CARMA Testing and Evaluation of Research Mobility Applications

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July 2019

DOT-VNTSC-FHWA-19-15

Prepared for:
Federal Highway Administration
Turner-Fairbank Highway Research Center
Office of Operations Research & Development | Enabling Technologies
6300 Georgetown Pike, McLean, VA 22101

U.S. Department of Transportation
John A. Volpe National Transportation Systems Center

Notice

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 2019	3. REPORT TYPE AND DATES COVERED October 2017 – July 2019

4. TITLE AND SUBTITLE CARMA Testing and Evaluation of Research Mobility Applications	5a. FUNDING NUMBERS HW40B1, SE239/SE240
6. AUTHOR(S) Tim Tiernan*, Pavle Bujanovic**, Philip Azeredo*, Wassim G. Najm*, and Taylor Lochrane**	5b. CONTRACT NUMBER DTFH6116V00026
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) *Advanced Vehicle Technology Division, V337 Volpe National Transportation Systems Center U.S. Department of Transportation Cambridge, MA 02142	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FHWA-19-15
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) ** Office of Operations Research & Development | Enabling Technologies Turner-Fairbank Highway Research Center Federal Highway Administration 6300 Georgetown Pike, McLean, VA 22101	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report presents the results of a test and evaluation effort that assessed the performance of three research mobility applications implemented by the open-source second-generation Cooperative Automation Research Mobility Applications (CARMA2) platform. This platform enables the research and development of cooperative automated driving system capabilities to support the advancement of transportation systems management and operations, and facilitates cooperative tactical maneuvers of automated driving systems with other vehicles and roadway infrastructure through wireless communication. The CARMA2 plugin mobility applications include vehicle platooning, speed harmonization, and cooperative on-ramp merge using automatic longitudinal control. This report describes the test procedures and identifies key performance measures for each of the three applications. Testing was conducted at the U.S. Army's Aberdeen Test Center and involved a fleet of five 2013 Cadillac SRX passenger vehicles that the Federal Highway Administration's Saxton Transportation Operations Laboratory had equipped with the CARMA2 platform. Using a new "All Predecessor Following" platooning algorithm, the tests demonstrated the successful platooning of five CARMA2-equipped vehicles traveling up to 60 mph with time gaps as low as 0.6 second. The results of the test data analysis also revealed opportunities to improve the capability and performance of the three applications as their algorithms undergo further development and are implemented on the third-generation CARMA (CARMA3) platform.

14. SUBJECT TERMS Automated vehicles, cooperative automated vehicles, connected vehicles, cooperative automation research mobility applications, CARMA, mobility applications, platooning, speed harmonization, ramp merge, adaptive cruise control, cooperative adaptive cruise control, test procedures, and performance measures.	15. NUMBER OF PAGES 61
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

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

Abbreviation	Term
ACC	Adaptive Cruise Control
ADMAS	Advanced Distributed Modular Acquisition System
APF	All Predecessor Following
API	Application Programming Interface
ATC	Aberdeen Test Center
CACC	Cooperative Adaptive Cruise Control
CADS	Cooperative Automated Driving System
CARMA	Cooperative Automation Research Mobility Applications
DSRC	Dedicated Short-Range communications
FHWA	Federal Highway Administration
FV	Following Vehicle
HTTP	HyperText Transfer Protocol
HV	Host Vehicle
IHP	Integrated Highway Prototype
ISO	International Standards Organization
km	kilometer
LED	Light-Emitting Diode
LV	Lead Vehicle
m	meter
m/s	meters per second
mph	miles per hour
NGC	Navigation, Guidance, and Control
OEM	Original Equipment Manufacturer
PV	Preceding Vehicle
REST	Representational State Transfer
ROS	Robot Operating System
s	second
TFHRC	Turner-Fairbank Highway Research Center
U.S.	United States
UI	User Interface
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

Executive Summary

The Volpe National Transportation Systems Center, in conjunction with the Federal Highway Administration's Turner-Fairbank Highway Research Center (TFHRC), tested and evaluated the performance of three research mobility applications implemented by the second-generation Cooperative Automation Research Mobility Applications (CARMA2) open-source platform. This unique platform facilitates cooperative tactical maneuvers of automated driving systems with other vehicles and roadway infrastructure through wireless communication. The CARMA2 mobility applications included car platooning, speed harmonization, and cooperative on-ramp merge using automatic longitudinal control. Testing was conducted at the U.S. Army's Aberdeen Test Center and involved a fleet of five 2013 Cadillac SRX passenger vehicles that the TFHRC's Saxton Transportation Operations Laboratory had equipped with the CARMA2 platform.

This report describes the applications and test procedures, identifies key performance measures, discusses the test results, and recommends improvements for each of the three mobility applications:

Platooning

Vehicle platooning is a promising solution for increasing highway capacity and alleviating traffic, which closely ties the motion of a string of vehicles following a lead vehicle under automatic longitudinal control. By design, each of the following vehicles matches the speed of the lead vehicle and maintains a constant, specified time headway with the preceding vehicle. The CARMA2 implemented the All Predecessor Following (APF) control structure that was devised to suppress intra-platoon errors in position and speed, and increase platoon stability without compromising safety. Using this new APF platooning algorithm, the tests demonstrated the successful platooning of five CARMA2-equipped vehicles traveling at 60 miles per hour (mph) with 0.6 second (s) time gap. Compared to the CARMA1 proof-of-concept based on cooperative adaptive cruise control (CACC), the CARMA2 APF platooning algorithm showed the following improvements:

1. Reduction in targeted time gaps from 1.2 s to 1.0 s for all tested routes.
2. Speed and time gap stability at time gap of 0.6 s.
3. Limited time gap errors between -0.2 and 0.25 s, as opposed to CACC from -0.9 to 0.7 s.
4. Elimination of speed errors (less than 0.5 mph), versus CACC from -5 to 3 mph.

Potential improvements to vehicle platooning include (1) the development of an "Eco-Approach" type algorithm for vehicles to minimize throttle movements for terrain and other road users ahead, and (2) guidance for developers to balance secondary objectives (i.e., driver acceptance measures and fuel economy) against the primary objectives of matching the lead vehicle speed and target headway time gaps.

Speed Harmonization

Speed harmonization is a traffic management framework that aims to reduce speed differentials and smooth the flow of traffic with dynamic, real-time adjustment of vehicle speed recommendations or commands. The CARMA2 test of this application demonstrated the basic design intent to facilitate changes to commanded speeds via cellular and potentially other wireless technologies as if being sent from a traffic control center. Absolute speeds and a fixed change to a commanded speed presently in use were successfully tested. An "application disable" parameter was incorporated and successfully tested, which allowed select vehicles to be unaffected by the commanded speed request. Signal availability on the ATC track, located in quite a remote area, was a significant challenge limiting the scope of the test and evaluation effort.

Potential improvements to speed harmonization include the investigation of alternative ways to (1) allow full coverage of the wireless communications being used for all vehicles in the test area, and (2) replace the "application disable" in the Route file to be independently disabled on the driver-interface tablet.

Cooperative On-Ramp Merge

The cooperative on-ramp merge application was designed to automatically position the host vehicle at a specific waypoint to emulate a "stop bar", adjacent to the lane of traffic that one to four CARMA2-equipped vehicles in a platoon are approaching at highway speeds. As the approaching vehicle(s) got closer, the application prompted the driver to allow the automatic longitudinal control to accelerate from a stop and join the platoon from the rear. The driver manually adjusted the lateral position (i.e., steers) onto the adjacent lane.

This on-ramp merge application was a special use case of the more encompassing cooperative lane change application. The limited amount of time available for testing demonstrated the limitations of the existing Route file that uses a single set of geo positions along the centerline of the main two lanes of the test track to unambiguously define the route of a vehicle approaching from an adjacent lane. Good progress was made; however, challenges to automatically stop and hold a vehicle at a specific waypoint and then accelerate to the correct speed of vehicle(s) approaching in an adjacent lane from the rear were not reliably resolved.

Potential improvements to ramp merge include (1) the use of capabilities from higher fidelity maps for trajectory planning, and (2) the revision of test procedures to have a more fully-scripted plan for synchronized timing of all vehicles used in the test.

Finally, the results of the test data analysis revealed opportunities to improve the capability and performance of the three applications, as their algorithms undergo further development and are implemented on the third-generation CARMA (CARMA3) platform.

1. Introduction

The Federal Highway Administration (FHWA) developed the innovative Cooperative Automation Research Mobility Applications (CARMA) platform to encourage research and collaboration among industry, academia, and federal, state, and local governments, with the goal of improving transportation efficiency and safety [1]. CARMA enables the research and development of cooperative automated driving system (CADS) capabilities to support the advancement of transportation systems management and operations using automated driving technology. Designed with open-source software and to be vehicle/technology agnostic, the unique CARMA platform facilitates cooperative tactical maneuvers of automated driving systems with other vehicles and roadway infrastructure through wireless communication.

1.1 Objective

This report describes the applications, presents the test procedures, and discusses the validation results of platooning, speed harmonization, and cooperative on-ramp merge plug-ins using a second-generation CARMA (CARMA2) platform that enables automatic longitudinal control of the host vehicle (HV) and wireless communication with other equipped vehicles and the infrastructure.

1.2 CARMA2

The CARMA platform provides navigation, guidance, and control (NGC) functionality to manage automated vehicle motion [2]. Navigation determines where the vehicle currently is with respect to the earth and with respect to the desired path of travel. Guidance decides how the vehicle is to move from its current location to its destination. Control covers the actuation of the vehicle's physical systems to induce changes in motion, typically causing the wheels to rotate faster or slower and turning the steering wheel. This platform essentially enables a "middleware" capability that abstracts the vehicle into an application programming interface (API) that vehicle guidance algorithms can use. Moreover, this platform connects directly to the vehicle hardware to execute low-level control commands and to ingest a variety of vehicle situation data, including position data from an external global navigation satellite system receiver. It also connects to add-on hardware, such as environmental sensors and communication devices.

The CARMA platform consists of several components that communicate with each other using the Robot Operating System (ROS) framework. The platform also enables vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications using various communication protocols, such as cellular or dedicated short-range communications (DSRC) messaging.

In addition to NGC functionality, the CARMA platform provides the following:

- Computational services such as data logging, roadway geometry interpretation, and message formatting for communications with other cooperating entities.
- Data API for external data collection, primarily motivated by a need to display real-time information in graphical form to interested parties, such as the HV's driver.
- Command API that allows the HV's driver to issue commands to the platform.

1.3 Applications

The following subsections provide a high-level description of each of the three applications addressed in this report: vehicle platooning, speed harmonization, and cooperative on-ramp merge.

1.3.1 Vehicle Platooning

This research defines a vehicle platoon as follows. Using wireless communication, a vehicle platoon consists of organized behavior and negotiations between vehicles, in order to support formation and safe close following. A vehicle platoon consists of a leader that provides information and rules (e.g., maximum platoon size, command speed, intra-platoon gaps, etc.) to cooperate with at least one follower [3]. Wireless communication provides enhanced information so that platooning 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.

In contrast to vehicle platooning, the first-generation CARMA (CARMA1) platform focused on the cooperative adaptive cruise control (CACC) proof-of-concept application. A CACC system builds upon adaptive cruise control (ACC) by receiving and processing vehicle state messages from preceding vehicles using V2V communication. These messages are fused with the forward-looking sensor data to provide the ACC controller with more information to improve the vehicle response beyond the view of the forward-looking sensor. This enables the vehicles to follow closer than default ACC settings [3].

Vehicles in a CACC string can still drive freely, as individual agents, according to the information received through on-board sensors and wireless communication. On the other hand, vehicles in a platoon (1) use organized behavior, (2) negotiate with other platooning vehicles, and (3) are forced to abide by the platoon rules set forth by the leader in order to realize the greatest benefit to the platoon, as well as to the entire traffic stream [4].

1.3.2 Speed Harmonization

Speed harmonization dynamically adjusts vehicle speed recommendations in order to reduce speed differentials. Speed harmonization can be applied near areas of congestion, collisions, or special events to optimize mobility and safety. Speed harmonization has been implemented in a few locations in the United States (U.S.) with some success, but the current approach faces significant challenges. As presently implemented, speed harmonization is conducted with the use of variable speed limit signs or dynamic message signs. This method of implementation is susceptible to unpredictable and uncoordinated driver response. Moreover, these signs are costly for state and local agencies to deploy, operate, and maintain. Despite these challenges, simulation has shown that speed harmonization does not require perfect driver compliance to significantly improve traffic flow and performance. V2I-based speed harmonization, in which speed guidance is communicated directly to vehicles, would be more effective and simpler to implement than using roadside signs [5].

Connected automated vehicles provide a more direct method of implementing speed harmonization, whereby the infrastructure provides speed commands directly to the vehicle and the vehicle responds directly to those commands without driver intervention. Figure 1 illustrates the overall concept of speed harmonization with connected vehicles [6].

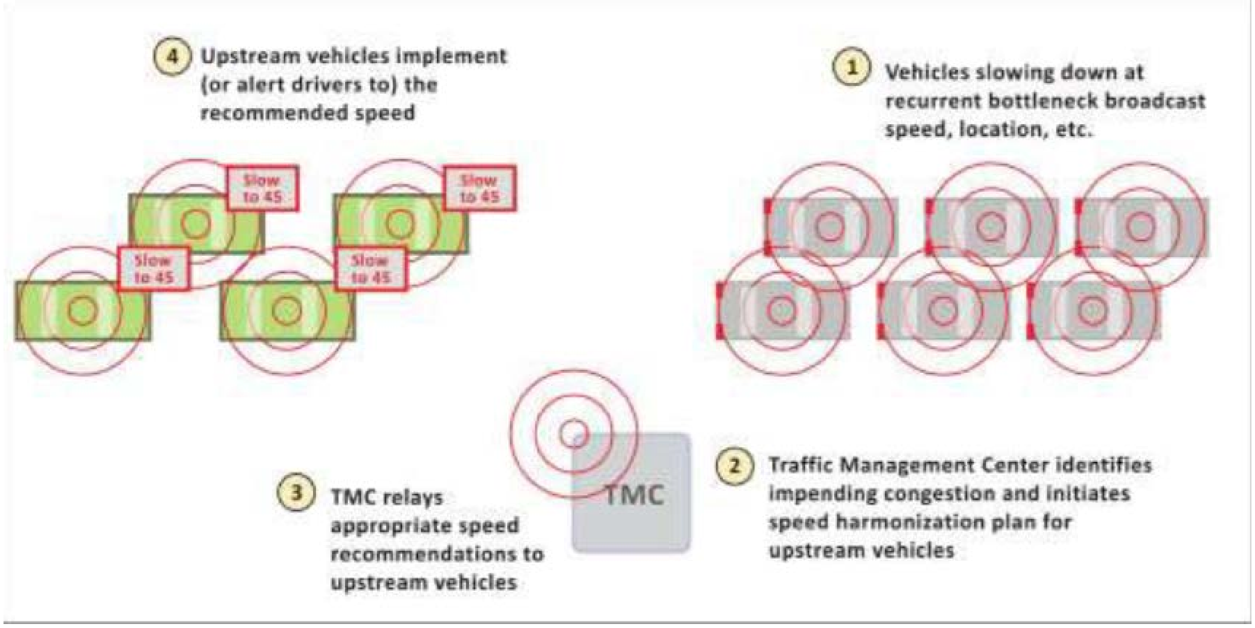


Figure 1. Speed Harmonization Application [6]

1.3.3 Cooperative On-Ramp Merge

On-ramp entrance automation, as part of a cooperative maneuver context, is a potential solution for congested traffic situations caused by traffic merging in urban environments [7]. For the drivers, performing a ramp entrance is a complex maneuver since both the merging driver and those already on the main road have to be able to interpret the situation of the traffic around them. From the driver's point of view, the difficulty arises along the on-ramp where the merging vehicle's driver has to discern whether to accelerate or decelerate to merge onto the main road. Concurrently, drivers of the vehicles already on the major road may have to modify their speeds to permit the entrance of the merging vehicle, thus affecting the traffic flow. An automated on-ramp merging system would facilitate the merging vehicle to fluidly enter the major road to avoid congestion on the minor road, and/or would modify the speed of the vehicles already on the main road to minimize the effect on that already-congested main road.

1.4 Previous CARMA1 Applications

The U.S. Department of Transportation‘s John A. Volpe National Transportation Systems Center (Volpe Center) has previously supported FHWA’s Turner-Fairbank Highway Research Center (TFHRC) in its research effort to advance connected-automated vehicle mobility applications using the what is presently referred to as CARMA1 (concept) [8]. The CARMA1 concept was developed using MATLAB/Simulink, and was executed with a dSpace MicroAutoBox, to implement a proof-of-concept CACC system. The Volpe Center, in conjunction with TFHRC, has developed 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. Closed-track testing was performed on a paved 7.2-kilometer (km) (4.5 miles), two-lane test track at the U.S. Army Aberdeen Test Center (ATC) in Maryland. ATC acquired and installed the data acquisition systems, executed the test procedures, and collected and transferred the test data to TFHRC and the Volpe Center for analysis.

CARMA1 testing focused on the test and evaluation of CACC to enhance the stability of longitudinal movements of a string of vehicles. CACC represents an advancement of ACC systems by utilizing V2V DSRC to exchange state information among vehicles in a string. In order to test the CACC application, CARMA1 added autonomous trajectory planning to the first (lead) vehicle. The CACC application was implemented on a TFHRC’s fleet of five 2013 Cadillac SRX vehicles with a production ACC system.

A series of common tests were conducted under three basic configurations to evaluate performance using a 60→45→60 miles per hour (mph) route file:

1. Pure ACC – lead vehicle (LV) is manually driven to a specific speed profile around the track, while one to four following vehicles (FVs) are driven with ACC at a higher set speed in the production ACC mode with minimum time gap setting (around 1.2 seconds (s)).
2. Hybrid – LV is driven under robotic (i.e., automatic) longitudinal control with geo-position and commanded speed profile specified in a route file, while one to four FVs are driven with ACC at a higher set speed in the production ACC mode with minimum time gap setting (around 1.2 s).
3. CACC – LV and FVs, with the CACC application enabled, are driven under robotic longitudinal control with geo-position and commanded speed profile specified in a route file for the LV.

The CARMA1 CACC system, with four FVs closely matching LV speed and commanded time gap, showed significant improvement over the production ACC. Speed under/over LV speeds was limited between -2.5 meters/second (m/s) to 1.2 m/s during accelerations and decelerations, and very closely matched the LV speeds during steady-state speed conditions. Radar-based time gaps were between -0.4 to 0.7 s from the target time gap during accelerations and decelerations, and very closely matched the desired time gaps during steady-state speed conditions. By comparison, the production ACC system achieved under/over LV speeds between -5 m/s to 2.5 m/s during accelerations and decelerations, and very closely matched the LV speeds during steady-state speed conditions. In addition, radar-based time gaps varied from -0.5 to 0.3 s from the target time gap during accelerations and decelerations, and very closely matched the desired time gap during steady-state speed conditions.

The CACC improvements in the observed performance of four FVs closely matching the LV speed and commanded time gap were somewhat offset in secondary objectives associated with driver acceptance. Complete details of the CARMA1 results can be found in [8]. Selective plots including those used in this report can be found in Appendix A. The CARMA2 platooning application made significant improvements to both primary and secondary objectives as discussed in the following sections.

2. Platooning

Platooning is intended to closely tie the motion of a group of vehicles following a LV, all under automatic longitudinal control. In the CARMA2 platooning algorithm, the goal is to have each of the FVs closely resemble the speed of the LV while making necessary adjustments in the distance headway as the platoon accelerates or decelerates.

2.1 Application Description

Using wireless communication and automated longitudinal control, CARMA2-equipped vehicles form platoons to move as a single unit with small, constant time headways. Vehicle platooning is a promising solution for increasing highway capacity and alleviating traffic. By leveraging V2V communication, vehicles can exchange information and negotiate with one another, allowing vehicles to platoon. Knowledge of the surrounding vehicle states allows the HV to partially automate the driving task, leading to safer and more efficient traffic networks.

In addition to vehicles driving at smaller time headways than manual driving, and thus increasing capacity, platooning has the potential to further improve traffic conditions by eliminating “ghost shockwaves”. Such shockwaves are fluctuations in speed that may develop in traffic due to slight accelerations or decelerations, which are amplified upstream. Various simulation studies have shown that platooning can suppress such disturbances as vehicles move upstream, which not only benefits vehicles in the platoon, but also upstream traffic [4].

One of the primary goals of the platooning algorithm implemented by CARMA2 is suppressing intra-platoon errors in position and speed, and increasing string stability without compromising safety. The algorithm uses the All Predecessor Following (APF) control structure, developed through research sponsored by FHWA. The research showed that prioritizing information from the first vehicle (i.e., LV) in the platoon, over other vehicles, increases string stability. Also, prioritizing the LV allows for the HV to avoid being negatively affected by small intra-platoon errors caused by other vehicles. However, for safety reasons, it may not be possible to always prioritize the leader; a vehicle may need to consider other predecessors. Therefore, a weighting formula was developed where the HV prioritizes the information coming from the farthest downstream vehicle for which it is safe to do so. Receiving information from all downstream vehicles in the platoon (i.e., APF topology) is required for this control algorithm as, depending on the state of the platoon, priority may be assigned to any downstream vehicle [4].

Both CACC strings and vehicle platoons can follow various spacing policies. Most common among these policies are the constant time policies and the constant distance policies. Constant time policies most often aim to keep a constant time gap, which is the time between the front bumper of a trailing vehicle and the back bumper of a preceding vehicle. However, as noted in [4], if a platoon of vehicles aims to keep a constant time with any other vehicle except the immediately preceding vehicle, then it must rely on a constant time headway policy, which is the time between the front bumpers of any two vehicles (or any other identical part of two different vehicles; e.g., back bumpers). Constant distance policies (i.e., constant distance gap and constant distance headway) are not as common for user comfort reasons.

In the APF algorithm, the selected spacing policy was a constant time headway policy because all vehicles focus on following the first vehicle (i.e., the leader) of the platoon. For low speeds, a minimum distance headway was used so that vehicles would never be commanded to be uncomfortably close to each other. During these low speeds, the target time headway would, thus, effectively increase.

For example, if the desired time headway is 1.0 s and the minimum distance headway is 16 meters (m), then the desired distance headway at any time is equal to max(16 m, 1.0 s × v) where v is the velocity of the HV in m/s. Thus, in this example, for any v less than 16 m/s, the desired distance headway would be set to 16 m while the desired time headway would become greater than 1.0 s. That is, if v = 8 m/s, then the desired distance headway would be 16 m; this implies that the desired time headway would therefore increase to 2.0 s (i.e., 16 m/ (8 m/s)). In essence, this means that the desired time headway will be kept at some constant value as long as the speed is not below some threshold (in this example, 16 m/s); otherwise, the desired time headway will increase accordingly to prevent vehicles from approaching each other at low speeds.

2.2 Plugin Operation

The Platooning plugin package is an external CARMA plugin containing the implementation of the APF platooning algorithm. When the HV is a follower in a platoon, it uses the APF algorithm to generate a longitudinal trajectory plan with one complex maneuver. A complex maneuver means, given start location and end location, the speed profile cannot be pre-computed (as usually done in the guidance trajectory plan) and needs to be determined in real time within the plugin. It satisfies the requirement of the APF algorithm because in the APF algorithm the vehicle speed is changed based on two parameters: how the current distance headway compares with the desired distance headway (see previous section for how the desired distance headway is calculated) and the command speed of the current functional leader, which serves as a baseline speed on which adjustments are made depending on if the vehicles are too close or too far from one another. There are three main components in the platooning plugin:

1. *Main class*: handles all communications with the CARMA platform in the ROS network and determines the state – follower or leader – of the platooning vehicle.
2. *PlatoonManager class*: handles and processes all DSRC messages from the current platoon.
    a. If the HV is a platoon leader, it will store the information of all other platooning members. That information includes data such as current location, current speed, current Basic Safety Message ID, and current command speed.
    b. If the HV is a platoon follower, it will keep all information about platoon vehicles in front of it because it will actively follow any one of them as a functional leader.

3. *CommandGenerator class*: calculates the command speed of the HV based on the current state of itself and its current functional leader. It will use the command speed of the current functional leader as a baseline speed and adjust it through a proportional-integral-derivative controller to maintain a correct distance and time headway with this leader.

2.3 Test Procedures

This section describes the test procedures that were used to conduct characterization testing of one- to five-vehicle platoon at the U.S. Army's ATC in Aberdeen, Maryland. The tests involved a fleet of five 2013 Cadillac SRX passenger vehicles that the FHWA's Saxton Transportation Operations Laboratory had equipped with the CARMA2 platform. Each test procedure may be used with different route files to change the dynamics of the LV. The desired time headway for the FVs is a configurable variable within the CARMA2 platooning application. The following describes the generic test steps needed for all CARMA2 mobility applications, followed by the specific test steps for platooning.

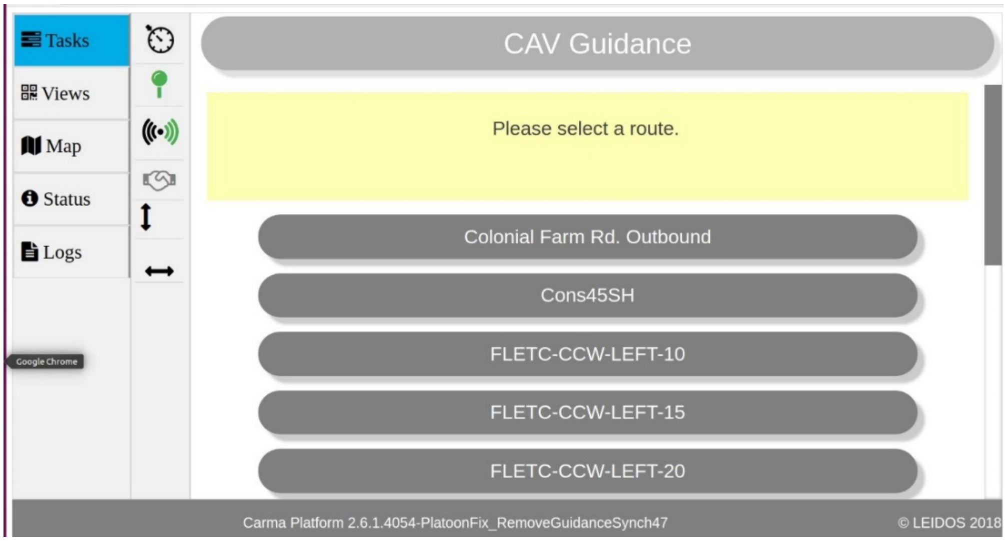
2.3.1 Generic CARMA2 Test Procedures

2.3.1.1 Evasive maneuver "bail" procedures: Drivers will 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 CARMA2. Generally, brake or throttle activation overrides any automatic controls. It should be noted that steering is not automatically controlled at any time in CARMA2. 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.

2.3.1.2 Route files: These are used to provide specific geolocation (latitude and longitude) for the desired path of each vehicle. The path is described with latitude and longitudinal data along the centerline of the track in 20-m increments around the 7.2 km (4.5-mile) ATC track. The geolocations are called "Waypoints" that are not only used to identify the path but also to set or make changes to the following parameters:

1. *Speed*, used for the target command speed or speed limit.
2. *LaneCount*, the number of lanes present.
3. *LaneIndex*, the desired lane.
4. *DisableAlgorithm*, used to temporarily disable specific applications.

Each vehicle must have a selected route file and be located on the route to initiate automatic longitudinal control. Figure 2 is a screen shot of the CARMA2 user interface (UI) used for route file selection.



Please select a route.

Carma Platform 2.6.1.4054-PlatoonFix_RemoveGuidanceSynch47

Figure 2. Route Selection Menu [9]

All routes are designed for the counter-clockwise direction and start at a common location as shown in Figure 3 below. The start and end points of a single loop route are shown as the "362 route start" point.

Figure 3. ATC Track with Reference Waypoints

2.3.1.3 Initial Set Up: This is to have one to five vehicles down the track from the "route start" point shown in Figure 3, stopped with 20-30 m separation distances between each vehicle, and all vehicles centered in the outside lane. Drivers select the test conductor's requested route file and application plugin(s) via the UI tablet.

2.3.2 Platooning Initial Formation

Following the test conductor's instructions, the LV (1st vehicle) manually accelerates up to 5 mph of the initial route speed and engages automatic control. Simultaneously, the driver in each of the FVs roughly matches the LV speed while following the immediately preceding vehicle. Then, the driver engages automatic control once the immediately preceding vehicle has already engaged automatic control; each driver knows when the preceding vehicle has engaged automatic control because it is indicated by the light-emitting diode (LED) lights mounted in the rear of each vehicle. The intent of this process is to have each vehicle sequentially engage automatic control prior to platooning. Platooning is disabled in the route file until 49th waypoint as seen in Figure 3. As such, platooning is initiated sequentially starting with the LV and continuing with each FV as the vehicles pass the platooning start waypoint. The platooning start point, set for a 45-mph initial speed, can be adjusted in the route file as needed to allow for higher initial route speeds that require more time for automatic control engagement and platoon formation. The intent is to have a fully-formed platoon and stable before the LV passes reference waypoint 100.[1]

2.3.3 Platooning Intermediate Conditions

After waypoint 100, once the platoon has fully formed, the test design intent is to allow LV speed commands between 5 and 70 mph, as called for in the specific route file for the run. Drivers have practiced with each route file and expect several different conditions, including constant speeds, changing speeds, and associated decelerations or accelerations until the end of route. Drivers continue to maintain their vehicles centered in the outside lane.

2.3.4 Platooning End of Route

At the end of the route, platooning and automatic control are disabled by CARMA2. On occasion, one or more vehicles apply a rather harsh brake effort. For safety considerations, prior to the end of the route, the first and third FVs move to the inside lane. This allows platooning to continue to the end of the route to allow more observations, and provides an open lane with approximately twice the time headway in case of sudden braking. Drivers return to the starting position or off track under manual control as instructed by the test conductor.

---

[1] Waypoints are 20 m apart.

2.4 Performance Measures

This section describes the primary performance measures and identifies the associated data elements and metrics. These performance measures will be used to evaluate the performance of the CARMA2 APF platooning application under various test scenarios. In general, the APF system should exhibit less variation and more consistency between vehicles than the 2016 proof-of-concept CACC application [8]. 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 vehicle platooning's performance is platoon 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.

2.4.1 Speed Accuracy/Stability

One of the objectives of this platooning test is to accurately follow the speed of the preceding vehicles (PVs) via the DSRC transmittal of the current state of the LV and/or PV's speed and acceleration. For this evaluation, there are several potential sources of speed measurements, including the production wheel speed, the PinPoint GPS speed, and the GPS speed from the ATC's Advanced Distributed Modular Acquisition System (ADMAS). The Volpe Center decided to use the average production wheel speed of the non-driven wheels (*vehspdavgn*) because it is a vehicle system-level reading independent of the internal CARMA2 speed based on GPS. Figure 4 and Figure 5 illustrate the observed difference in the three speed measurements using data from the LV during a 45→60→45 miles per hour (mph) test using a 2 loop route file as described in section 2.3.1.2. The LV is manually driven to just over 45 mph (20.1 m/s) where the driver then engages automatic control at around 100 s "Elapsed time". At this point, the commanded speed is set to a constant speed of 45 mph until just before 300 s when the commanded speed is increased to 60 mph (26.8 m/s), and then held constant until around 575 s. At around 575 s, the commanded speed is reduced back to 45 mph.

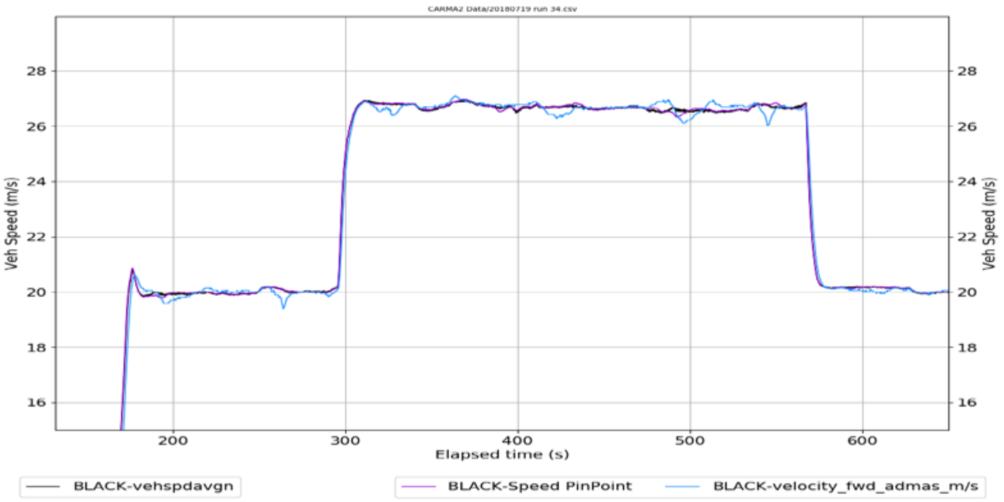


Figure 4. Speed Measurement Data Elements - 45→60→45 MPH

To observe the difference in speed measurements between the three data elements (i.e., production average non-driven wheel (black), GPS based PinPoint used by CARMA2 (violet), and GPS based ADMAS (blue)), Figure 5 zooms into the Elapsed time between 360 and 480 s with a constant 60 mph commanded speed. The vehicle speed data from the production average non-driven wheel (black) have the smallest amount of noise, and thus this data element is considered the best representation of actual vehicle speed. The total range of speed between 26.9 m/s and 26.5 m/s has less than 1 mph (≈0.45 m/s) variation, which is considered very good control and is likely to show a constant 60 mph on the vehicle's speedometer.

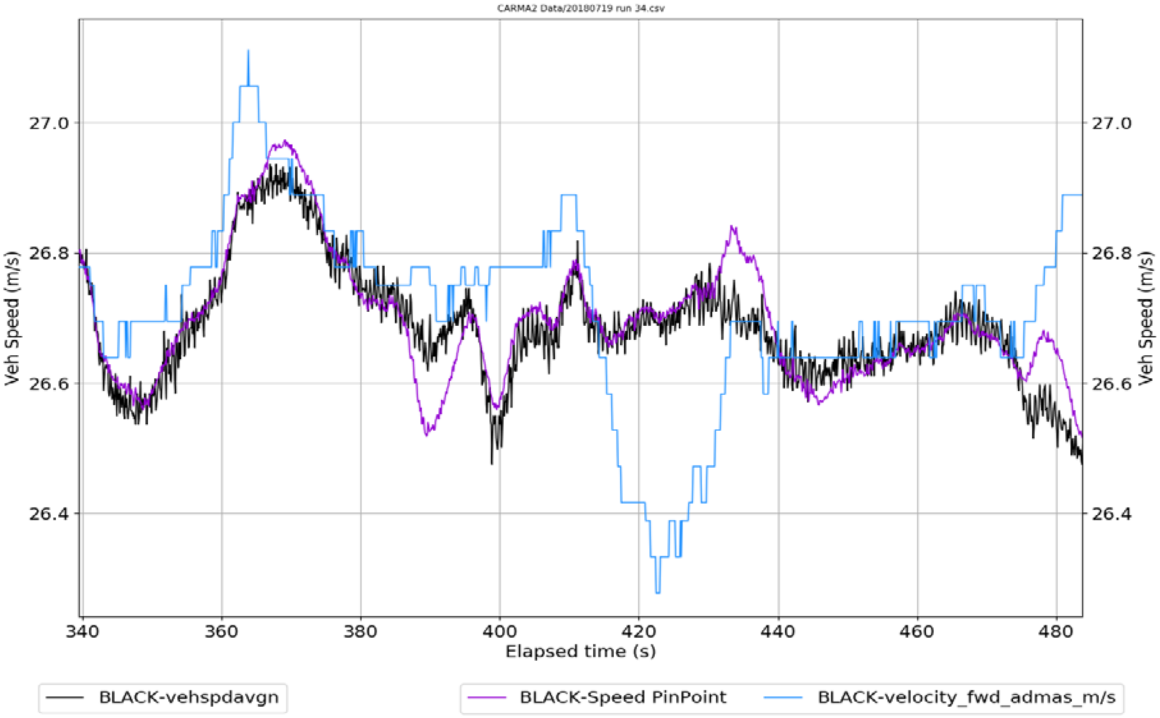


Figure 5. Speed Measurement Data Elements - 60 MPH Steady State

2.4.2 Acceleration Accuracy/Stability

Since one objective for platooning is for the HV to closely parallel the speed of the PVs, the acceleration between the vehicles should follow similar profiles. LV's speed and acceleration changes are broadcast to all FVs in the platoon, with the expectation that the minimum and maximum accelerations will not increase towards the tail of the platoon. For this evaluation, two potential sources of acceleration measurements were considered: production vehicle accelerometer (violet) and a 0.9-s calculated moving average of ADMAS GPS (blue) data. ADMAS data were used to derive the acceleration value from GPS speed measurements, and these acceleration values were smoothed by calculating the moving average as follows:

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

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

Figure 6 illustrates a comparison of the two acceleration measurements for the LV from the 45→60→45 mph test route file (same route as used for speed measurements). Figure 7 and Figure 8 show a close-up (zoomed plots) for the 45 to 60 mph acceleration measurements and the 60 to 45 mph deceleration measurements, respectively.

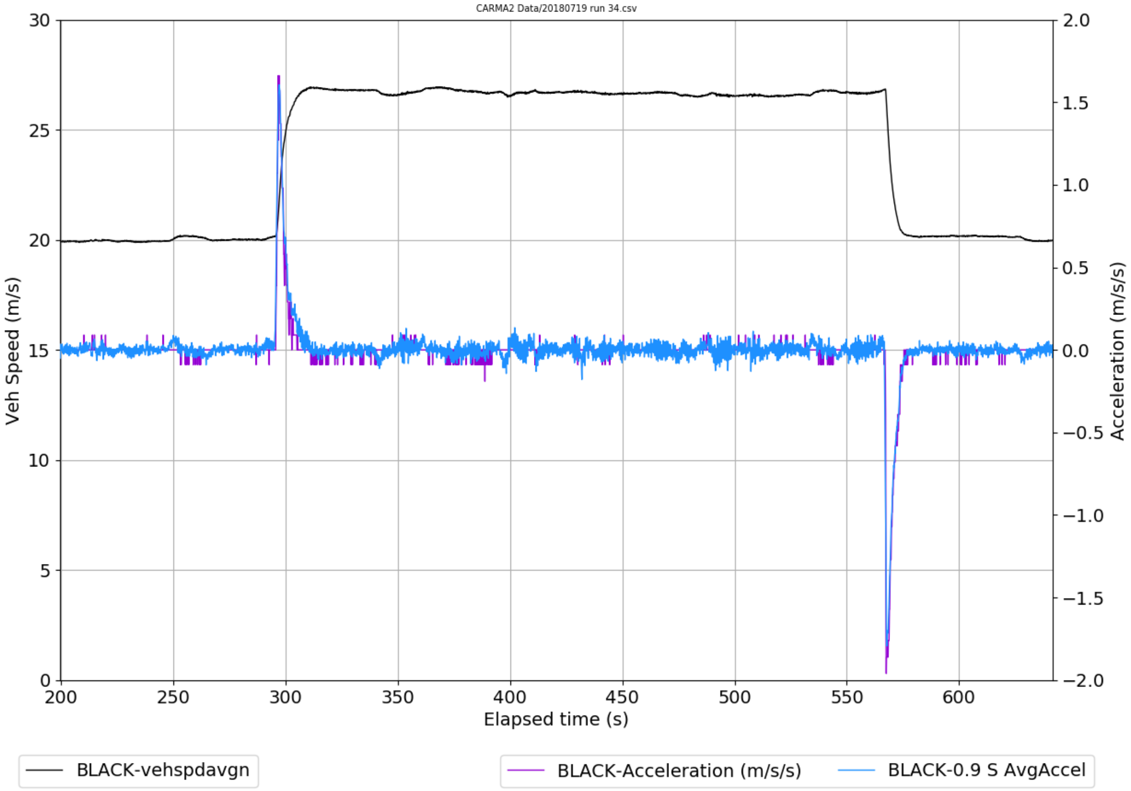


Figure 6. Acceleration Measurement Data Elements – 45→60→45 MPH

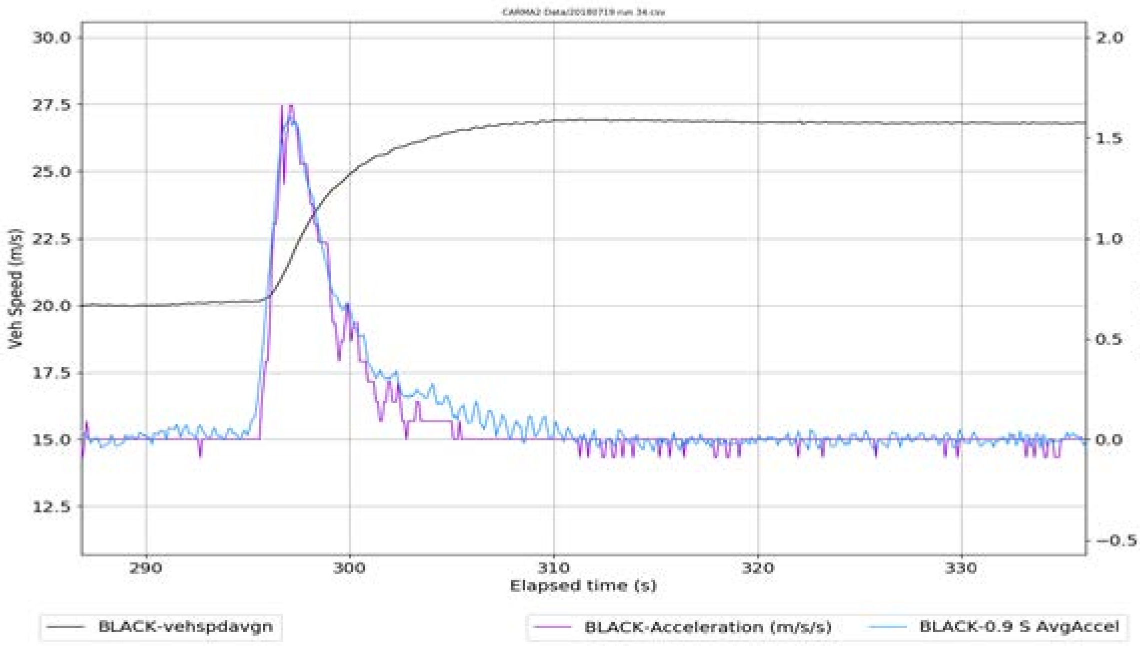


Figure 7. Acceleration Measurement Data Elements – 45→60 MPH

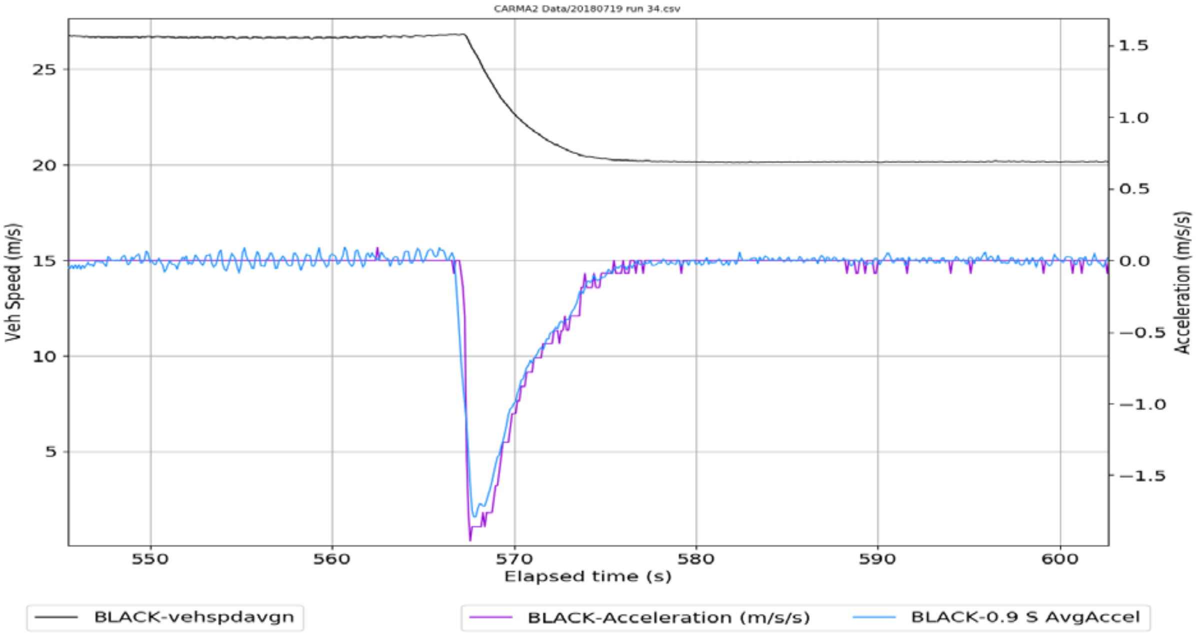


Figure 8. Deceleration Measurement Data Elements – 60→45 MPH

The Volpe Center has chosen the independent production vehicle acceleration as the preferred measurement. The data are very similar between the two measurement sources. The choice of using the production sensor is twofold:

1. The production sensor is being used in safety-critical vehicle functions, such as electronic stability control, and has gone through extensive design verification and product validation by the original equipment manufacturer (OEM).
2. Driver acceptance and standards by International Standards Organization (ISO) for both accelerations and decelerations are specified as maximum limits. The production sensor (violet) has slightly higher peaks than the GPS-based 0.9-s moving average (blue).

2.4.3 Gap/Range Measurements

Generally, an objective of platooning systems is to consistently maintain the commanded distance and/or time gap. In the event that there are variations in the distance and/or time gap, increasing gaps are preferred over decreasing gaps because decreasing gaps pose potential safety concerns due to a shorter time window to perform crash avoidance maneuvers. The CARMA1 CACC proof-of-concept tested in 2016 used radar-based closest-in-path range from the production vehicles to measure and control the time gap [8]. The research CARMA2 APF platooning algorithm used PinPoint GPS to measure and control the distance/time headway. Here, distance headway is measured using the distance between a GPS antenna on the PV and a GPS antenna on the FV, along the path of the route, while the radar measures the gap from the front bumper of the FV to the rear bumper of the PV. Thus, there is a one vehicle length difference between the distance gap and distance headway measurements. The SRX owner's manual specifies the vehicle length at 4.834 m (≈ 15.86 feet).

A different route file was used from that in Figures 4-8. This route file expands the change in commanded speeds from the 45 mph to 60 mph, a change of 15 mph (6.7 m/s), to one that changes between 5 mph (2.2 m/s) to 55 mph (24.6 m/s), a change of 50 mph (22.4 m/s).

For this test, a commanded time headway of 1.24 s was chosen because it corresponds to a time gap of 1.0 s when moving at 45 mph, which is a speed one might expect to see in semi-congested highway traffic (Note: this corresponds to a time gap of 1.06 s at 60 mph). The minimum desired distance headway was 16 m. Thus, for speeds below 12.9 m/s (28.9 mph), the desired distance headway was fixed at 16 m and the desired time headway would vary. For speeds above 12.9 m/s, the desired distance headway would exceed 16 m and the desired time headway would be fixed at 1.24 s. Note that the desired distance headway may be derived from the equation presented earlier (i.e., desired distance headway = max(16 m, 1.24 sec × v), where v is the velocity in m/s).

Figure 9 and Figure 10 illustrate observed differences between radar-measured gap (Radar) and GPS-adjusted gap (GPS-measured headway minus 4.834 m) measurements between the Black LV and Green FV1 for the following conditions:

- Figure 9: Zoom to view a single acceleration – 90 s and 55 mph steady state – deceleration cycle.
- Figure 10: Close up view (second zoom) portion of 55 mph steady state.

Ideally, the range measurements of both radar and GPS-adjusted gap would be the same. We observed a difference of up to 2 m higher in GPS-adjusted gap data throughout the run, somewhat less during speed transitions.

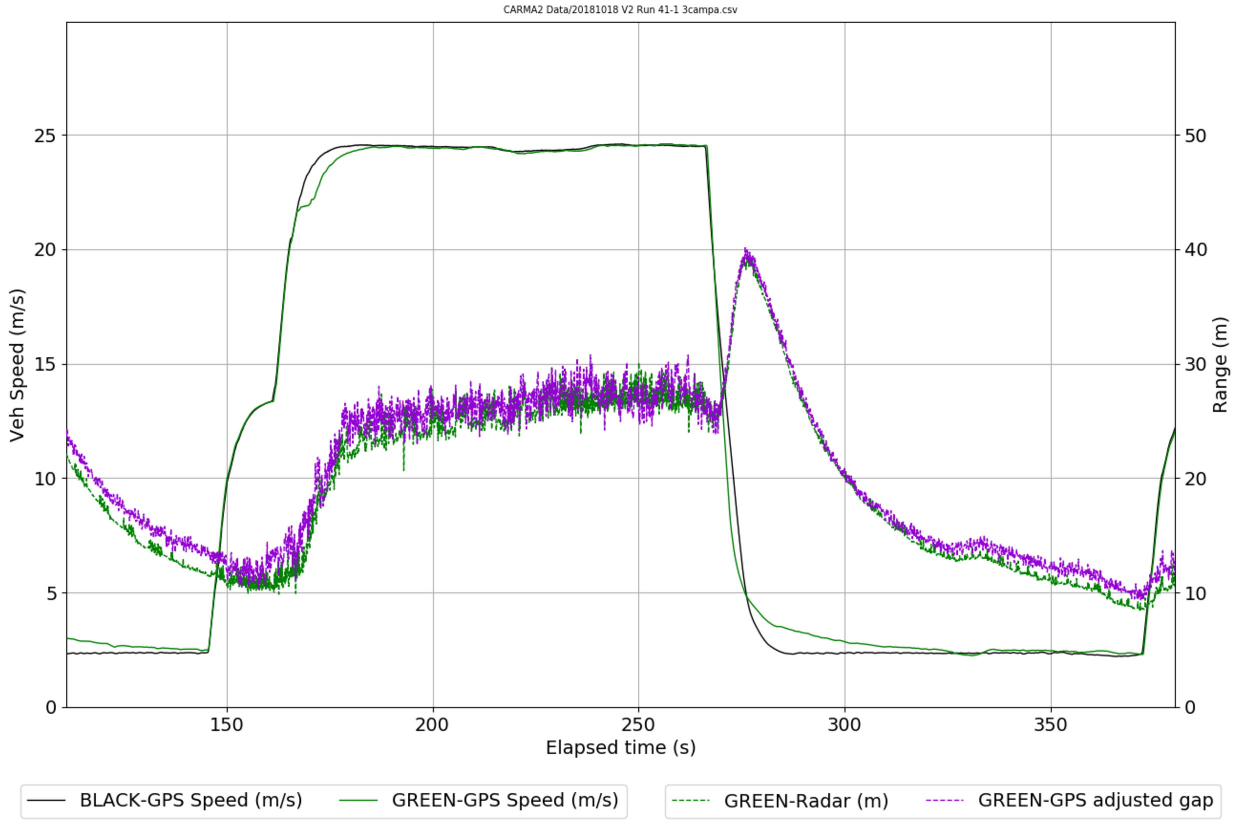


Figure 9. Range Measurement Data Elements 5→55→5 MPH (Green FV1 to Black LV)

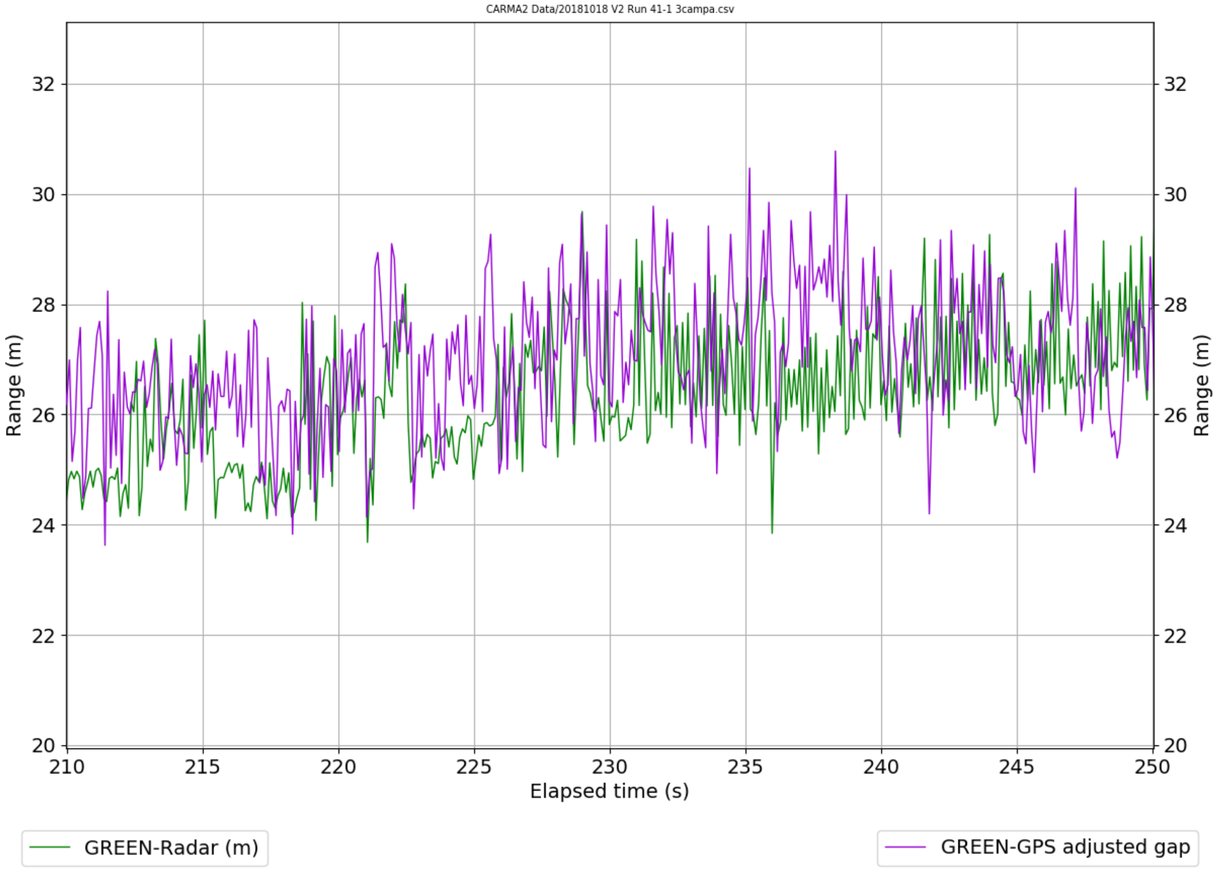


Figure 10. Range Measurement Data Elements 55 MPH (Green FV1 to Black LV)

The Volpe Center has chosen to use the production vehicle forward-looking radar sensor for vehicle range measurements for the following reasons:

- GPS-derived range appears to have more noise and up to around 2 m bias higher than the radar data.
- Radar is used for the production forward collision waning system and has likely undergone extensive design verification and product validation testing by the OEM.
- Radar, although used by the 2016 CACC proof-of-concept testing, is independent from the CARMA2 APF platooning algorithm.
- Radar is a common range measurement available for both 2016 CACC and 2018 APF platooning data sets.

In the balance of this report, Time Gap (s) is calculated as the radar-based separation (*range*) divided by the average wheel speed of the non-driven wheels (*vehspdavgn*):

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

2.5 Test Results

This section presents the results of a series of tests designed to evaluate the CARMA2 APF platooning application. Previous CACC testing was primarily focused on speeds between 45 and 60 mph. Table 1 provides a list of route file speeds used by the LV in APF platooning tests.

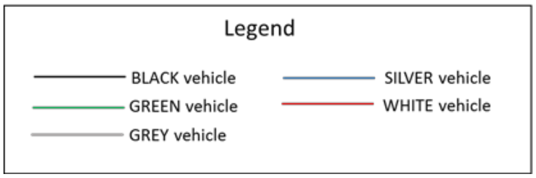
Table 1. Route File Speed Summary

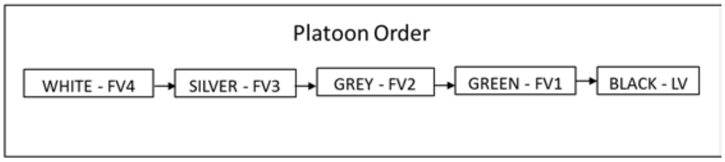
Route File Name	Description	Initial Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	Range of Accel[1] (mph)	Time at New Speed[2] (s)	Range of Decel[3] (mph)	Time at New Speed[4] (s)
45-60-45	Single loop with moderate holds	45	45	60	15	50 - 100	-15	50 - 100
45-60-45 2 loop	Two loops with >250 (s) 60 mph hold times	45	45	60	15	250 - 275	-15	80-100
30-55-30-55	Single loop with short hold times	30	30	55	25	5 - 25	-25	5 - 10
55-5-55-5	Single loop with moderate hold times	55	5	55	50	40 - 60	-45	40-60
60-25-60-25	Single loop with short to moderate hold times	60	25	60	35	10 - 50	-35	5 - 10

Notes	
1	Speed change of accelerations (mph)
2	LV estimated range of time at the new speed before a new speed change (seconds)
3	Speed change of decelerations (mph)
4	LV estimated range of time at the new speed before a new speed change (seconds)

The following notes apply to the majority of the results presented in this section:

- *Order of vehicles in the platoon (always moving counterclockwise on the track)*: Plot legends help to identify the vehicle order in the platoon. The example below illustrates the relationship between the Legend and platoon order. The first vehicle listed in the Legend is Black, which is the LV; second listed is Green, the FV1; third listed is Grey (FV2); fourth listed is Silver (FV3); and fifth listed is White (FV4).
- *Plot Colors*: Plot colors are the same as the vehicle colors except the silver vehicle is shown in blue and the white vehicle is shown in red.





2.5.1 Speed Time Gap and Distance Headway/Stability

Figure 11 and Figure 12 illustrate results of a five-vehicle platoon (LV plus 4 FVs) using the 45→60→45 mph 2 loop route file with 1.24 and 0.84 s commanded time headways, respectively. These time headways were selected because at 45 mph they correspond to time gaps of 1.0 s and 0.6 s, respectively. Note that at 60 mph, these time headways correspond to time gaps of 1.06 s and 0.66 s, respectively.

Route files between 45 and 60 mph were used for tuning the CARMA2 APF platooning algorithm performance, and are similar to those used for evaluation of the 2016 CARMA1 CACC system. The CARMA2 APF plots show close tracking of four FV speeds compared to the LV speed. Also, the time gaps between consecutive vehicles are all close to the time gaps noted above (i.e., 1.0 s to 1.06 s for a desired time headway of 1.24 s and 0.6 to 0.66 s for a desired time headway of 0.84 s). For comparison, Figure 13 shows a five-vehicle platoon with 1.24 s commanded time gap for the 2016 CACC system using a 60→45→60 mph LV route file.

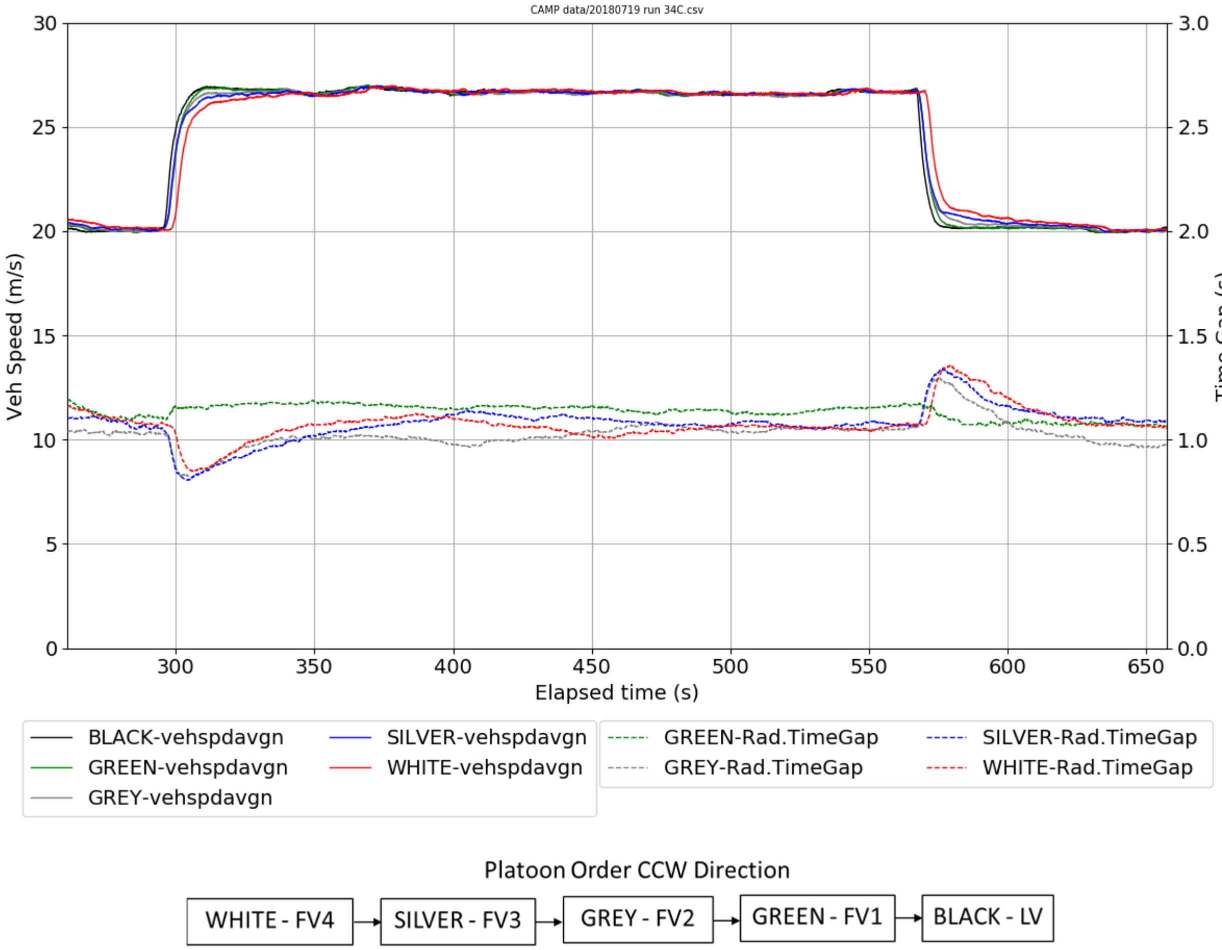


Figure 11. 1.24 s Commanded Time Headway and 45→60→45 LV Commanded Speeds

In Figure 11, lines that are towards the top end of the figure are average vehicle speed of the non-driven wheels (left hand Y axis), and lines that are towards the lower end of the figure are the corresponding radar-based time gaps (right hand Y axis). LV commanded speed increases from 45 mph (20.1 m/s) to 60 mph (26.8 m/s) before Elapsed time of 300 s. As desired, the Green vehicle (FV1) maintains a time gap slightly above 1.0 s while the time gaps of the other FVs decrease to around 0.8 s. By Elapsed time of 350 s, all FV gaps are back to a time gap that is slightly higher than the 1.0 s and, in addition, their speeds closely resemble the LV speed. After the LV commanded speed is decreased back to 45 mph (20.1 m/s) near Elapsed time of 575 s, the speeds of the FVs closely follow the LV speed and their time gaps, with the exception of FV1, increase slightly to less than 1.4 s. Nonetheless, by the end of the run, all the FVs are close to achieving a time gap of 1.0 s that is desired at 45 mph.

Figure 12 reduces the desired time headway to 0.84 s. The platoon order, route file, legends, and axis scales are the same as in Figure 11. Observed results are very similar; all FV speeds closely follow the LV and their time gaps are slightly higher than expected with some small deviations at the beginning of the acceleration and deceleration phases.

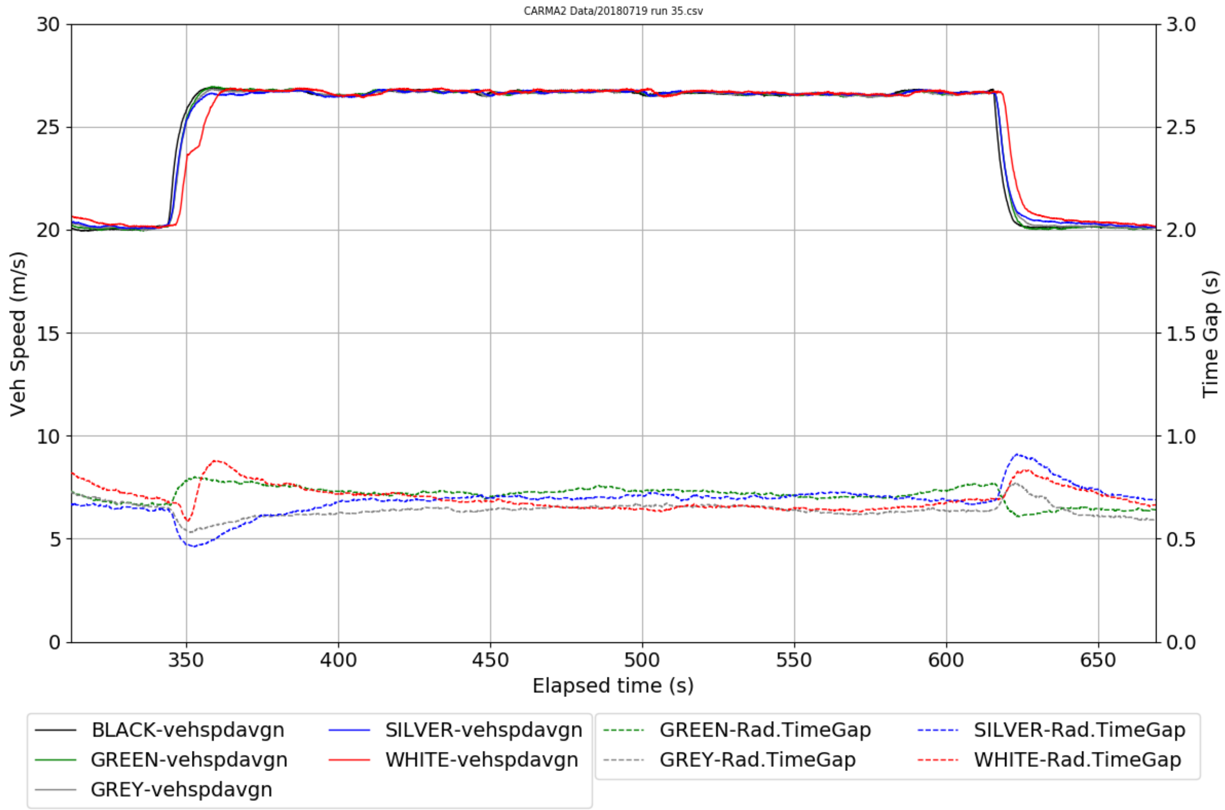


Figure 12. 0.84 s Commanded Time Headway and 45→60→45 LV Commanded Speeds

Figure 13 is taken from Reference [8] to compare the speed and time gap stability plots between the CARMA1 2016 CACC system and the CARMA2 platooning. Commanded time gap is 1.2 s. Route file is a single loop (about ½ of the total elapsed time) 60→45→60→45 mph route.

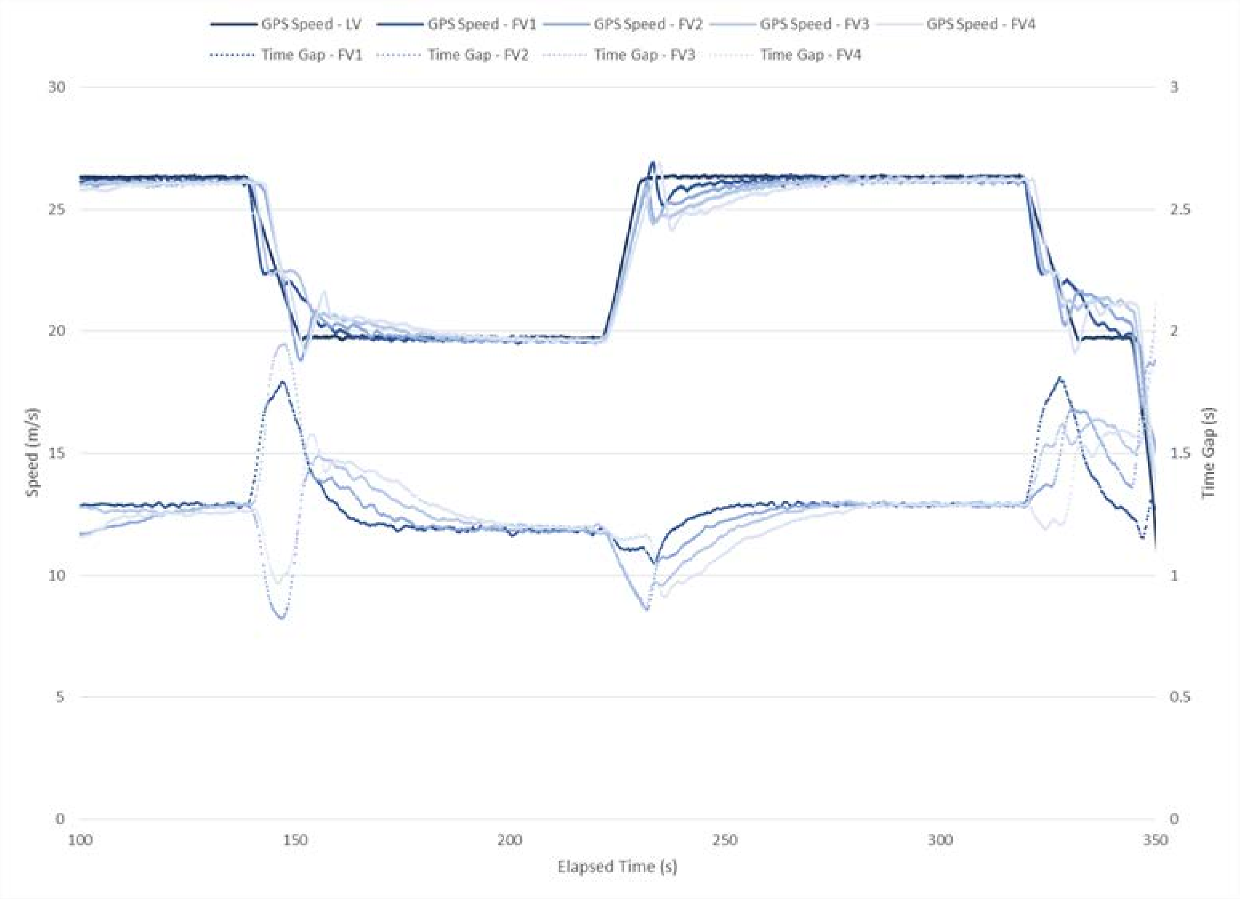


Figure 13. 2016 CACC 1.24 s Commanded Time Gap and 60→45→60 LV Commanded Speeds [8]

Figure 14 and Figure 15 illustrate GPS-based distance headway data using the same runs used for Figure 11 and Figure 12, respectively. Vehicle speed (left hand Y axis) data have been repeated to provide a common visual reference; however, radar-based time gap data have been replaced by GPS-based distance headway (right hand Y axis) to the LV. Distance headway to the LV plots allows us to compare both the headway distance between each vehicle and its predecessor (looking between curves) and each FV's headway distance to the LV with one set of four plots.

Figure 14 distance headway shows good stability of the platoon with respect to the LV and between each of the 4 FVs and its preceding vehicle with the exception of the anomaly observed with (Grey dotted line) FV2 to LV data between Elapsed time 540 and 575 s. The rapid "seesaw" between a low of ~40 and high of ~80 m is not supported by vehicle speed data or radar-based time gap data, and is considered to be caused by a data acquisition, plotting, or processing error because two SRX vehicles cannot change relative position by ~40 m so quickly without corresponding speed and time gap changes that were not observed in the data. With the noted exception, the average headway distance between vehicles is ~34 m and headway distance from FV4 to LV is ~135 m.

In Figure 15 where commanded headway time gap is reduced by 32% from 1.24 s (1.0 s gap time @ 45 mph) to 0.84 s (0.6 s gap time @ 45), the average headway distance between vehicles is ~23 m and the headway distance from FV4 to LV is ~92 m with no observable difference in stability using the 45→60→45 mph LV commanded speed route file.

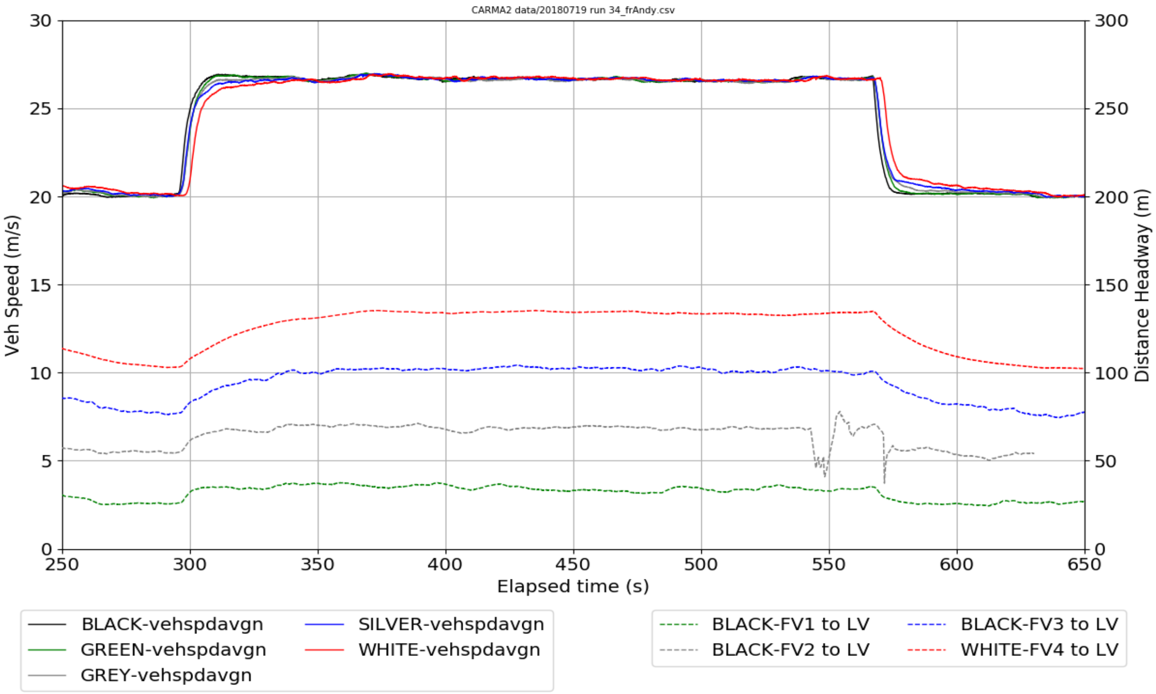


Figure 14. 1.24 s Commanded Time Headway and 45→60→45 LV Commanded Speeds

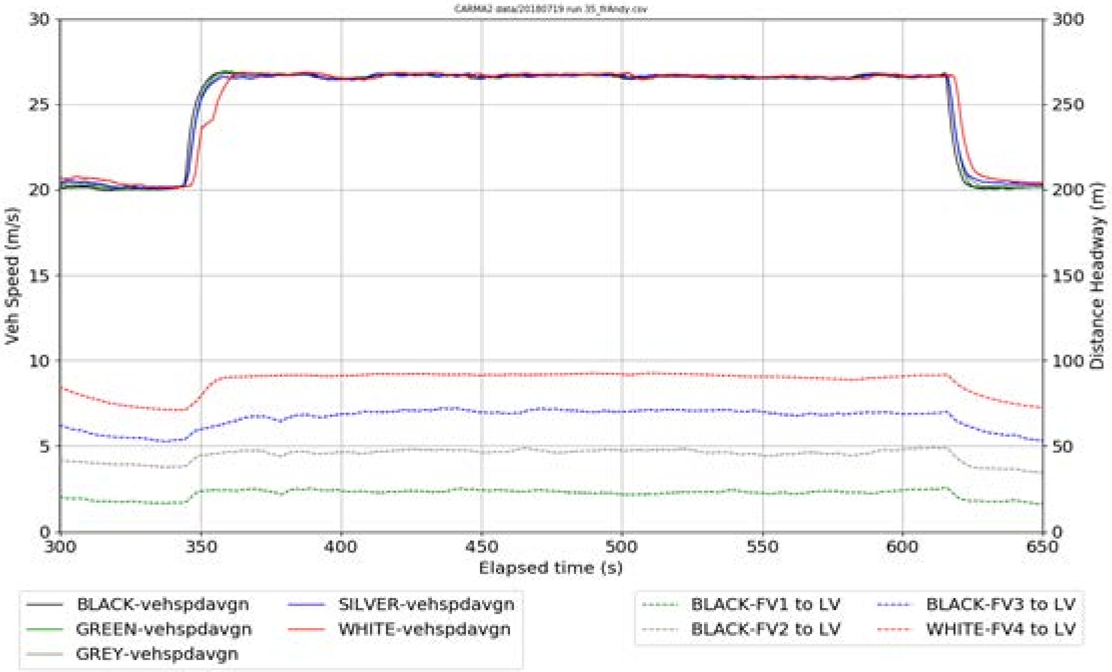


Figure 15. 0.84 s Commanded Time Headway and 45→60→45 LV Commanded Speeds

To test an expanded range of LV commanded speeds, a different route file is run, with LV commanded speeds of 55→5→55→5 mph. Commanded headway time gap of 1.24 s (1.0 s gap time @ 45 mph) except where vehicle speed falls below 25 mph (11.2 m/s) at which time, design intent is for a fixed 11.2 m distance gap (equivalent to 16 m distance headway: 11.2 m + 4.8 m vehicle length) to be invoked. The speeds and the length of time the LV was to hold, once that target speed was achieved, were developed in collaboration with the Crash Avoidance Metrics Partners.

The results in Figure 16 shows one of the shortcomings of using radar-based time gaps as a performance measure. Despite changing the Time Gap scale from 0-3 to 0-8 s, as the 4 FV speeds fall below 10 m/s (~22 mph), doing so faster than the LV, the Green (FV1) time gap goes off scale.

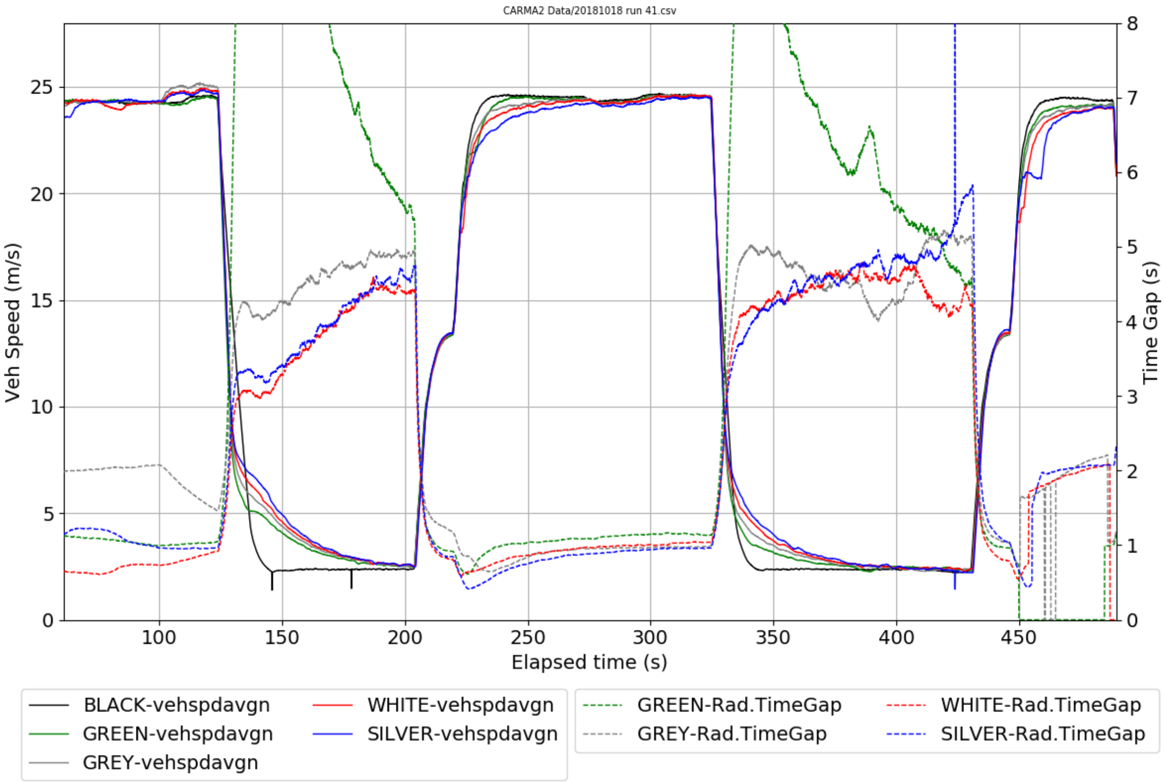


Figure 16. Time Gaps with 55→5→55→5 mph LV Commanded Speeds

Figure 17 changes the Y axis to Range and captures the maximum Green (FV1) range of ~70 m at Elapsed time of ~170 s while FVs 2-4 are in the range of 20-30 m. Figure 18 changes the Y axis to GPS-based Distance Headway providing a good illustration of the relative response to their respective preceding vehicles and to the LV. The APF platooning algorithm demonstrated the following positive results:

- Opened up the gap on a heavy LV deceleration that is very important to driver acceptance.
- Did not go unstable, all FV vehicles speeds and gaps responded smoothly with minimum oscillation.
- Minimum gaps during the run were always above 2 vehicle lengths, ~10 m.

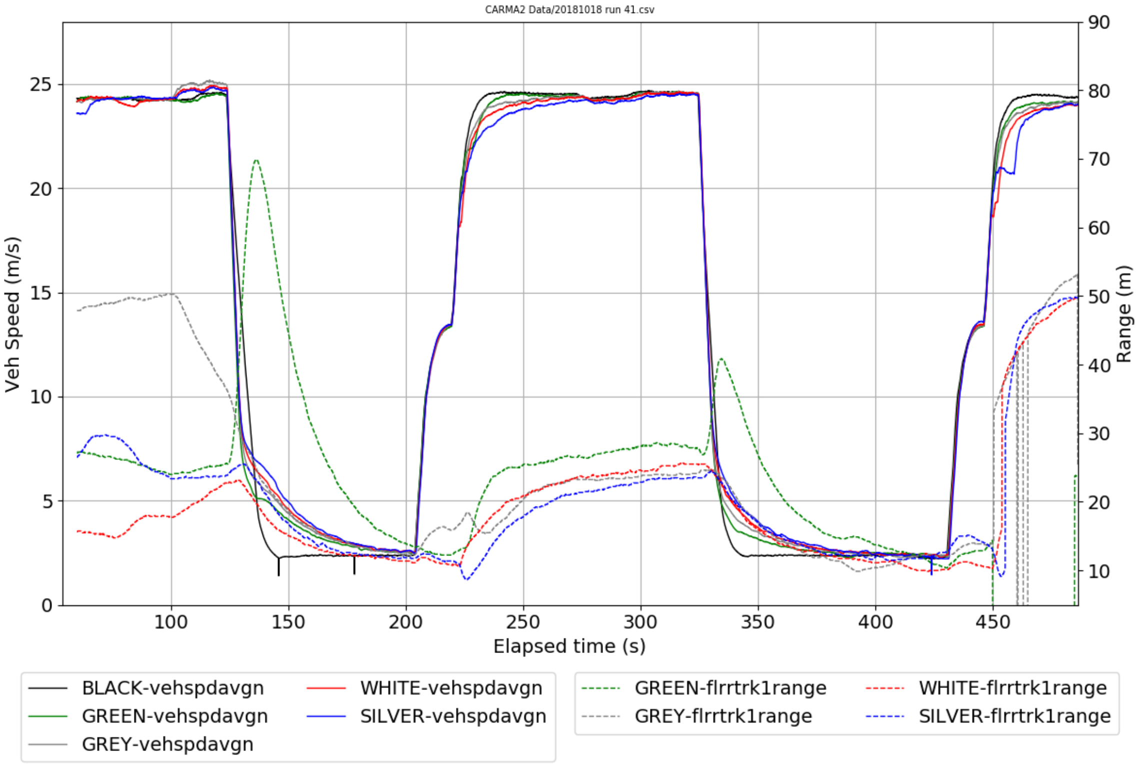


Figure 17. Ranges with 55→5→55→5 mph LV Commanded Speeds

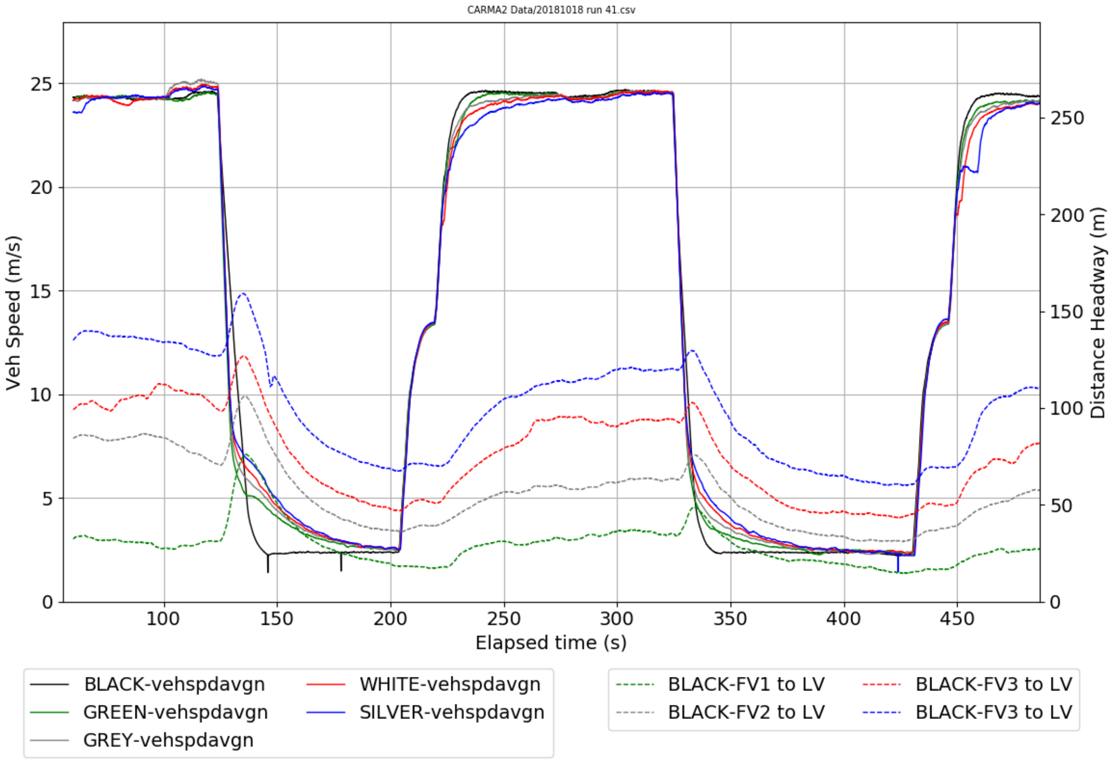


Figure 18. Distance Headways with 55→5→55→5 mph LV Commanded Speeds

2.5.2 Acceleration and Commanded Axle Torque/Stability

In addition to closely matching the LV speed and maintaining commanded time headways, there are other platooning performance parameters that are considered important for overall driver acceptance. Driver acceptance requires that the vehicle dynamics feel naturalistic and perform within normal driving expectations.[2] This analysis selected the commanded axle torque and its concomitant vehicle acceleration as additional performance measures for platooning. Both parameters have limits that are set within the CARMA2 control system and are calibrated during development of the platooning application.

Figure 19 shows plots of commanded torque ranging from 2000 to -500 Nm and resulting vehicle acceleration from 1.7 to -2.0 m/s^2 using a route file 45→60→45 mph LV commanded speed and 4 FVs with 1.24 s commanded time headway (1.0 s gap time @ 45 mph) platooning test.

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[2] ISO ACC standard allows 2.0 m/s^2 acceleration and -3.5 m/s^2 averaged over 2 s. These values are used in this report to define normal driving.

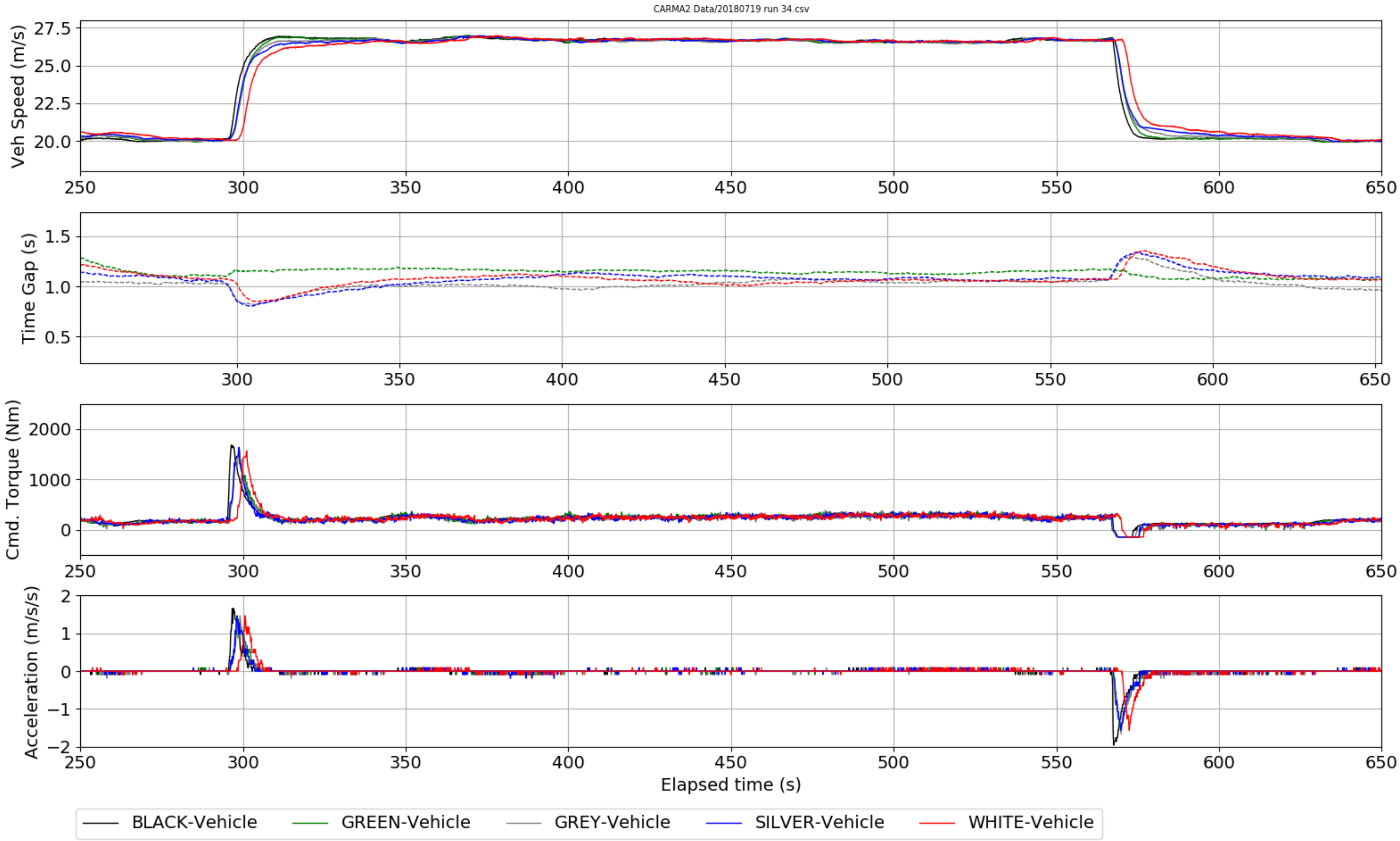

Figure 19. Commanded Axle Torque and Vehicle Acceleration

Taking a closer look at speed and time gap stability during the acceleration, steady-state of 60 mph, and deceleration timeframes, Figure 20 shows that all five vehicles achieve the target speed of 26.8 m/s between Elapsed time of 325 – 350 s and maintain a narrow speed range of 26.5 to 27 m/s until after Elapsed time of 560 s where the commanded speed is changed back to 45 mph. Moreover, the time gaps of the four FVs during the acceleration to 60 mph (26.8 m/s) reach a minimum of about 0.8 s, but recover to above 1.0 s later during a 50-s period. During steady state, vehicles move well with the appropriate time gap. However, around the deceleration maneuver (~570 s), the LV command speed changes from 60 mph to 45 mph. At this moment, the time gap of three of the four FVs rises above 1.25 s for a brief period.

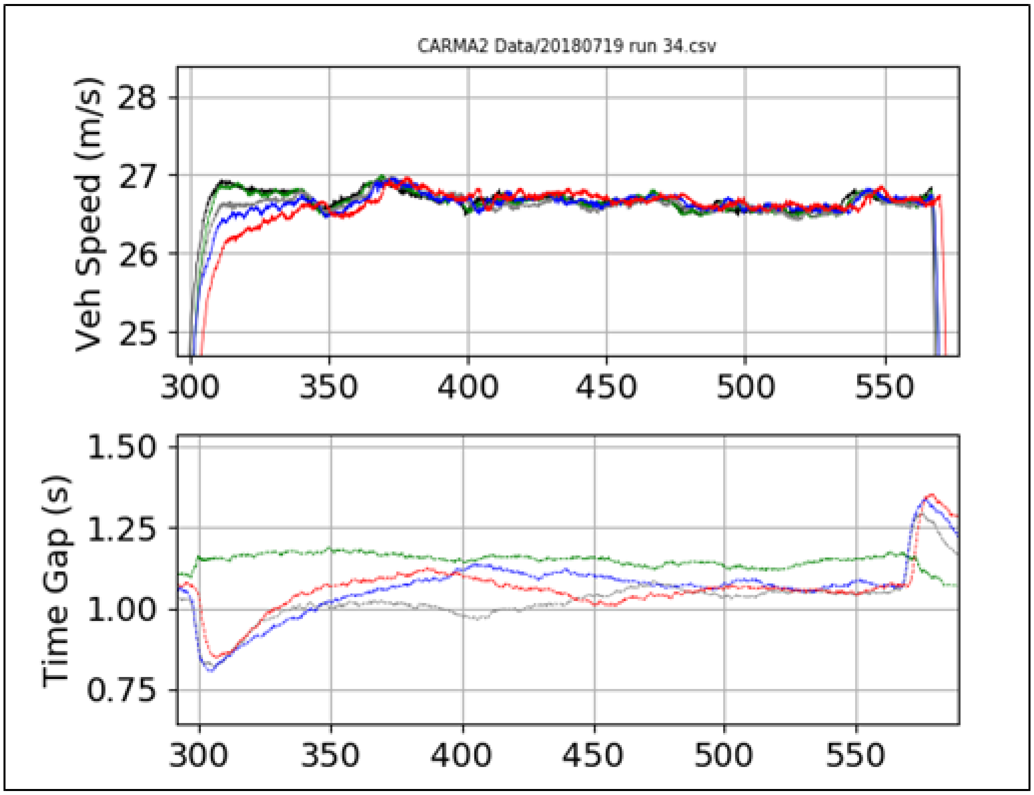

Figure 20. Speed and Time Gap Stability at Commanded 45-60-45 mph LV Speeds

2.5.3 Throttle Plate Motion and Fuel Economy

Figure 21 adds plots of two other platooning performance measures to the speed and time gap plots shown previously, and zooms in to focus on a 10-s window from 420 to 430 s Elapsed time. The two added performance measures are also considered important to driver acceptance: throttle plate angle and fuel economy. Excessive throttle motion is detrimental to fuel economy[3] and can cause driver-perceptible vehicle surge.

As seen in Figure 21, the throttle angle plot of the Black (LV) has less fluctuation than any of the FVs. This is considered to be, at least in part, due to each FV trying to maintain the desired distance/time headway to its current LV. To adjust the distance/time headway, a vehicle ought to change its relative speed with respect to its leader. This APF platooning algorithm has an inherently more complex task than the LV only trying to maintain a constant speed. Track test and development time were primarily focused on closely matching the LV speed and maintaining the targeted time headway setting, which it did very well. Additional test and development time will be needed to understand and optimize trade-offs between speed and distance/time headway control, and throttle motion and fuel economy.

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[3] Fuel economy effects of traditional speed control, ACC, CACC, and platooning will be addressed in the conclusions and recommendations section.

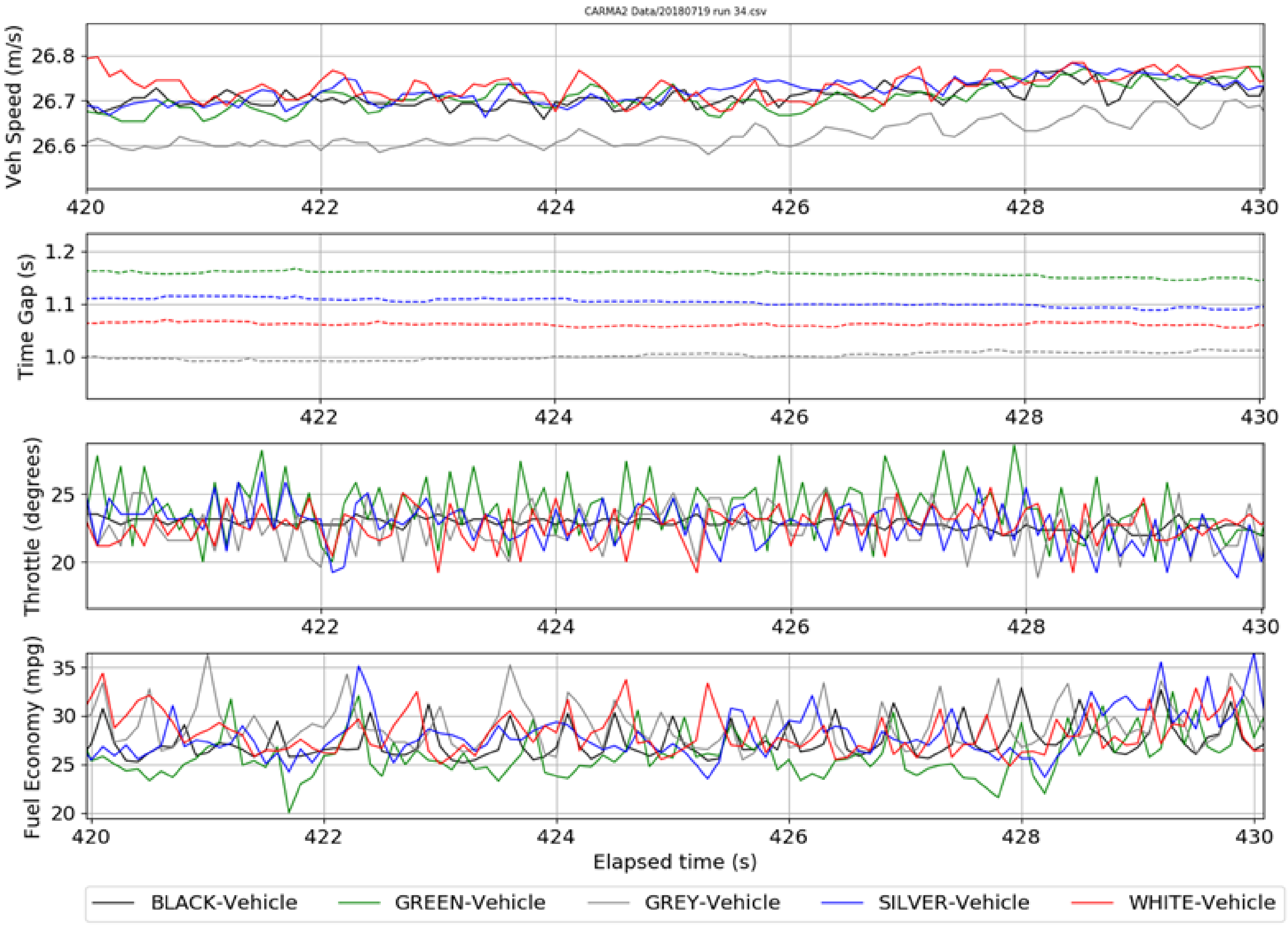

Figure 21. Throttle and Fuel Economy Performance in Five-Vehicle Platoon

2.5.4 Brake Light Activation

Brake lights must be illuminated under certain deceleration conditions following the Federal Motor Vehicle Safety Standards; however, at constant speeds, brake lights should not be (under normal circumstance) on or flickering. It could be hazardous when the time gap is low (e.g., 0.6 s) and/or at high speeds where the FV drivers may react by braking their own vehicle. Figure 22 adds the Brake Light Flag parameter and shows no brake light activation for any of the four FVs during the LV commanded constant speed of 60 mph portion of the test.

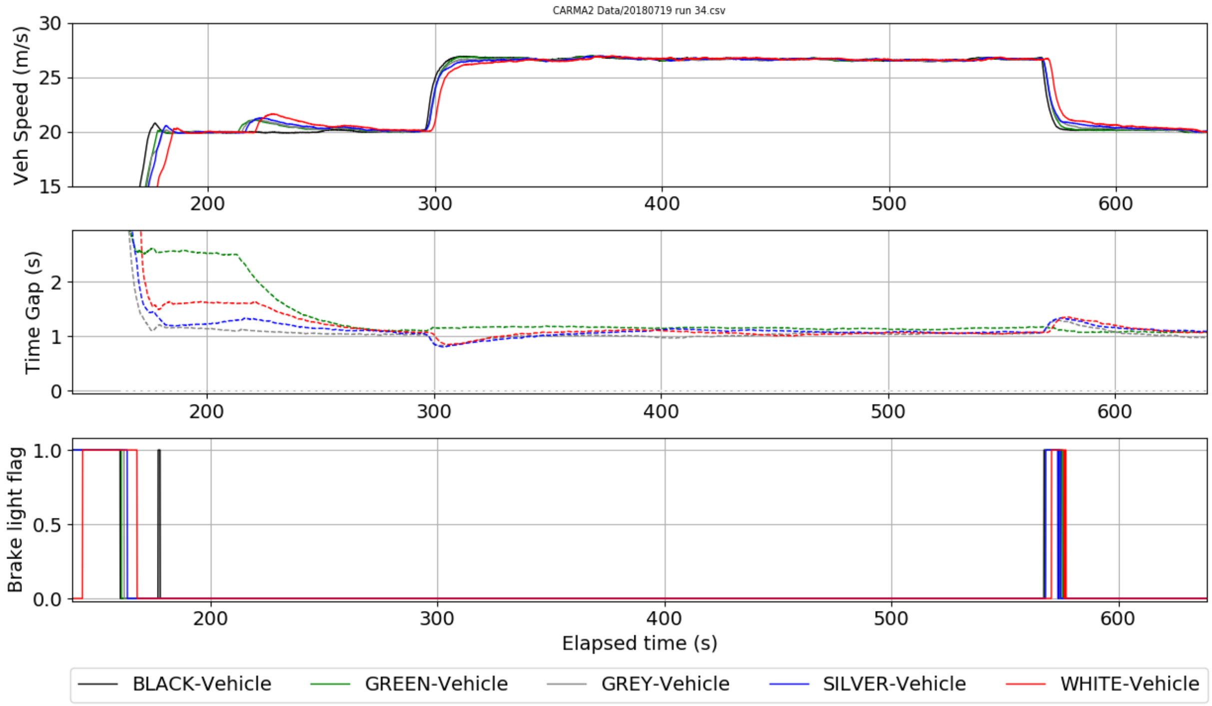

Figure 22. Vehicle Speed, Radar Time Gap, and Brake Light Flag in Five-Car Platoon

2.5.5 Length of Platoon

Length of the platoon is an important performance measure since it is a global measure of the platooning impact on mobility improvement and driver acceptance. In the future, CADS-equipped vehicles driving at smaller distance/time headways than manual driving will increase roadway capacity. Mobility improvement may involve many parameters; however, the total length of roadway occupied by the platoon is one key parameter. All other parameters being held constant, minimizing the amount of roadway needed for any given group, string, or platoon of vehicles is an important parameter of the “roadway cost”. In addition, minimizing the platoon length is also considered an impediment for “cut-ins” by other road users. This is important because reducing “cut-ins” will have a positive effect on driver acceptance. Figure 23 illustrates our definition of the platoon length. It can be derived from the sum of all four radar range measurements and adding the vehicle lengths of all four FVs, or from the GPS latitude and longitude data between the LV and each of the four FVs in the platoon. Latitude and longitudinal data used in the headway calculations are based on antenna-to-antenna GPS measurements. All five SRXs have a common GPS antenna location towards the rear of the vehicle. Table 2 shows sample results of the headway distance using the radar- and GPS-based calculations.

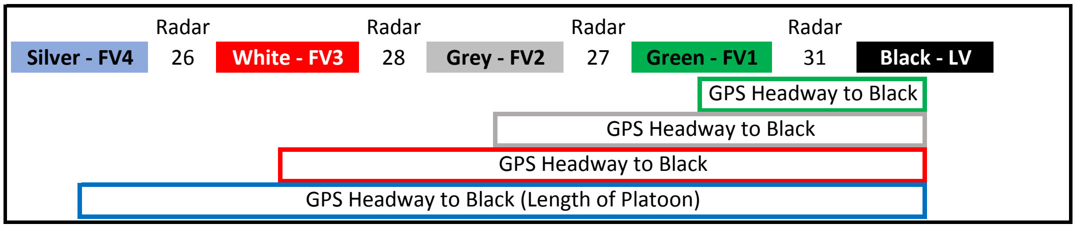

Figure 23. Headway (m) of Platoon Illustration

Table 2. Sample of Radar Based and GPS Based Headway

Vehicle Length (m)	Vehicle Color	Radar to Preceeding (m)	Radar-Based Headway to Black (m)	GPS-Based Headway to Black (m)
4.8	Black			
	Green	31	36	40
	Grey	27	68	70
	White	28	100	100
	Silver	26	131	132

The actual length of the platoon would be one vehicle length longer than the calculation in Table 2 if the LV length were included.

Figure 24 presents an example plot of platoon length (headway distance from FV4 to LV) for a five-vehicle platoon, which is added to the plots of vehicle speeds and time gaps from a fairly complex ~300 s run with the route file repeating LV commanded speeds of 60-25-60 mph. Time gap is shown using the inside right Y axis, and platoon length (headway from Silver (FV4) to LV) is shown on the outside right Y axis by the solid violet line. Better control of the platoon length, between Elapsed time of ~100 – 120 s, is observed earlier in the run; however, this control is not quite as good in the later part of the run as the platoon length increases between Elapsed time of ~200 – 250 s.

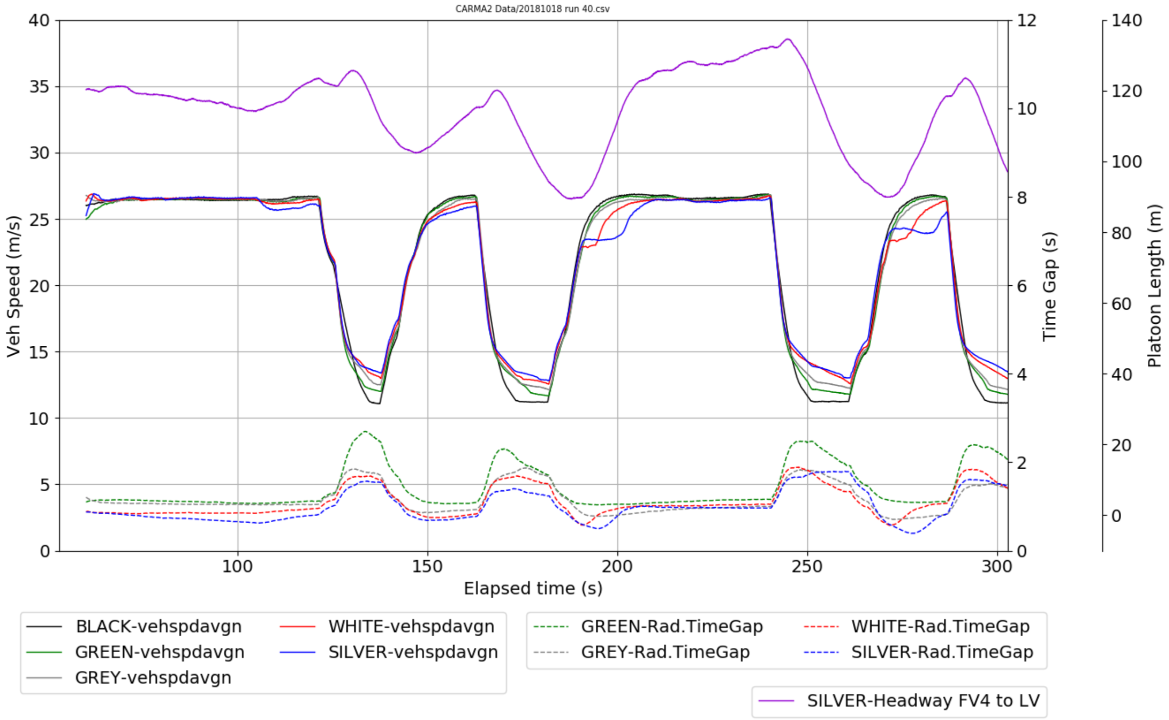

Figure 24. Platoon Length Example of four FV Platoon at 60-25-60 mph LV Commanded Speeds

3. Speed Harmonization

This section describes the concept of a traffic management system that improves traffic flow by harmonizing the speed of equipped vehicles. There is a wide range of potential technical implementations of speed harmonization; however, they all share the basic ability to remotely (conceptually from a traffic control center) command and change the speed of certain vehicles at a specific geo-position along a highway/roadway.

3.1 Application Description

Speed harmonization is a traffic management framework that aims to reduce speed differentials and smooth the flow of traffic with dynamic, real-time adjustment of vehicle speed recommendations or commands. It aims to improve traffic performance, increase safety, enhance mobility, and/or reduce environmental impacts. Existing studies have posited that vehicle speeds tend to fluctuate when traffic transitions from free flow to congested conditions, and that decreasing traffic speeds can smooth the speed trajectory of incoming vehicles and reduce vehicle speed variations without adversely impacting traffic capacity. This current activity focuses on the vehicle-side implementation of the speed harmonization, including command receipt and execution [10].

3.2 Plugin Operation

The speed harmonization plugin, included with the CARMA2 platform, enables remote server control of the vehicle's speed. The speed harmonization server is deployed remotely in the cloud. Once the HV is registered and engaged (or under automated control), the server communicates with the plugin running in the HV a set of messages exchanged via HTTP/REST[4] through a cellular modem installed on the HV. In turn, the HV sends periodic data, including its speed, location, and automation status, to the server. Based on this information, the server will use the assigned algorithm for the registered HV to come up with the appropriate commanded speed. The speed harmonization plugin then inserts a complex maneuver, a maneuver capable of dynamic speed command updates, into the HV's motion profile that will allow it to execute the speed commands. The plugin's *maneuver class* ensures that speed and acceleration limits are within the bounds set within the CARMA2 platform.

The remote server is able to send speed commands at a variable rate. Once the HV receives the commanded speed, the *guidance package* takes the commanded speed into account and, based on the plugin's priority, calculates vehicle trajectory and issues that appropriate speed command to the vehicle's longitudinal controller to execute. The vehicle simply maintains the last speed command it received, or if one was not yet sent, it simply maintains the current speed of the vehicle until the first

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[4] **HTTP** stands for **H**yper**T**ext **T**ransfer **P**rotocol and is a way to transfer files. **RE**presentational **S**tate **T**ransfer, or **REST**, is a set of constraints that ensure a scalable, fault-tolerant and easily extendible system.

speed command is received. This continues until the speed harmonization plugin is deactivated by the user or route file, out-prioritized by another plugin, or the connection with the server times out or otherwise fails.

Prior to receiving speed commands, the HV must register with the speed harmonization server. Once the speed harmonization plugin on the HV's CARMA2 platform is activated, the HV will attempt to connect to the server to register its vehicle ID and acquire an assigned vehicle session ID from the server as confirmation. The server tracks all of the HV sessions and status updates in a backend SQL database. This registration causes the server to create an instance of the appropriate logical class in the server and allow that code to control the HV, sending speed commands at whatever rate the algorithm deems necessary.

3.3 Test Procedures

This section describes the test procedures that were used to conduct characterization testing of one to five vehicles utilizing the Speed Harmonization application at the U.S. Army's ATC in Aberdeen, Maryland. The tests involved a fleet of five 2013 Cadillac SRX passenger vehicles that the TFHRC's Saxton Transportation Operations Laboratory had equipped with the CARMA 2 platform. Each test procedure may be used with different route files to change the dynamics of the vehicles.

3.3.1 Generic CARMA2 Test Procedures

3.3.1.1 Evasive maneuver "bail" procedures: Same as ***2.3.1.1 Evasive maneuver "bail" procedures*** used for platooning.

3.3.1.2 Route files: Same as ***2.3.1.2 Route files*** used for platooning. Speed Harmonization can be independently disabled at specific waypoints using the *DisableAlgorithm* Route file parameter.

3.3.1.3 Initial Set Up: One to five vehicles down the track from the route start, stopped with 50 m separation distances, centered alternatively between the inside and outside lanes. Drivers select the test conductor's requested Route file and application plugin(s) via the UI tablet.

3.3.2 Speed Harmonization Initial Engagement

Following the test conductor's instructions, the first vehicle manually accelerates up to 5 mph of the initial Route file speed and engages automatic control. Simultaneously, each of the FVs matches the first vehicle's speed while maintaining the target separation distance and engages automatic control once the vehicle immediately ahead already has, as indicated by the LED lights mounted in the rear of each vehicle. The intent is to have each vehicle sequentially engage automatic control prior to Speed Harmonization. Speed Harmonization is disabled in the route file until the reference point "130 wide" waypoint. Point 130 is the beginning location along the back side of the track where additional paved road is inside adjacent to the two primary lanes, allowing more room for evasive maneuvers.

3.3.3 Speed Harmonization Intermediate Conditions

The test design intent is to allow from one to five equipped vehicles to change the commanded speed from that specified in the Route file to that received through the vehicle resident cellular modem. Drivers manually control separation from the vehicle ahead and maintain their center of lane position while observing the speed change. Speed Harmonization commanded speeds can be a specific speed or a plus or minus speed from the Route file. Testing conducted at ATC was typically run using a -5 mph speed change with the location of the server residing on a PC inside one of the vehicles under test to simplify testing.

3.3.4 Speed Harmonization End of Cellular Transmission

At the end of the test or as disabled in the Route file, the vehicles return to the Route file commanded speeds. Drivers return to the starting position or off track under manual control as instructed by the test conductor.

3.4 Performance Measures

The following data elements and performance measures are utilized to evaluate speed harmonization:

1. Route commanded speed (data element name- *route speed*) waypoint-based target speed from Route file.
2. Vehicle speed (data element name – *vehspdavgndrvn_srx*) vehicle average speed of non-driven wheels.
3. Speed Harmonization commanded speed or speed delta from test procedures/logs.
4. Speed Harmonization enabled flag – *SpeedHarm enabled.*
5. Brake light flag (data element – *brklightflag_SRX*) driver control brake light “on” if observed.

3.5 Test Results

Several test runs were conducted with the Speed Harmonization calling for a specific travel speed. Vehicles receiving the signal responded as expected at the appropriate waypoint either by accelerating or decelerating from their present speed, as called for in the Route file, to the speed specified in the Speed Harmonization communication. Other runs were conducted using a -5 mph delta speed command. The constant delta speed is useful to allow using one Speed Harmonization set-up/ configuration with many different Route files. Most of the runs used the -5 mph delta speed command to facilitate using Speed Harmonization with any route file without introducing abrupt accelerations or decelerations, which proved useful in efforts for integrating multiple functions as described in Section 4, Ramp Merge.

Despite efforts to implement a track-wide cellular network capable of continuous communications with multiple vehicles, a reliable network was not achieved. As such, the majority of testing and our test results presented in this section were conducted with one vehicle where the server resided on a dedicated/stand-alone PC inside the vehicle. Simultaneous speed harmonization and platooning plugins were demonstrated on I-95 public road testing.

The Route file used in the testing enabled speed harmonization at specific locations on the track. Unless Speed Harmonization is enabled, the Route file speed limit is used for the commanded speed. Figure 25 illustrates a single vehicle (green vehicle) using a constant speed Route file with a 45 mph speed limit. Speed harmonization is initially disabled until the vehicle passes a waypoint (elapsed time ≈ 58 s) where it is enabled, continues to be enabled until a second waypoint (elapsed time ≈ 152 s) is passed where it is disabled for a short distance, and then is enabled again near the end of the run (elapsed time ≈ 165 s). The Speed Harmonization (-5 mph) delta speed command was being broadcast throughout the run. 5 illustrates plots for the following parameters:

1. Route speed of 45 mph (20.1 m/s), specified in the route file (*black dashed line, right side scale*).
2. Green vehicle speed in m/s (*green solid line, near left scale*).
3. Speed harmonization 0-disabled or 1-enabled (*violet solid line, far left scale*).

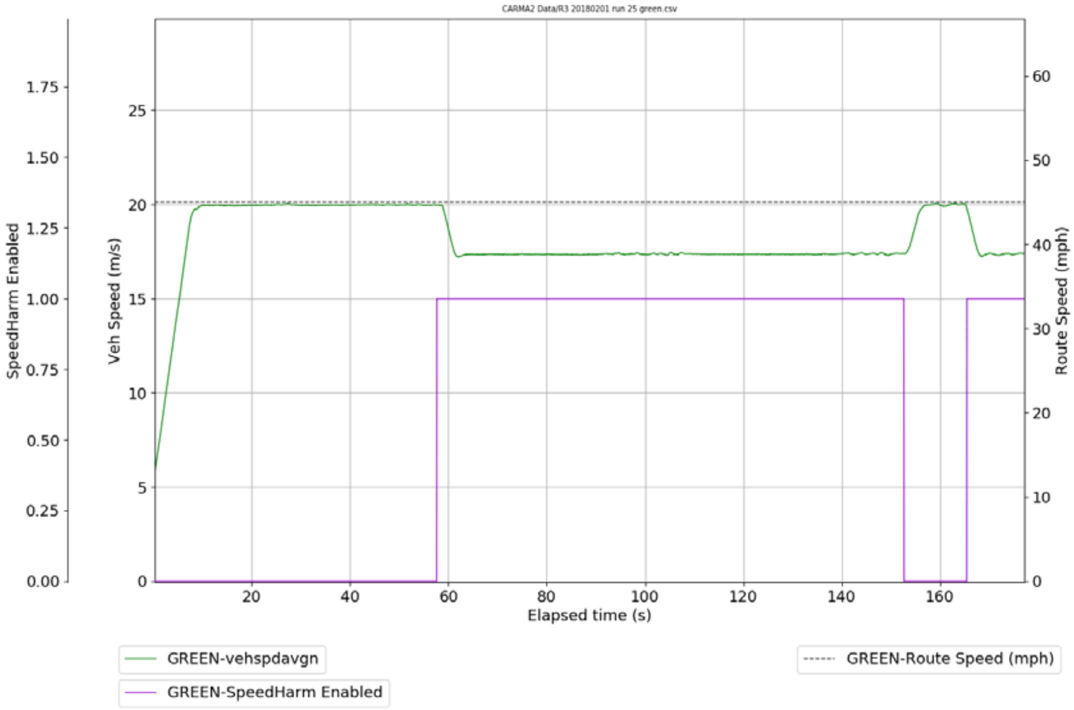

Figure 25. Speed Harmonization with 45 mph Route, -5 mph Commanded Speed

Figure 26 zooms into the deceleration commanded by the Speed Harmonization at elapsed time ≈ 55 s.

The following observations are noted:

1. Brake light activation (*red dashed line, far right side scale)* at elapsed time ≈ 59 s*.*
2. The delay from ≈ 55 s at speed harmonization-enabled flag (*violet dashed line, near right side scale)* to ≈ 59 s at brake light activation does not reflect the traditional "response delay" time measurement from the actual time the speed harmonization command is issued until the deceleration command is implemented by the guidance control system. This is because the speed harmonization-enabled flag is taken directly from the Route file and not from when communicated to the control system, while the brake light flag is a vehicle-level signal likely as a result of the deceleration rate or brake command.
3. The rate of deceleration is derived as follows: delta speed/delta time estimated to be -2.75 m/s divided by 4 s ≈ -0.7 m/s^2.

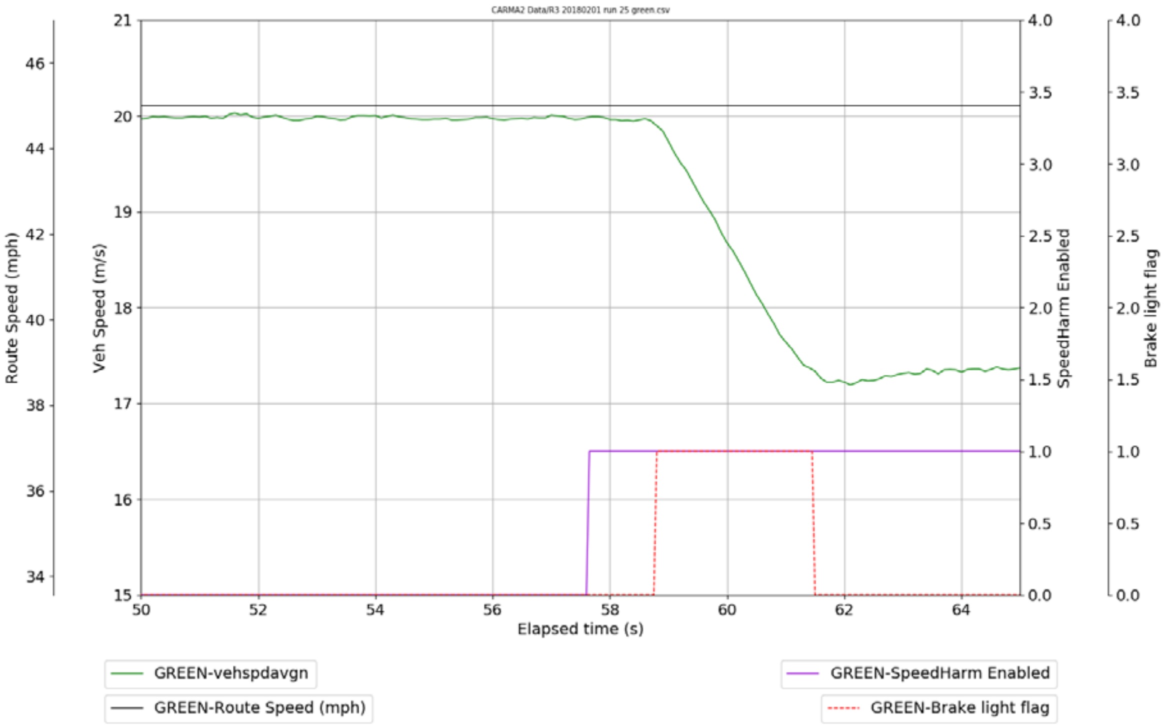

Figure 26. Deceleration Zoom for Speed Harmonization with 45 mph, -5 mph Command Speed

4. Cooperative On-Ramp Merge

This section describes the Cooperative On-Ramp Merge special "use case" of the broader cooperative merging application, and the specific test procedures and performance measures used for initial development and testing at ATC. As described in [11], "the concept of cooperative merging leverages V2V and V2I communications to enable CADS-equipped vehicles to signal other vehicles via DSRC of their intention to merge into traffic streams. Using this information, merging vehicles may identify upcoming acceptable gaps on the mainline and make lane changes when possible. In addition, upstream managed lane vehicles may cooperate by adjusting their speeds to create a gap for the requesting vehicle. The trajectories of merging vehicles are then optimized."

4.1 Application Description

The Cooperative On-Ramp Merge plug-in is intended to automatically position the HV at a specific waypoint to emulate a "stop bar" adjacent to the lane of traffic/travel that one to four CARMA2-equipped vehicles in a platoon are approaching at highway speeds. As the approaching vehicle(s) get closer, the HV user interface prompts the driver to allow the automatic longitudinal control to accelerate from a stop and join the platoon from the rear. Prompting the driver to allow automatic control from a stop, as opposed to, just self-initiating the acceleration, is considered a safety requirement to assure that the driver is comfortable and ready for the maneuver. When prompted, the driver depresses the throttle slightly (brakes are still applied automatically to hold the vehicle stopped) to signal automatic brake release and launch of a complex trajectory that is designed to position the HV at the appropriate speed behind the approaching vehicle(s) in the adjacent lane. The driver manually adjusts the lateral position (i.e., steers) onto the adjacent lane.

This application is intended to time the acceleration of an HV from a stop in an adjacent lane such that the HV will be at the appropriate speed to join a four-vehicle platoon at the rear. For safety consideration, the driver is requested to depress the throttle momentarily when prompted by the UI and to steer the vehicle into the same lane as the platoon when it passes.

4.2 Test Procedures

A test procedure was devised to prove out the Cooperative On-Ramp Marge plugin application. The intent of this procedure is for the HV to accelerate from a stop, merge onto an adjacent lane, and join the rear of a previously-formed platoon of one to four CARMA2-equipped vehicles approaching in the same adjacent lane. This test procedure consists of the following steps:

4.2.1 Generic CARMA2 Test Procedures

4.2.1.1 *Evasive maneuver "bail" procedures: Same as 2.3.1.1 Evasive maneuver "bail" procedures used for platooning HV bail maneuver* – Ramp Merge HV driver primarily stays in the same lane adjacent to the platoon lane, and secondarily brakes.

4.2.1.2 *Route files: Select specified "route" with "Cruising", "Platooning", and "Speed Harmonization" plugin applications on all vehicles.* Add "Coordinated Lane Change" to the Ramp Merge HV via the UI prior to "START CAV Guidance".

4.2.1.3 *Initial Set Up:*

- Position from one to four platooning vehicles (LV, 1-3 FVs), stopped and centered in the outside lane 20 – 30 m apart with the LV 30-40 m before Waypoint 95, as seen in Figure 27.
- Position the On-Ramp Merge HV, stopped and centered in the inside lane at Waypoint 100.

Figure 27. ATC Ramp Merge Set up Map

4.2.2 Ramp Merge Initial Engagement

- On test conductor's command, the on-ramp merge HV manually accelerates to 5 mph of the Route file commanded speed and engages automatic longitudinal control. Observe that the HV decelerates to a stop at Waypoint 135, with CARMA2 automatic braking applied.
- On test conductor's command, platooning vehicles manually accelerate to 5 mph of the Route file commanded speed and engage sequentially to form a platoon. Observe that speed harmonization has reduced the LV speed to 5 mph below the Route file commanded speed.

4.2.3 Ramp Merge Intermediate Conditions

- On UI prompt, the on-ramp merge HV driver accelerates to 5 mph.
- Verify that the HV accelerates as platooning vehicles approach in the adjacent lane.
- On UI prompt to change lanes, the on-ramp merge HV driver checks for clearance, activates the turn signal, and changes lanes.
- Verify all vehicles are platooning.
- HV bail maneuver – Primarily stay in the same lane adjacent to the platoon lane, secondarily

brake.

4.2.4 On-Ramp Merge End of Route

At the end of the route, platooning and automatic control are disabled by CARMA2. Drivers return to the starting position or off track under manual control as instructed by the test conductor.

4.3 Test Results

Early testing focused on the "Coordinated Lane Change" plugin to facilitate a request by the HV for a gap to be created between two CARMA2-equipped vehicles in an adjacent lane, sufficient to allow the HV to change lanes between them. This DSRC-based plugin proved difficult to implement. Instead, the plugin focus changed to the Cooperative On-Ramp Merge application to support the FHWA priority for an integration of platooning, speed harmonization, and ramp merge applications required for the I-95 public road demonstration of an Integrated Highway Priority (IHP) use case scenario where a single vehicle would join an existing four-vehicle platoon from the rear with the platooning LV under speed harmonization.

The following is a list of observations about the execution steps and their challenges for the Cooperative On-Ramp Merge application and test procedures:

1. HV (Silver car) under automatic control must come to a stop at a specific waypoint and hold. Coming to a stop and holding for an extended time is a new and atypical maneuver for the system, triggering "time-outs" of the basic guidance/trajectory planning functions.
2. A one- to four-vehicle platoon is approaching in the outside adjacent lane, released by the test conductor from the Ramp Merge HV. The computational challenge of the control system is that the HV must determine the last vehicle in the approaching platoon and calculate the speed profile and trajectory needed to merge from behind.
3. HV driver is prompted to "throttle over" allowing the vehicle to accelerate to a commanded speed. The prompt is showing the HV driver a "commanded speed" increasing from 0 on the UI. The HV driver steps on the throttle while automatic control takes over and accelerates the vehicle from a low speed. Acceleration from a stop or low speed has not been a focus area, the low-end longitudinal controller proved to be challenging. Repeatability of the release time, driver reactions, and HV acceleration rates were less than desired compounding the computational challenge.
4. As the HV is accelerating up to the command speed, the HV driver is moving laterally towards the platoon in the adjacent lane. The design intent is to have the HV join from the rear; however, for a considerable time, the HV is moving parallel to the platoon as it passes longitudinally. By design, the platooning plugin allows "ad-hoc" formation where there is no predetermined following vehicle order. As such, the Ramp Merge HV moving parallel to the existing platoon often tried to join behind the wrong vehicle.

5. Test procedures need to be developed to more realistically reflect the dynamics of a Ramp Merge HV positioning on a ramp and existing platoon approaching in an adjacent lane, which improve the repeatability of the speed profile and trajectory plan for joining the end of the platoon.

Chapter 4 in [11] provides details of successful execution a ramp merge with a four-vehicle platoon and the LV under speed harmonization use case conducted on the Express Lanes facility on I-95 with the CARMA2 Cooperative Merging Application. Development testing at ATC concluded May 24, 2018 without achieving full design intent testing successfully.

5. Conclusions and Recommendations

This report presented the results of the analysis that was conducted for the test and evaluation of three mobility applications utilizing capabilities afforded by connected and cooperative automated vehicle technologies. The goal of the analysis is to better understand how these applications are advancing their functional capabilities, in order to realize their potential benefits in improving mobility, traffic flow stability, and safety. Another goal of the analysis is to identify opportunities for further improvement of these capabilities. Test procedures and performance measures were developed and used to provide a summary of test results for each application. Each of the three applications was discussed based on the results of the testing and analysis conducted in the following order:

- CARMA2 APF Platooning
- CARMA2 Speed Harmonization
- CARMA2 Cooperative On-Ramp Merge

The development and testing of these three applications were prioritized to support the TFHRC's IHP I-95 express lane demonstration discussed in [11].

5.1 APF Platooning

The APF-based platooning algorithm demonstrated significant improvement for primary objectives to closely match the LV speed and maintain a close match to the targeted time gap. When compared to the CARMA1 CACC-based platooning proof-of-concept level, the CARMA2 APF platooning algorithm showed the following improvements for 45→60→45 mph Route files unless otherwise noted:

1. APF targeted time gaps were reduced from 1.2 s to 1.0 s for all tested Route files.
2. APF achieved speed and time gap stability at targeted time gap of 0.6 s.
3. APF time gap errors were limited to -0.2 to 0.25 s versus CACC from -0.9 to 0.7 s.
4. APF speed errors were virtually eliminated (less than 0.5 mph) versus CACC from -5 to 3 mph.

Secondary performance objectives, primarily associated with driver acceptance and cited as areas for improvement for CACC proof-of-concept report [8], were also virtually resolved. Driver acceptance requires that the vehicle dynamics feel naturalistic and perform within normal driving expectations[5], as well as considering the following factors:

1. Commanded torque value stability
2. Acceleration rates
3. Throttle plate movement and fuel economy effects

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[5] ISO ACC standard allows 2.0 m/s^2 acceleration and -3.5 m/s^2 deceleration, averaged over 2 s. These values were used to define normal driving in this report.

4. Brake light activation only on decelerations associated with commanded speed changes in the route file.

Fuel economy effects associated with driver acceptance can best be explained as follows. The most basic OEM-supplied speed control is marketed as a “Comfort and Convenience” product. For best fuel economy, the throttle should be held at a constant position thereby allowing vehicle speed to vary for small changes in wind conditions, road grade, curvature, and surface friction. Doing so results in the vehicle increasing and decreasing speed, but maintaining a minimum change in engine RPM and mass flow of air/fuel through the engine as it traverses the path and, all other things being equal, using the minimum amount of fuel. The trade-off for the driver has always been to keep a constant and selectable speed that allows the driver to adjust the time of arrival (by speeding up or slowing down) using automatic throttle control at the expense of fuel economy.

The addition of platoon Length as a performance measure has been introduced to provide a measure more directly related to road use cost, and as a more useful performance measure than traditional response time or other suggested measures of a platoon to respond to a change in LV. Traditional response time performance measure may encourage more aggressive response detrimental to fuel economy without benefit to improving mobility, traffic flow stability, and safety.

5.2 Speed Harmonization

The speed harmonization application demonstrated the basic design intent to facilitate changes to commanded speeds via cellular and potentially other wireless technologies as if being sent from a traffic control center. Absolute speeds and a fixed change to a commanded speed presently in use were successfully tested. A route file “application disable” parameter was incorporated to allow select vehicles to be unaffected by the request, which was also successfully tested. These features proved beneficial to integration effort using multiple applications at the same time as discussed in [11]. Signal availability on the ATC track, located in quite a remote area, was a significant challenge limiting testing and evaluation.

5.3 Cooperative On-Ramp Merge

This ramp merge application is a special use case of the more encompassing Coordinated Lane Change application. The limited amount of time available for testing demonstrated the limitations of the existing Route file that uses a single set of geo positions along the centerline of the main two lanes of the test track to unambiguously define the route of a vehicle approaching from an adjacent lane. Good progress was made; however, challenges to automatically stop and hold a vehicle at a specific waypoint and then accelerate to the correct speed of vehicle(s) approaching in an adjacent lane from the rear were not reliably resolved. The following Recommendations section attempts to address some of these challenges in more detail.

5.4 Recommendations

This section is intended to provide some potential recommendations to improve the CARMA2 applications as they undergo further advancements in future efforts.

5.4.1 APF Platooning

- Replace/repurpose Route files speed limit commands to replace the “step functions” with functions to match accelerations and decelerations that are optimized for platoon lengths and driver comfort. This could, in part, be based on mobility benefits estimations using computer simulations balanced by naturalistic driving studies, preferably of traditional speed control and/or ACC. Alternatively, develop an “Eco-Approach” type algorithm for vehicles to minimize throttle movements for terrain and other road users ahead.
- Provide guidance for developers to balance secondary objectives with the primary objectives to match LV vehicle speed and closely match target time gaps.
- Be careful not to lose the improvement in driver confidence of the nearly-simultaneous movement of the FV in response to the LV presently achieved.

5.4.2 Speed Harmonization

- Investigate ways or technologies that will allow full coverage of the wireless communications being used for all vehicles and/or adjust testing locations where more alternatives are available.
- Investigate alternatives to replace “application disabled” in the Route file to be independently disabled on the UI tablet.

5.4.3 Cooperative On-Ramp Merge

- Utilize capabilities of higher fidelity maps for trajectory planning.
- Revise test procedures to have a more fully-scripted plan for synchronized timing of all vehicles used in the test.

5.4.4 Utilization of Expected CARMA# Added Capabilities

The addition of lateral control in CARMA3 with its inherent improvements for positioning, object recognition, vehicle modeling, and functional- and application-specific arbitration represents an opportunity to set/start to understand and verify application-specific functional requirements prior to higher level application development. To even partially realize application-specific improvement, the following sub-systems should have functional objectives set and verified:

- Positioning accuracy, including availability specification.
- Map matching accuracy present and future push ahead.

- Trajectory planning.
- Longitudinal control from 0 to 75 mph with detailed dynamic performance objectives.
- Lateral control – position in lane, time to lane crossing, minimum and maximum lateral speed versus longitudinal speed dynamic performance objectives.

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[11] Leidos, *Applying Bundled Speed Harmonization, Cooperative Adaptive Cruise Control, & Cooperative Merging Applications to Managed Lane Facilities,* Final Report FHWA Saxton Transportation Operations Laboratory, Project No. DTFH6112D00020 T0 26 to be published 1st quarter 2019.

Appendix A: Comparative Plots from 2016 CACC Proof-of-Concept

The production system performance contrasts significantly with the CACC performance, which is shown in Figure 28. As seen in Figure 29, 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.

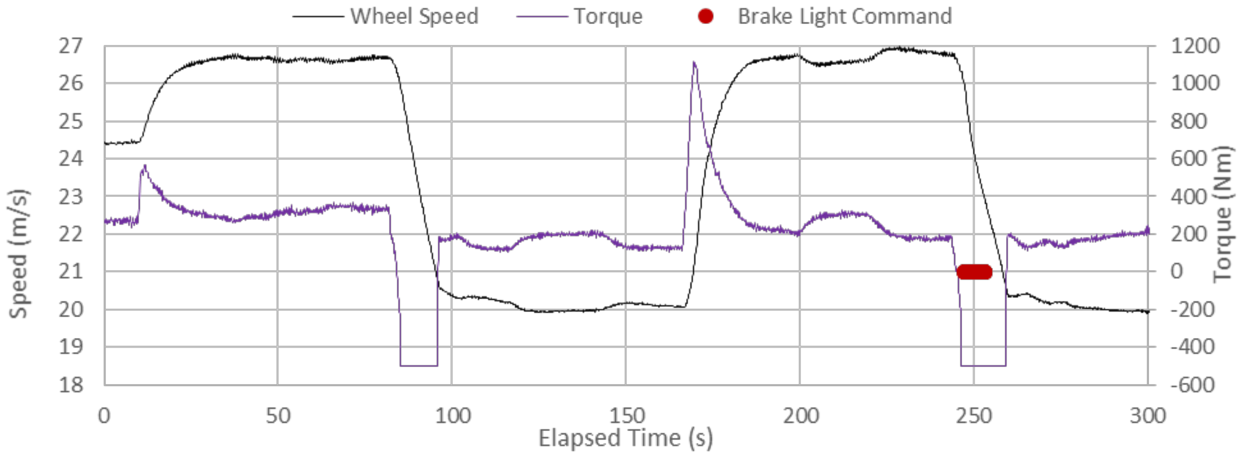

Figure 28. Production ACC LV Torque (60→45→60 mph)

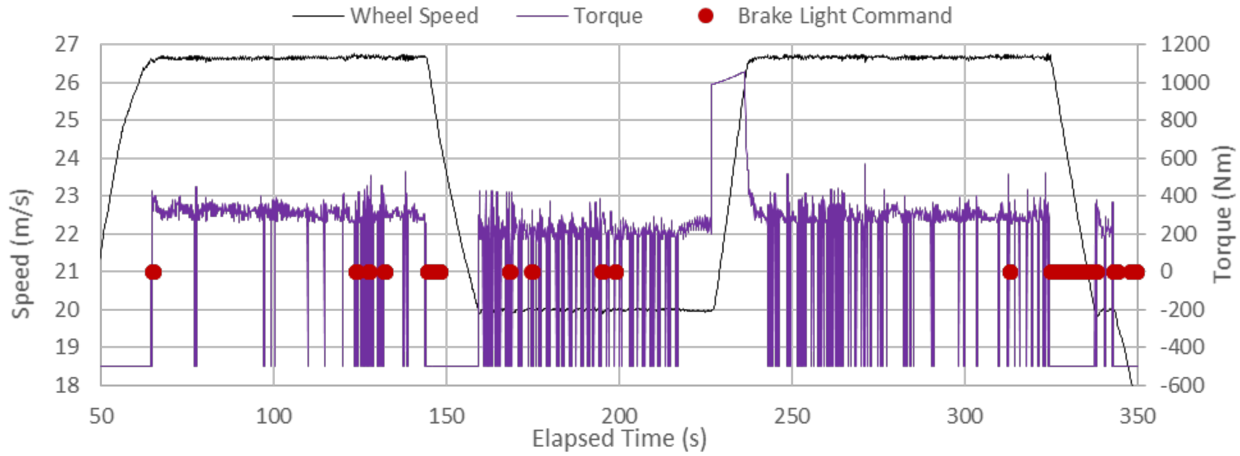

Figure 29. Custom CACC LV Torque (60→45→60 mph)

An example of the frequency of the modulation from positive to negative torque is shown for the production ACC LV controller in Figure 30, and for the CACC LV controller in Figure 31. 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 four changes in a single second. This maximum rate occurred during a period of constant speed, and not during a deceleration period.

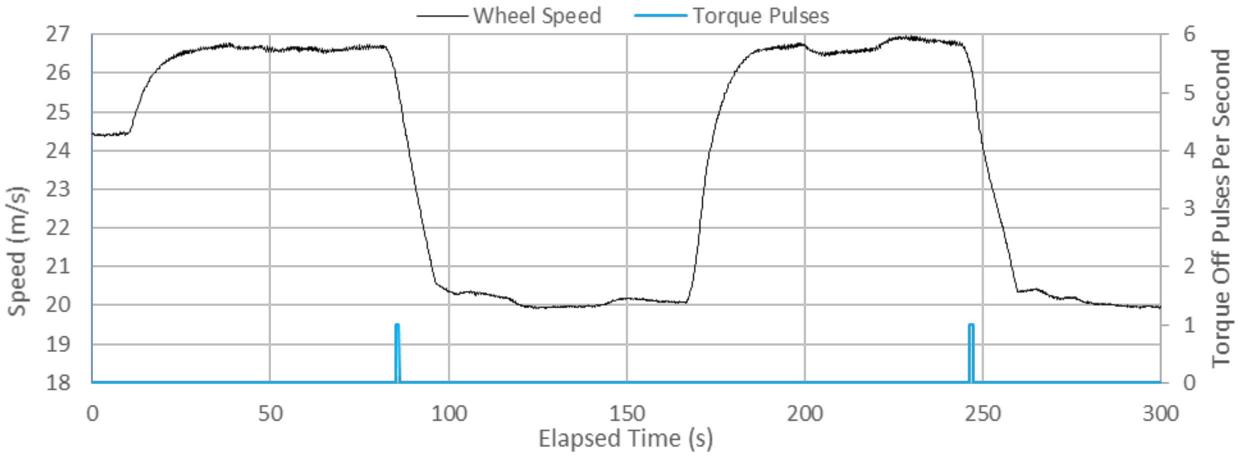

Figure 30. Production ACC LV Torque Modulation Rate (60→45→60 mph)

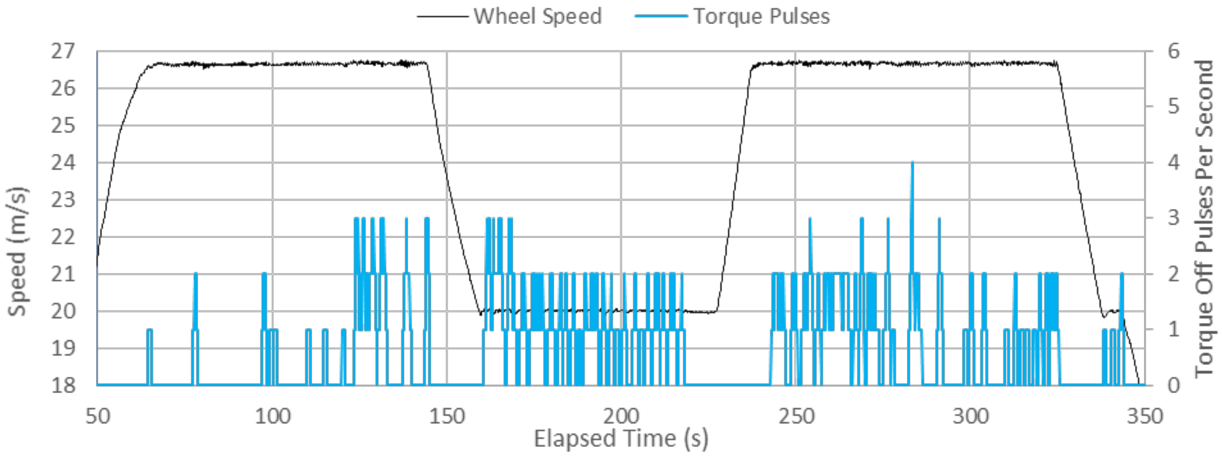

Figure 31. Custom CACC LV Torque Modulation Rate (60→45→60 mph)

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-state speed to restore the desired time gap. CACC systems should avoid excessive torque modulation when taking the comfort of the vehicle occupants into consideration.

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DOT-VNTSC-FHWA-19-15