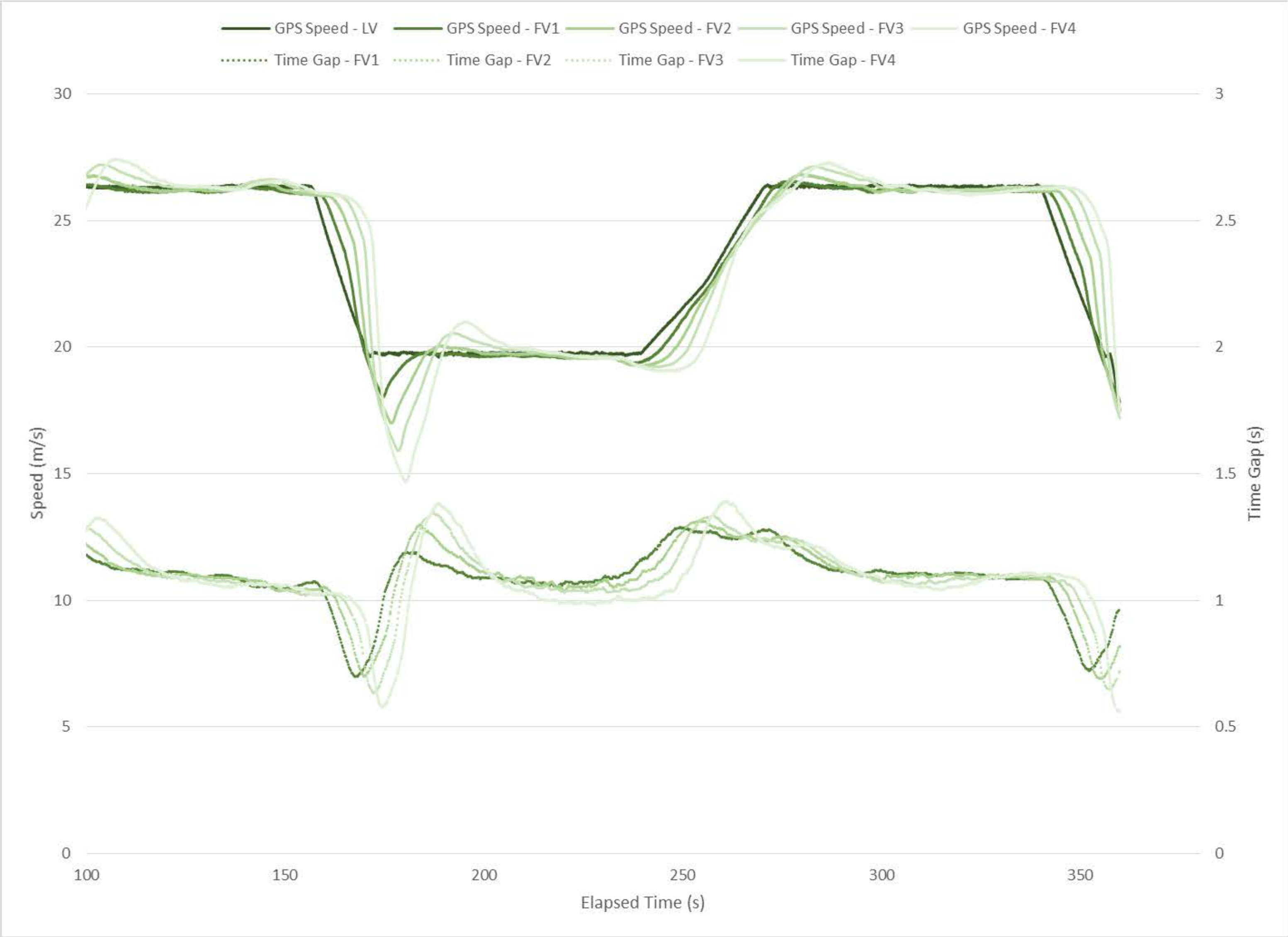


Figure 44. Hybrid 20170727 1641 Speed and Time Gap

Figure 45. CACC 20170728 1456 Speed and Time Gap

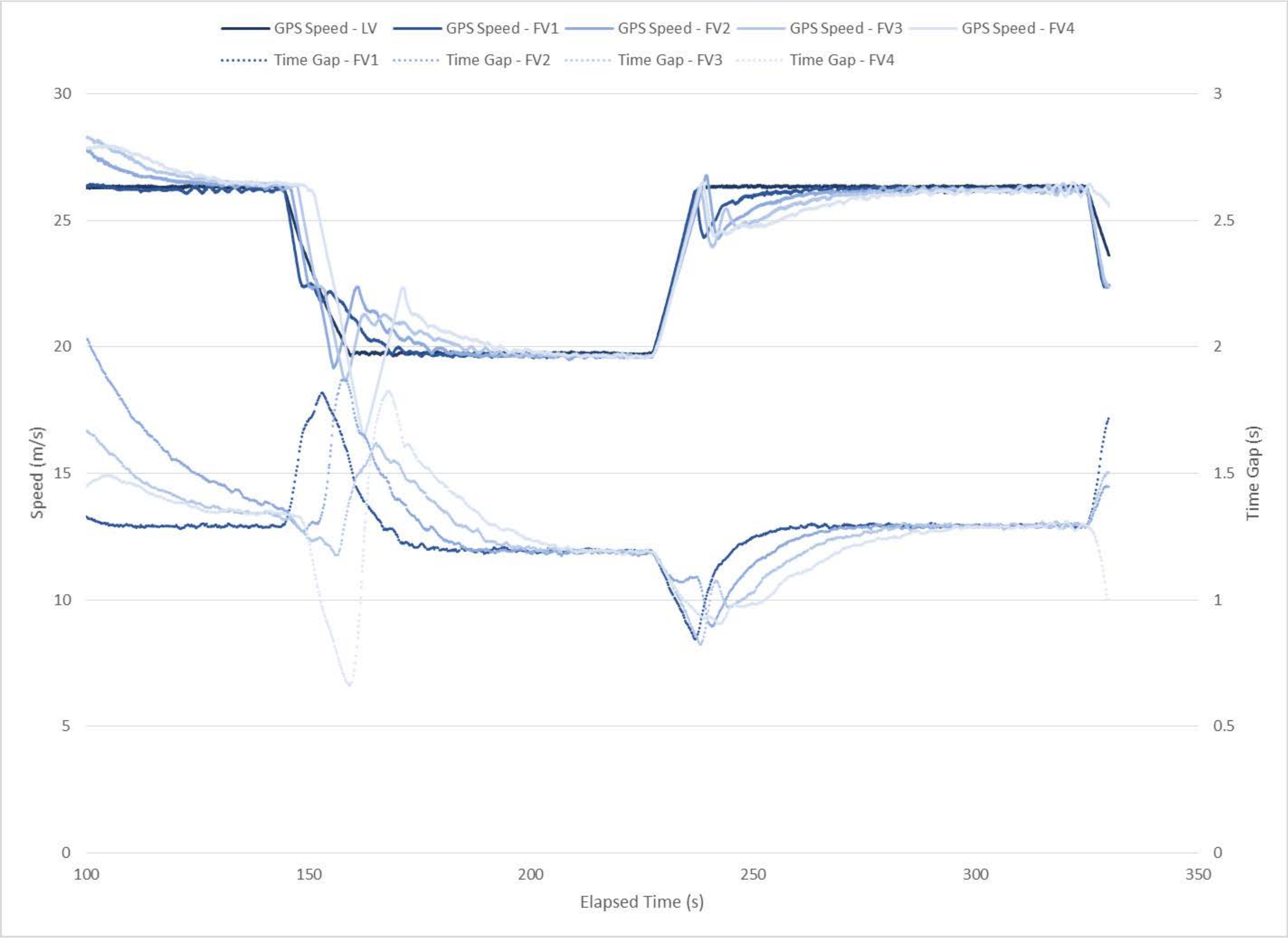


Figure 46. CACC 20170728 1504 Speed and Time Gap

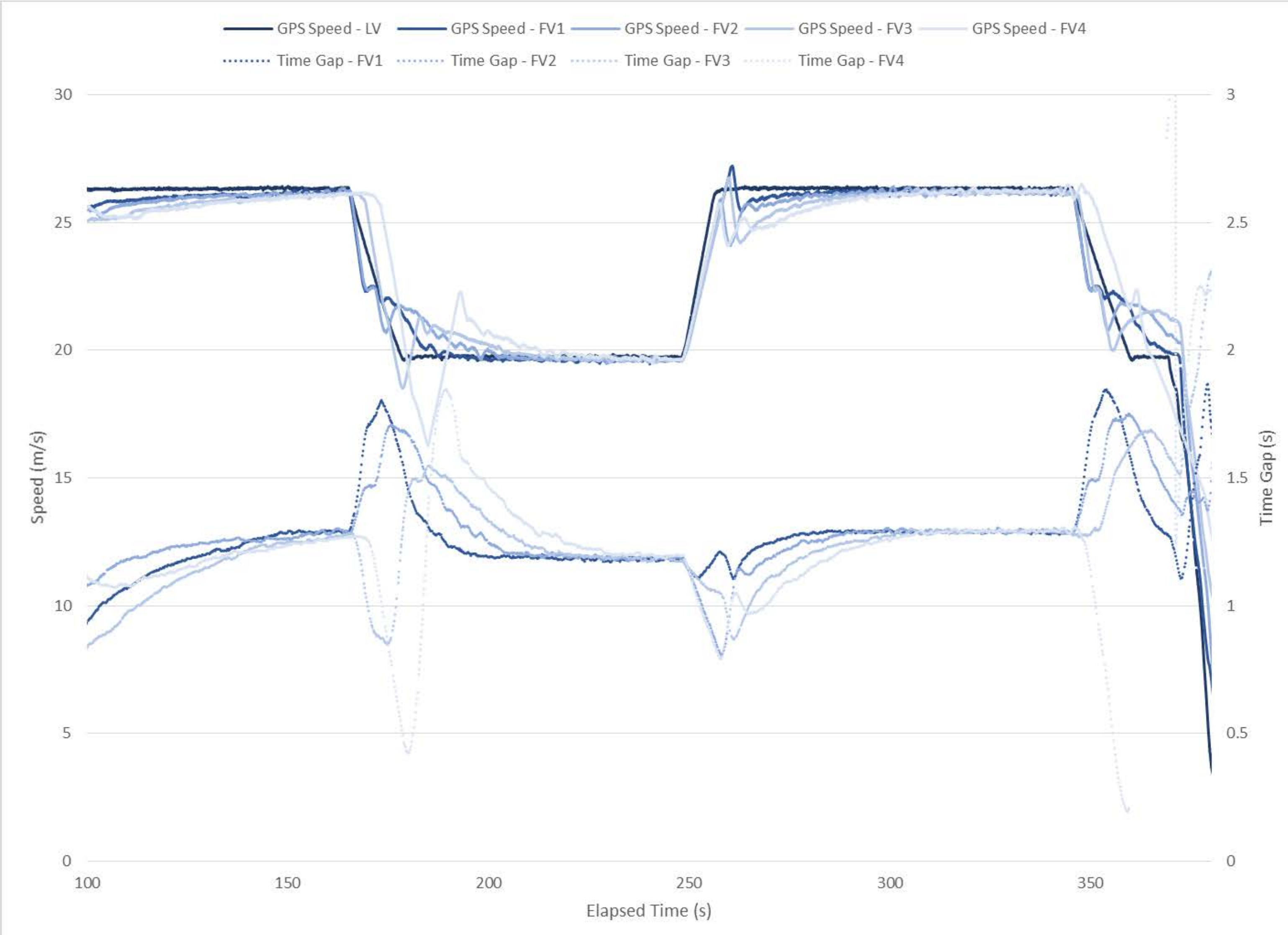


Figure 47. CACC 20170728 1515 Speed and Time Gap

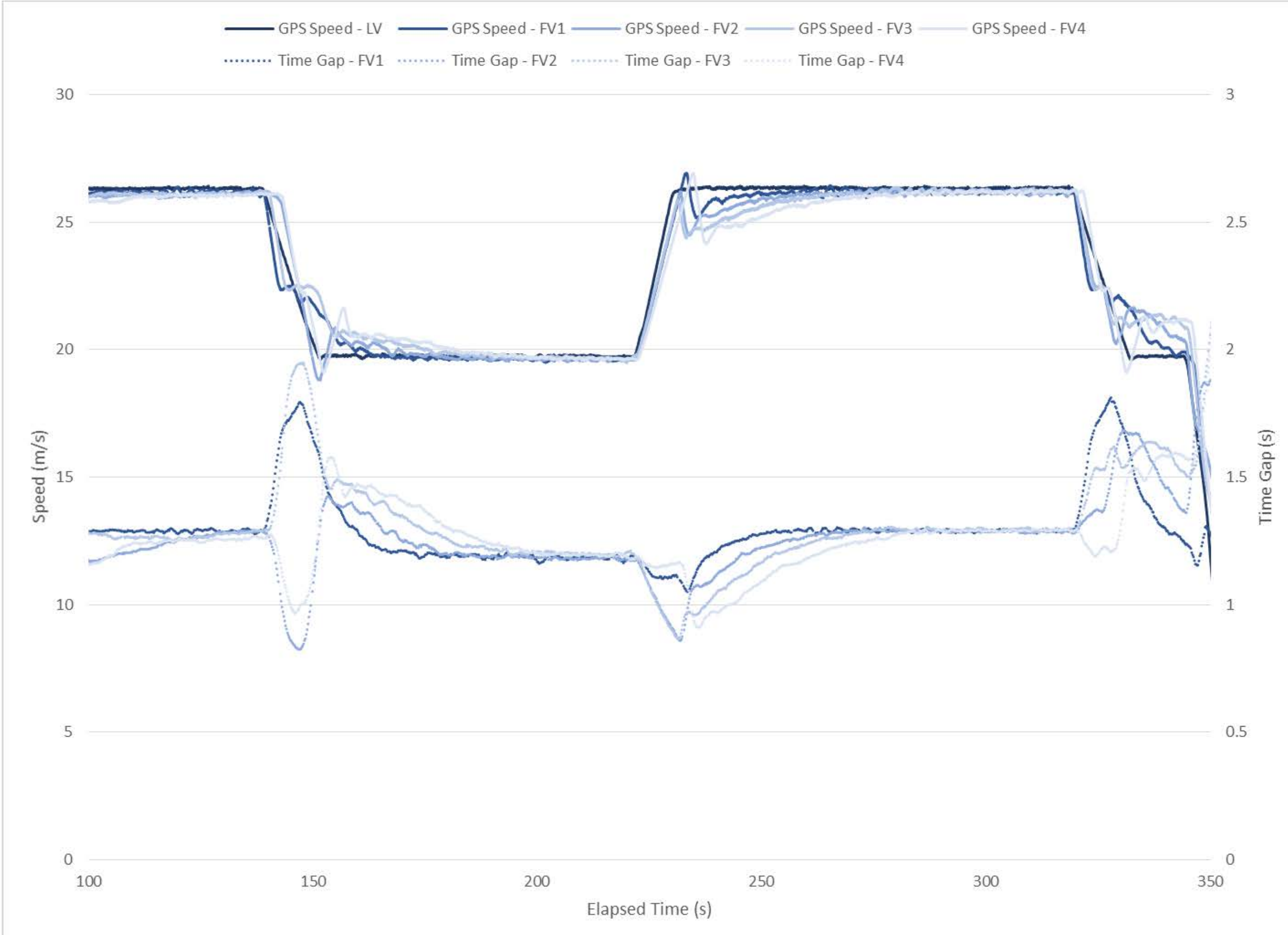
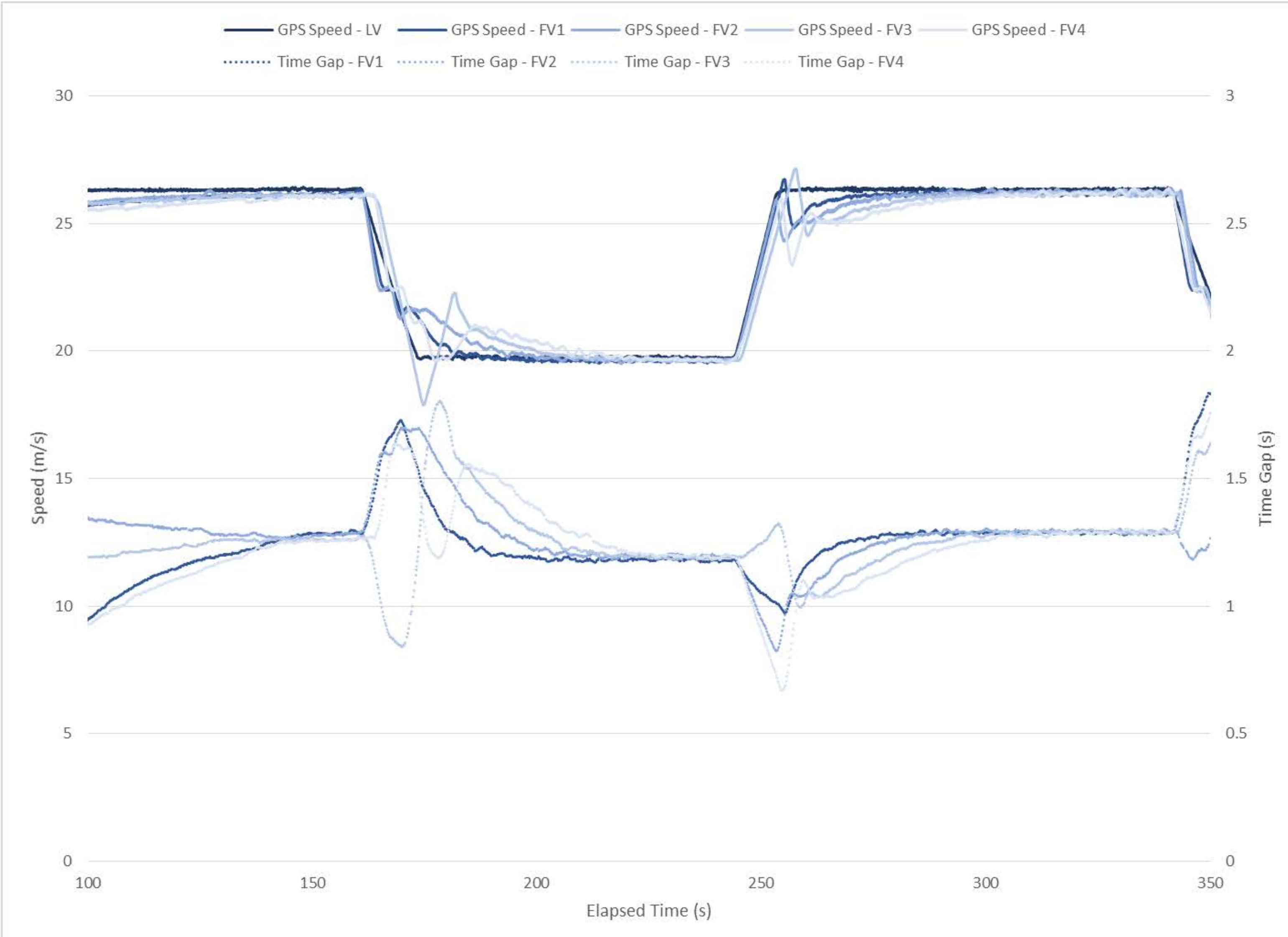


Figure 48. CACC 20170728 1522 Speed and Time Gap



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