U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

A Test Track Evaluation of Tesla Model S and Mercedes C300 Automatic Emergency Brake (AEB) System Performance

August 2017

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Test Track Evaluation of Tesla Model S and Mercedes C300 Automatic Emergency Brake (AEB) System Performance		5. Report Date August 2017 6. Performing Organization Code NHTSA/NSR-130
7. Author(s) Garrick J. Forkenbrock, NHTSA Andrew C. Snyder, Ian J. Davis, Bryan C. O'Harra, Transportation Research Center, Inc.		8. Performing Organization Report No.
9. Performing Organization Name and Address National Highway Traffic Safety Administration Vehicle Research and Test Center P.O. Box 37 East Liberty, OH 43319		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Ave., S.E. Washington, D.C. 20590		13. Type of Report and Period Covered: Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The objective of the work described in this report was to evaluate the automatic emergency brake (AEB) system performance of a 2015 Tesla Model S 85D and a 2015 Mercedes C300 4MATIC using a series of test-track based emulations of real-world crash-imminent scenarios.

Three rear-end and two intersection-based pre-crash scenarios were used for the tests described in this report. The lead vehicle stopped (LVS), lead vehicle moving (LVM), and lead vehicle decelerates (LVD) rear-end tests were based on those specified in the NHTSA FCW and CIB NCAP test procedures, but were adjusted to include a greater number of subject vehicle (SV) and principal other vehicle (POV) speed combinations, and included three repeated trials per test condition rather than seven. Variants of the left turn across path (LTAP) and straight across path (SAP) intersection scenarios are commonly used to assess vehicle-to-vehicle communication (V2V) based safety application performance in the research community. LTAP and SAP tests described in this report were performed with near miss and crash imminent timing.

Generally speaking, the AEB performance of the Tesla Model S and Mercedes C300 was largely comparable. Both vehicles were able to achieve crash avoidance in a majority of the rear-end scenarios discussed in this report. For both vehicles, ACC generally provided enough braking to achieve crash avoidance without also requiring CIB to intervene. Neither vehicle effectively responded to the POV in the LTAP or SAP scenarios.

17. Key Words:		18. Distribution Statement:	
Advanced Crash Avoidance Technology, AEB, Automatic Emergency Braking, Autopilot, Autosteer, Crash Imminent Braking, Automated Vehicles, Test Track Performance Evaluation, Tesla Model S		This document is available to the public from the National Technical Information Service Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 49	22. Price

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

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CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
in	inches	2.54	centimeters	cm
ft	feet	30.48	centimeters	cm
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.45	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per inch^2	0.07	bar	bar
psi	pounds per inch^2	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per second^2	0.30	meters per second^2	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (Fahrenheit) - 32°C	Celsius	°C

Approximate Conversions to English Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.39	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.62	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per inch^2	psi
kPa	kilopascals	0.145	pounds per inch^2	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per second^2	3.28	feet per second^2	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

LIST OF ACRONYNMS

ACC	Adaptive Cruise Control
AEB	Automatic Emergency Braking
CIB	Crash Imminent Braking
DBS	Dynamic Brake Support
Euro NCAP	European New Car Assessment Program
FCW	Forward Collision Warning
GAWR	Gross Axle Weight Rating
GVWR	Gross Vehicle Weight Rating
LCC	Lane Centering Control
LRR	Long Range Radar
LVS	Lead Vehicle Stopped
LVM	Lead Vehicle Moving
LVD	Lead Vehicle Decelerating
NHTSA	National Highway Traffic Safety Administration
NCAP	New Car Assessment Program
POV	Principal Other Vehicle
SRR	Short Range Radar
SSV	Strikeable Surrogate Vehicle
SV	Subject Vehicle
TPS	Throttle Position Sensor (data reported as a percentage of WOT)
TTC	Time to Collision
V2V	Vehicle-to-Vehicle Communication
WOT	Wide Open Throttle (maximum throttle pedal displacement)

EXECUTIVE SUMMARY

The objective of the work described in this report was to evaluate the automatic emergency brake (AEB) system performance of a 2015 Tesla Model S 85D and a 2015 Mercedes C300 4MATIC using a series test-track based emulations of real-world crash-imminent scenarios.

Three rear-end and two intersection-based pre-crash scenarios were used for the tests described in this report. The lead vehicle stopped (LVS), lead vehicle moving (LVM), and lead vehicle decelerates (LVD) rear-end tests were based on those specified in the NHTSA forward collision warning FCW and CIB NCAP test procedures, but were adjusted to include a greater number of SV and POV speed combinations, and included three repeated trials per test condition rather than seven. Variants of the left turn across path (LTAP) and straight across path (SAP) intersection scenarios are often used to assess vehicle-to-vehicle communication (V2V) based safety application performance in the research community. LTAP and SAP tests described in this report were performed with near miss and crash imminent timing.

Generally speaking, the AEB performance of the Tesla Model S and Mercedes C300 was largely comparable. In summary:

- Both vehicles were able to achieve crash avoidance in a majority of the rear-end scenarios discussed in this report.
- For both vehicles, ACC generally provided enough braking to achieve crash avoidance without also requiring CIB to intervene.
- Neither vehicle effectively responded to the POV in the LTAP or SAP scenarios.
- The LVM_25_10 test group performed with no ACC or LCC was the most challenging LVM series for both vehicles. Each of the three trials performed with the Tesla Model S, and one of the three trials performed with the Mercedes C300, concluded with an SV-to-POV impact.
- The LVD_25_25 test group performed with no ACC or LCC was the most challenging LVD series for both vehicles. SV-to-POV impact occurred during each of the three trials performed with the Tesla Model S, and during two of the three trials performed with the Mercedes C300.
- An SV-to-POV impact occurred during one LVD_35_35 trial performed with ACC and LCC both enabled. In this trial, ACC did not automatically reduce vehicle speed when the POV began to brake, but an FCW alert was presented and CIB braking was initiated.

1.0 RESEARCH OBJECTIVE

The objective of the work described in this report was to evaluate the automatic emergency brake (AEB) system performance of a 2015 Tesla Model S 85D and a 2015 Mercedes C300 4MATIC using a series of rear-end and intersection-based crash scenarios on a test track. The subject vehicle speed reductions, forward collision warning alert operation, crash avoidance capability, and AEB operational consistency are documented in this report.

2.0 TEST VEHICLES AND TECHNOLOGIES

An overview of the vehicles evaluated in this report is provided in S2.1 and S2.2. Test weights are provided in the appendix. A description of the crash avoidance technologies relevant to this evaluation are provided in S2.3.

2.1. 2015 Tesla Model S 85D

The 2015 Tesla Model S 85D used for the work described in this report, subsequently referred to as the "Tesla Model S" for brevity, is a fully-electric vehicle equipped with adaptive cruise control (ACC), AEB, lane centering control (LCC), and the option use ACC with LCC to allow the vehicle to operate as a SAE Level 2 automated vehicle (L2AV) for an extended period of time [1]. Tesla refers to the combination of ACC plus LCC as "Autopilot." When presented with another vehicle in its forward path[1], the Tesla Model S is capable of using the combination of ACC (if enabled), regenerative braking, and AEB to automatically reduce vehicle speed in an attempt to avoid a crash. A description of the forward-looking sensors used by the Tesla Model S is provided in Table 1. Tesla firmware version 7.1.103.14.1 was used for all intersection scenario-based tests performed with the Model S. Rear-end AEB scenarios used a unique version of firmware 7.1 intended to help NHTSA perform blind spot intervention (BSI) tests within the confines of the Transportation Research Center, Inc. (TRC) proving grounds without some of the GPS and road classification restrictions applied to the production firmware used for vehicles operating in the real-world on public roadways. The adjustments made by Tesla to accommodate this provision are not believed to have had any effect on the operation of the vehicle's ACC, FCW, AEB, or the outcome of the tests described in this report.

To condition the Tesla Model S brake pads and rotors prior to the evaluations performed in this study, a full FMVSS No. 135 brake burnish was performed [3].

2.2. 2015 Mercedes C300 4MATIC

Like the Tesla Model S, the 2015 Mercedes C300 4MATIC used for the work described in this report, subsequently referred to as the "Mercedes C300," is an all-wheel drive sedan equipped

[1] The Tesla Model S operator's manual specifies the vehicle's AEB system is designed to operate when a "frontal collision" is likely or imminent. It does not specify whether the system is capable of responding to oncoming vehicles or crossing traffic [2].

with ACC, AEB[2,3], and L2AV driving capability; although L2AV driving with the Mercedes C300 is only permitted for a short time (typically a matter of seconds, however the actual duration depends on the operating conditions) and its lateral capabilities are more limited. Automatic speed reductions achieved by the Mercedes C300 are affected by the combination of ACC, AEB, transmission downshifting, and engine braking. A description of the forward-looking sensors used by the Mercedes C300 is provided in Table 1.

Prior to being used for the evaluations described in this report, the Mercedes C300 was used to in a test program to validate NHTSA's AEB test procedures. Since a full FMVSS No. 135 brake burnish was already completed for that work, an FMVSS No. 126 "mini-burnish" was used to recondition the vehicle's brake pads and rotors [5]. This process ensured an objective baseline from which the vehicle's AEB braking performance could be assessed.

Table 1. Forward-Looking Sensors

Vehicle	Sensing Technology	
	Radar	Vision
Tesla Model S 85D	One Long-Range Radar (77 GHz)	Mono-camera
Mercedes C300 4MATIC	Two Short-Range Radars (24 GHz) One Long-Range Radar (77 GHz)	Stereo-cameras

2.3. Adaptive Cruise Control (ACC)

Like conventional cruise control, a vehicle's adaptive cruise control (ACC) is designed to maintain a constant travel speed. However, unlike conventional cruise control, ACC systems use medium- to long-range forward-looking sensors to determine if the SV driver is approaching a slower moving POV in their travel lane. If so, ACC reduces drive torque and/or applies the foundation brakes to adjust the speed of the SV to match that of the POV while also maintaining a driver-specified headway[4]. When compared to those provided by AEB, ACC-based speed reductions are initiated much earlier in the pre-crash time line (i.e., from a higher time to collision, or TTC), and rely on lower deceleration magnitudes. If the SV is operating with ACC enabled, and it approaches a POV with a sufficiently high relative speed, ACC-based braking alone may be unable to prevent a rear-end collision. In such a case, the vehicle's speed reduction may be initiated with ACC, but require an AEB intervention to actually prevent the crash.

[2] The 2015 Mercedes C-Class was available with one of two AEB systems: Collision Prevention Assist Plus (standard equipment) or Distronic Plus (an optional system with greater capabilities). The C300 described in this report was equipped with "Distronic Plus," which was part of the vehicle's Driver Assistance Package.

[3] The Mercedes C300 operator's manual indicates the vehicle's AEB system does not react to oncoming vehicles or crossing traffic [4].

[4] Both the Tesla Model S and Mercedes C300 have seven settings for ACC headway.

2.4. Crash Avoidance Technologies

The Tesla Model S and Mercedes C300 were both equipped with crash avoidance technologies inclusive of ACC and AEB systems. Most AEB systems are comprised of three crash avoidance technologies designed to reduce the likelihood of a forward-moving vehicle being involved in a rear-end crash with another vehicle traveling in the same direction directly in front of it: forward collision warning (FCW), crash-imminent braking (CIB), and dynamic brake support (DBS). Although the details of how a particular AEB system operates depend on a combination of a vehicle manufacturer's implementation and the driving situation, they typically use an FCW to alert the driver of the imminent collision, then automatically provide a CIB or DBS intervention (if necessary) to prevent or mitigate the rear-end crash. Additional details about these systems are provided in Sections 2.4.1 through 2.4.3.

2.4.1. Forward Collision Warning (FCW)

FCW utilizes forward-looking sensors[5] to monitor the distance between a moving vehicle (i.e., the SV) and another vehicle or object in its forward path. If the system determines that the relative speed of the vehicles and headway distance between the vehicles is such that a collision is likely, the system alerts the driver by means of auditory, visual (e.g., on the dash board, heads up display (HUD), and/or haptic (e.g., vibrations or movement in the seat, pedals, or steering wheel) alerts. The timing of an FCW alert relative to an imminent rear-end collision is intended to provide the driver with enough time to assess the potential hazard and respond with the appropriate combination of braking and/or steering needed to avoid the crash.

2.4.2. Crash Imminent Braking (CIB)

CIB systems also use forward-looking sensor data to determine when automatic braking is necessary to avoid or mitigate the effects of a crash in those situations in which the driver fails to apply any braking or steering in response to an FCW warning. In such a situation, a CIB system will automatically apply braking (between partial and full braking depending on system design and circumstances) in an attempt to avoid or mitigate the crash.

2.4.3. Dynamic Brake Support (DBS)

DBS applies supplemental braking in situations in which the system has determined that the braking applied by the driver is insufficient to avoid a collision. Typically, DBS relies on information provided by forward-looking sensor(s) to determine when supplemental braking should be applied. FCW most often works in concert with DBS by first warning the driver of the situation and thereby providing the opportunity for the driver to initiate the necessary braking. If the driver's brake application is insufficient, DBS provides the additional braking needed to

[5] Such sensors presently include radar, LIDAR (laser-based), camera(s), or combinations thereof. Future sensing technologies may include infrared and dedicated short-range communication (DSRC) radios.

avoid or mitigate the crash. The DBS systems of the vehicles described in this report were not evaluated.

2.5. Driver-Configurable Settings

Certain driver-configurable settings had the potential for affecting the outcome of the tests described in this report. Wherever possible, the most conservative settings were used.

2.5.1. FCW Settings

The Tesla Model S and Mercedes C300 were both equipped with an FCW system designed to activate before a CIB intervention. The Tesla Model S system allowed the driver to manually choose from one of three proximity settings. Prior to performing any of the tests trials described in this report, NHTSA experimenters confirmed that the most conservative FCW setting had been specified in accordance with the Tesla Model S operator’s manual. This setting, shown in Figure 1, allowed the alerts to be presented at the longest possible time to collision (TTC); i.e., the earliest possible alert timing.

Figure 1. Tesla Model S forward collision warning settings. The “early” setting was selected for all tests described in this report.

For each vehicle, the FCW alert included an auditory and visual component, presented concurrently. The visual alerts were presented in the center of the respective instrument panels, as shown in Figures 2 and 3. The Tesla Model S FCW auditory alert was presented through the vehicles audio system, whereas that provided by the Mercedes C300 originated from a piezoelectric speaker located behind the instrument panel.

Figure 2. Tesla Model S visual FCW alert
(as shown in the Tesla Model S operator’s manual [2])

Figure 3. Mercedes C300 visual FCW alert [6]

2.5.2. ACC Settings

Both vehicles provide the driver with an ability to select the SV-to-POV headway they wish to have the vehicle maintain while ACC is enabled and the POV ahead is being driven at or below the set speed of the SV. For most tests performed in this study, the farthest headway was generally selected (i.e., the most conservative setting). With this setting, the earliest possible ACC-based speed reductions would be expected to occur, thereby providing the vehicles with the greatest possible chance of avoiding an SV-to-POV impact. Figures 4 and 5 show the driver interfaces (i.e., stalks) and instrument cluster images for the Tesla Model S and Mercedes C300, respectively.

The one scenario where the farthest setting wasn't used was the lead vehicle decelerating (LVD) tests performed with ACC enabled (described in S2.7). These tests specify the SV and POV be driven at a constant headway of 45.3 ft (13.8 m) for three seconds before the POV brakes are applied. Maintaining this headway was not possible for either vehicle when the longest headway setting was used. Rather, this required use of the *shortest* ACC headway setting, for all LVD tests performed with both vehicles.

Figure 4. Tesla Model S adaptive cruise control and Autopilot stalk (left) and the corresponding proximity indication (right; presented on the left side of the vehicle's instrument cluster).

Figure 5. Mercedes C300 adaptive cruise control stalk (left) and the corresponding proximity indication (right; presented in the center of the vehicle's instrument cluster).

2.5.3. Regenerative Braking Settings

The Tesla Model S was equipped with a regenerative braking system. When the driver releases the throttle pedal, the vehicle's electric drive motors function as generators to convert kinetic energy into electricity to charge the vehicle's batteries. The Tesla Model S allows the driver to select one of two regenerative braking modes shown in Figure 6. From a braking perspective, the "standard" mode provides a greater deceleration (approximately 0.14g). All Tesla Model S tests described in this report were performed using the "standard" regenerative braking mode.

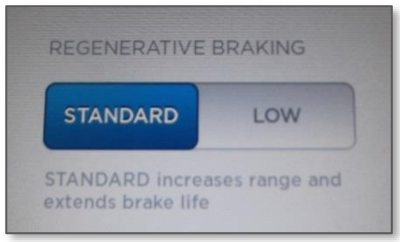

Figure 6. Tesla Model S regenerative brake settings. Selection is available from a menu on the center display touchscreen.

2.6. Test Locations

The tests described in this report were performed from July 26 to September 15, 2016 using three facilities at the Transportation Research Center, Inc. (TRC) proving grounds, located in East Liberty, OH, as shown in Figure 7.

The test surfaces of the skid pad and the skid pad north loop were concrete with nominal peak and slide frictional coefficients of 0.99 and 0.89, respectively. The vehicle dynamics area was untreated asphalt with nominal peak and slide frictional coefficients of 0.92 and 0.85, respectively. All tests were performed on dry pavement.

2.7. Test Scenarios

Five pre-crash scenarios were used in this study (using the test speeds described in S3.1):

- **Lead vehicle stopped (LVS)**. The subject vehicle (SV) approaches a stationary principal other vehicle (POV) present in the center of the SV's travel lane.
- **Lead vehicle moving (LVM)**. The SV approaches a slower moving POV present in the center of the SV's travel lane.
- **Lead vehicle decelerating (LVD)**. The SV approaches a decelerating POV present in the center of the SV's travel lane
- **Left turn across path (LTAP)**. The SV approaches a POV that is initially driven in the oppose direction to the SV, in the center of a lane adjacent to the SV's travel lane. Just prior to the SV reaching the POV, the POV either (1) performs a left turn in front of the

SV if the initial POV speed is 15 mph, or (2) decelerates to 15 mph then performs a left turn in front of the SV if the initial POV speed is 25 mph. In either case, the POV travels along a 38 ft radius during the turning stage of the maneuver.

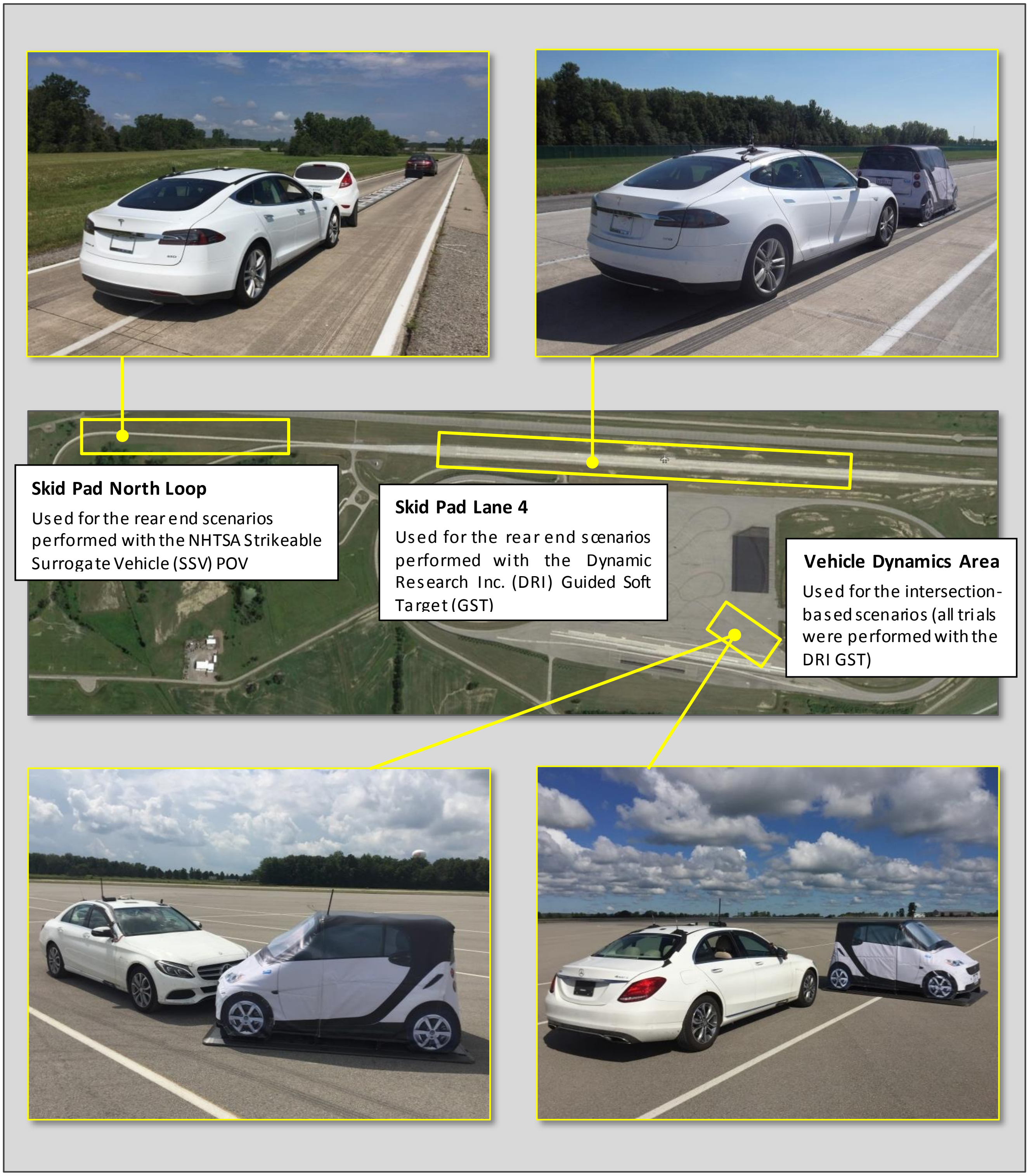

Figure 7. Test track facilities used for the scenarios described in this report.

- **Straight across path (SAP)**. The SV approaches a four-way intersection with perpendicular lanes. As the SV is about to drive through the intersection, the POV approaches from the left and crosses in front of the SV.

The test procedures used by NHTSA's New Car Assessment Program (NCAP) to evaluate the rear-end crash avoidance performance of light vehicle[6] FCW, CIB, and DBS systems include LVS, LVM, and LVD scenarios. The LVS, LVM, and LVD tests used for the work described in this report were based on those specified in the NHTSA FCW and CIB NCAP test procedures [7,8], but were adjusted to include a greater number of SV and POV speed combinations, and included three repeated trials per test condition rather than seven[7]. Each LVS, LVM, and LVD test condition used in this study was designed to conclude with an SV-to-POV impact if the SV did not brake automatically.

Variants of the LTAP and SAP test maneuvers are commonly used to assess vehicle-to-vehicle communication (V2V) safety application performance in the research community, and the scenarios they emulate will inevitably be addressed by higher-level automated vehicles. Unlike the LVS, LVM, or LVD scenarios used in this study, each LTAP and SAP scenario and speed combination described in this report included near miss and crash imminent test conditions. During the near miss condition, the POV timing was set such that the SV would miss the POV by approximately 1.6 ft. Conversely, each crash imminent condition was designed to conclude with an SV-to-POV impact if the SV did not brake automatically. During the LTAP tests, if the SV did not automatically brake, the impact was intended to occur when the POV was midway through its turn (i.e., when the right front corner of the POV would contact the center of the SV front bumper). For the SAP tests, the impact was programmed to occur when center of the SV front bumper would contact the longitudinal center of the POV.

2.8. Surrogate Vehicles

NHTSA's strikeable surrogate vehicle (SSV) was used for most of the rear-end AEB evaluations described in this report. All intersection-based tests (LTAP and SAP), and the rear-end AEB tests performed with ACC and LCC, used the Dynamic Research Inc. (DRI) guided soft target (GST).

2.8.1. NHTSA Strikeable Surrogate Vehicle (SSV)

NHTSA designed its SSV, shown in Figure 8, to facilitate AEB system evaluations, and it will be used by the agency's New Car Assessment Program (NCAP) to objectively assess CIB and DBS performance beginning with model year 2018 [9].

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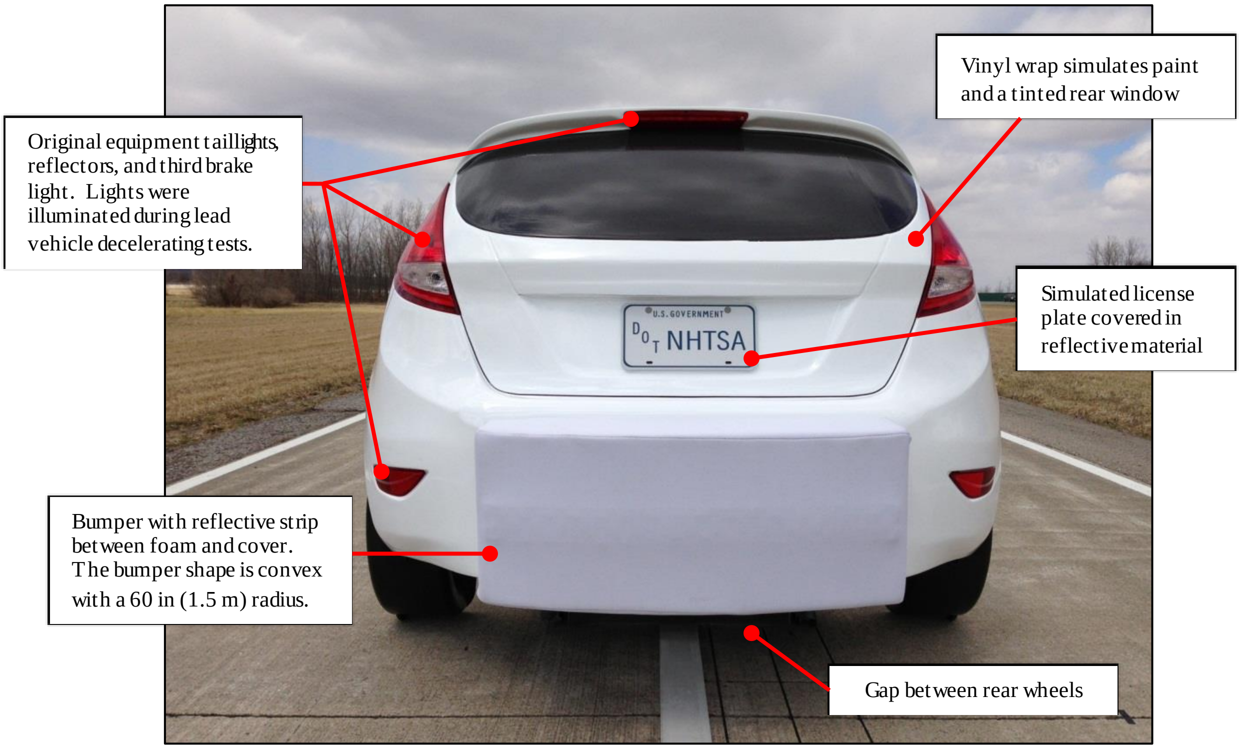
[6] NHTSA defines a light vehicle as having a Gross Vehicle Weight Rating (GVWR) less than 10,000 lbs.

[7] Increasing the number of SV and POV speed combinations beyond those specified by NHTSA's NCAP was intended to provide a better overall understanding of the SVs' AEB performance by using finer within-maneuver speed differentiation. However, this significantly increased the test burden. Since the work described in this report was not intended to formally assess the SVs' ability to satisfy the agency's CIB or NCAP criteria, this was addressed by reducing the number of repeated trials per test condition.



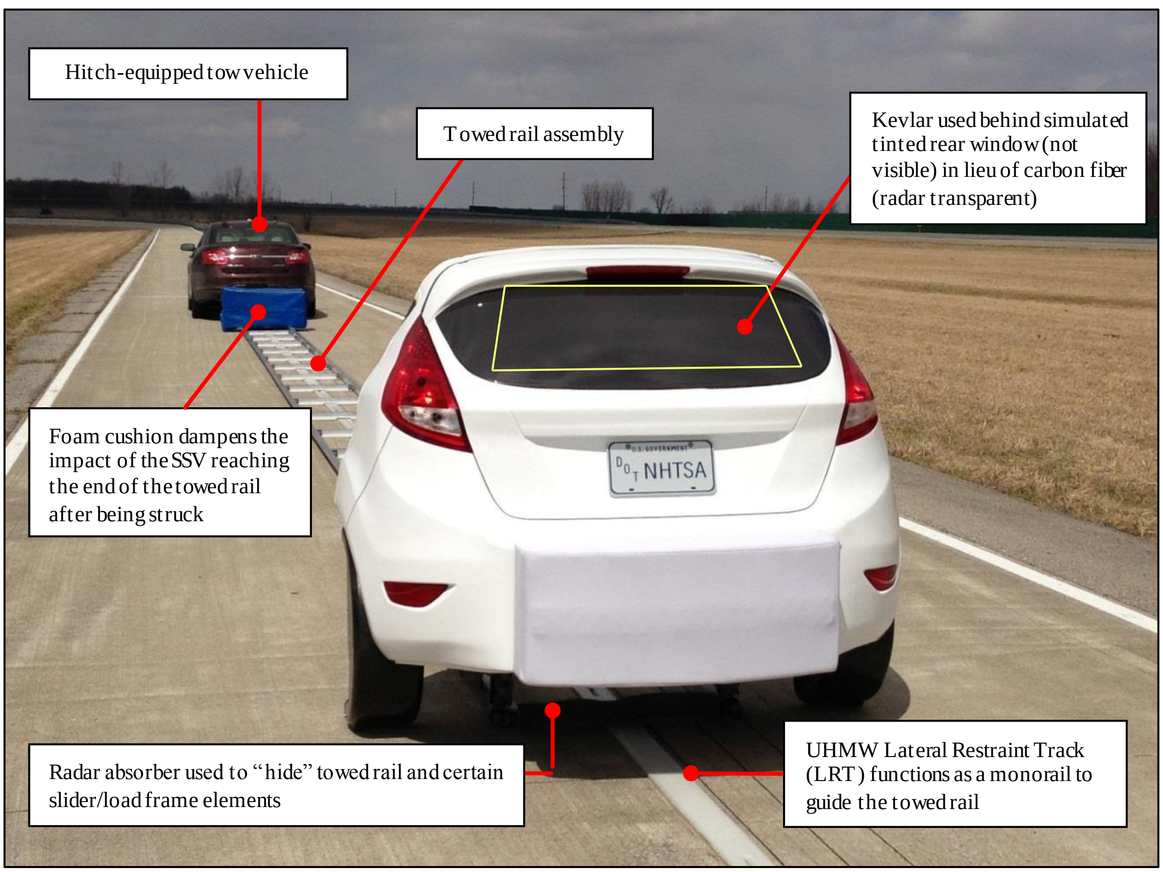


Figure 8. Important design elements of NHTSA's SSV

The SSV provides visual and dimensional characteristics representative of an actual vehicle when approached from the rear to promote accurate identification and classification by the AEB system of the vehicle being evaluated. Since the SSV body was based on a dimensional scan of a 2011 Ford Fiesta, its height and width dimensions are inherently realistic. To maximize visual realism, the SSV shell is wrapped with commercially available vinyl material to simulate paint on the body panels and rear bumper, and a tinted glass rear window. The SSV is equipped with a simulated United States specification rear license plate. The taillights, rear bumper reflectors, and third brake light installed on the SSV are original equipment from the production vehicle (see Figure 8). The SSV is rigid so it maintains the same shape (i.e., visually, dimensionally, and from a radar-sensing perspective) over time.

To reduce the potential of damage to the striking vehicle during an impact, the SSV is constructed from carbon fiber, Kevlar, and Nomex honeycomb, lightweight composite materials with favorable strength-to-weight characteristics. A foam bumper is attached to the rear of the SSV to reduce the peak forces realized immediately after an impact occurs.

Using highly-accurate test equipment and scans performed at frequency bands representative of those presently used by the automotive industry (i.e., 24 GHz and 77GHz), the Michigan Transportation Research Institute (MTRI) and the University of Michigan Transportation Research Institute (UMTRI) assessed the radar-return characteristics for the SSV, other surrogate vehicles, and actual vehicles at different elevation aspects and azimuths. Results from this evaluation were documented in a report titled, *"Radar Measurements of NHTSA's Surrogate Vehicle SSV"* [10]. This report indicates that the SSV exhibits automobile-like radar-scattering characteristics at tail-aspect for both radar bands of interest, and that it is suitable for evaluating radar-based detection systems.

2.8.2. Dynamic Research Inc. (DRI) Guided Soft Target (GST)

The Guided Soft Target (GST) system was developed to safely evaluate crash avoidance technologies beyond those designed to address rear-end crashes only. The GST system, shown

Figure 9. Dynamic Research Inc. Guided Soft Target (GST). The surrogate vehicle is shown on top of the low profile robotic vehicle (LPRV) platform.

in Figure 9, is comprised of the Low Profile Robotic Vehicle (LPRV), Soft Car (the surrogate vehicle), operator's base station, and a remotely operated safety steward dead man switch. This system allows the GST and SV to be configured in nearly any pre-crash scenario. Constant wireless communication between these two allow for precise closed-loop control.

The LPRV contains the drive motors for the GST as well as the communication and GPS systems. It is approximately four inches tall and weighs approximately 600 pounds. Its low profile allows a wide array of passenger cars and heavy vehicles to drive over it. To reduce the impact force of being run over, the LPRV has a pneumatic suspension which compresses when only 150 lbs is applied to the top of the platform. This compression allows the chassis to take the full force of being run over by any vehicle with axles loaded to less than 20,000 lbs. Top speed of the LPRV is limited to 53 mph, and its maximum acceleration is 0.12g.

The Soft Car is designed to appear realistic to the sensors used by contemporary crash avoidance systems: radar (24 and 76-77 GHz), camera, and LIDAR. To achieve realistic radar return characteristics, a combination of radar reflective and radar absorbing material is enclosed within the Soft Car's vinyl covers. Dimensionally, the Soft Car used for the work described in this study was approximately the size of a 2013 Smart ForTwo (see Figure 9). The Soft Car is secured to the top of the LPRV using Velcro attachment points, and is designed to emulate an actual vehicle. Internally, the Soft Car consists of a vinyl-covered foam structure. If a SV-to-POV impact occurs at low speed, the Soft Car is typically pushed off of the LPRV, which is pushed against the ground as the SV drives over it. At higher impact speeds, the GST breaks apart as the SV essentially drives through it. Reassembly of the GST occurs on top of the LPRV and takes approximately 5 minutes.

2.9. Test Speeds

The speeds used for each scenario were selected to best balance real-world relevance, available real estate, and POV limitations while still being able to safely perform each test condition. Depending on the scenario, SV speeds ranged from 15 to 35 mph. POV speeds ranged from 0 to 25 mph.

3.0 TEST RESULTS

The AEB performance of the two vehicles evaluated in this study is discussed in five ways. In S3.1, the range of speed reductions realized in each test condition is shown. Section 3.2 describes when FCW alerts were presented, and the ability of the vehicles to avoid an SV-to-POV impact. The operational consistency of the AEB systems is provided in S3.3. Finally, FCW and CIB non-activations are discussed in S3.4 and S3.5, respectively.

3.1. SV Speed Reductions

The range of SV speed reductions recorded for each test scenario, speed, and configuration used in this study are shown in Tables 2 and 3, for the Tesla Model S and Mercedes C300, respectively. If an SV-to-POV impact occurred, these values were calculated by subtracting the SV speed at the time of SV-to-POV impact from the SV steady-state speed before CIB was activated. Similarly, if an SV-to-POV impact did not occur, speed reductions were calculated by subtracting the SV speed at the time of minimum SV-to-POV range from the SV steady-state speed before CIB was activated. In each table, the following color convention was used:

- Darker green means that crash avoidance was achieved for each of the three trials performed within that combination of test conditions.
- Orange indicates that at least one SV-to-POV impact occurred within that test condition.
- Red means that an SV-to-POV impact occurred during each of the three trials performed within that test condition.

Note that some cells shown in Tables 2 and 3 indicate crash avoidance occurred, but show speed reductions less than those nominally needed to achieve crash avoidance. This was typically due to the fact the SV and POV had a ±1 mph speed allowance during a given trial (specified in NHTSA's FCW and CIB test procedures). However, certain ACC-enabled trials saw SV speed reduced prior to initial speed being taken, which correspondingly lowered the calculated amount of speed reduced when avoiding impact. In these instances, the speed reduction reported in Tables 2 and 3 is slightly less that the actual overall speed reduction realized by the SV.

Some cells shown in Tables 2 and 3 are labeled "Not performed" or "No speed reduction." The ACC system of both the Tesla Model S and Mercedes C300 could not be activated at the slowest SV speed used for the LVS and LVD test scenarios (15 mph), so these tests could not be performed[8].

Finally, no CIB activation was recorded during any LTAP or SAP test trial performed with the Tesla Model S or Mercedes C300. For this reason, speed reductions are not reported in Tables 2 and 3, and are not discussed in S3.1 of this report. For these trials, any differences in the initial SV speed from that at the time of the SV either (1) passing by the POV just after it passed completely by the front of the SV (i.e., during the near miss trials) or (2) SV-to-POV impact, can only be attributable to test variability[9].

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[8] The minimum speeds the Tesla Model S and Mercedes C300 ACC systems could be activated at were 18 and 20 mph, respectively.

[9] NHTSA's FCW and CIB NCAP test procedures allow SV and POV speed to vary up to 1 mph from the nominal target value.

Table 2. Tesla Model S SV Speed Reduction Summary.

Test Conditions				Test Summary		
Pre-Crash Scenario	Scenario Severity	Test Speeds (mph)		ACC off, LCC off	ACC on, LCC off	ACC on, LCC on
		SV	POV			
Lead Vehicle Stopped (LVS)	Crash Imminent	15	0	14.3 – 15.4	Not performed	
		20	0	19.6 – 19.7	19.7	19.7
		25	0	24.8 – 24.9	24.0 – 24.1[1]	23.9 – 24.0[1]
Lead Vehicle Moving (LVM)	Crash Imminent	25	10	10.1 – 12.5[2]	14.6 – 14.8	14.4 – 14.5
		35	10	24.7 – 25.5	21.8 – 22.2	24.2
		35	20	14.8 – 15.6	14.2 – 14.7	14.5
		45	20	24.7 – 25.1	23.9 – 25.0	24.3
Lead Vehicle Decelerates (LVD)	Crash Imminent	15	15	14.5 – 15.2	Not performed	
		25	25	1.0 – 18.5[3]	25.2 – 25.4	24.8 – 25.1
		35	35	15.5 – 20.1[4]	31.3 – 31.7	30.8 – 31.8[5]
Left Turn Across Path (LTAP)	Near Miss	25	15	No speed reduction		
		25	25			
	Crash Imminent	25	15	No speed reduction		
		25	25			
Straight Across Path (SAP)	Near Miss	15	15	No speed reduction		
		25	15			
		35	15			
	Crash Imminent	15	15	No speed reduction		
		25	15			
		35	15			

[1]Speed reductions are calculated using the SV speed at a TTC = 5.1s per the NHTSA CIB test procedure. At this time, ACC had already begun to slow the vehicle from the nominal speed of 25 mph.

[2]Relative impact speeds of 2.3, 3.0, and 5.6 mph occurred during Tests 69, 71, and 68, respectively. The NCAP performance criterion is crash avoidance for this scenario/speed combination.

[3]Relative impact speeds of 4.9, 15.9, and 20.0 mph occurred during Tests 105, 106, and 107, respectively. This scenario/speed combination is not specified in the CIB test procedure used by NCAP. No FCW alert was presented during Test 107. No CIB activation was observed during Tests 106 and 107.

[4]Relative impact speeds of 5.9, 6.8, and 3.7 mph occurred during Tests 117, 118, and 119, respectively. The NCAP performance criterion is a 10.5 mph speed reduction for this scenario/speed combination.

[5]Relative impact speed of 2.1 mph occurred during Test 156. This scenario/speed combination is not specified in the CIB test procedure used by NCAP.

Table 3. Mercedes C300 SV Speed Reduction Summary.

Test Conditions				Test Summary		
Pre-Crash Scenario	Scenario Severity	Test Speeds (mph) SV	Test Speeds (mph) POV	ACC off, LCC off	ACC on, LCC off	ACC on, LCC on
Lead Vehicle Stopped (LVS)	Crash Imminent	15	0	14.8 – 15.4	Not performed	
		20	0	20.0 – 20.4	20.1 – 20.3	19.7 – 19.9
		25	0	24.8 – 25.0	24.8 – 25.2	24.7 – 24.8
Lead Vehicle Moving (LVM)	Crash Imminent	25	10	8.4 – 14.6[1]	13.8 – 14.6	14.2 – 14.4
		35	10	24.9 – 25.4	25.1 – 25.4	24.6 – 25.0
		35	20	14.6 – 15.3	14.0 – 14.7	14.3
		45	20	25.0 – 25.2	24.7 – 25.4	24.6 – 24.7
Lead Vehicle Decelerates (LVD)	Crash Imminent	15	15	14.4 – 15.5	Not performed	
		25	25	12.1 – 25.3[2,3]	24.9 – 25.7	24.8 – 25.1
		35	35	24.5 – 24.8	32.3 – 32.5[4]	30.7 – 32.2[4]
Left Turn Across Path (LTAP)	Near Miss	25	15	No speed reduction		
		25	25			
	Crash Imminent	25	15	No speed reduction		
		25	25			
Straight Across Path (SAP)	Near Miss	15	15	No speed reduction		
		25	15			
		35	15			
	Crash Imminent	15	15	No speed reduction		
		25	15			
		35	15			

[1]Relative impact speed of 6.4 mph occurred during Test 31. The NCAP performance criterion is crash avoidance for this scenario/speed combination.

[2]Relative impact speed of 6.3 mph occurred during Test 73. This scenario/speed combination is not specified in the CIB test procedure used by NCAP.

[3]Relative impact speed of 9.8 mph occurred during Test 75. This scenario/speed combination is not specified in the CIB test procedure used by NCAP.

[4]ACC extended the SV-to-POV range beyond LVD test tolerances. Headways of 59.1 to 63.7 ft were observed during the validity period.

3.1.1. Lead Vehicle Stopped

The Tesla Model S and Mercedes C300 both achieved the speed reductions needed to realize crash avoidance during each LVS trial performed.

- For the LVS_15_0 scenario, speed reductions of 14.3 to 15.4 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 14.8 to 15.4 mph.
- For the LVS_20_0 scenario, speed reductions of 19.6 to 19.7 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 19.7 to 20.4 mph.
- For the LVS_25_0 scenario, speed reductions of 23.9 to 24.9 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 24.7 to 25.2 mph. *The LVS_25_0 evaluation criteria specified by NHTSA in the CIB NCAP test procedure is a speed reduction ≥9.8 mph.*

3.1.2. Lead Vehicle Moving

With the exception of the LVM_25_10 scenario performed without ACC or LCC, the Tesla Model S and Mercedes C300 both achieved the speed reductions needed to realize crash avoidance during each LVM trial performed.

- For the LVM_25_10 scenario performed without ACC or LCC, speed reductions of 10.1 to 12.5 mph were recorded for the Tesla Model S. Impacts occurred during each trial performed in this test series, and impact speeds of 2.3 to 5.6 mph were realized. *The LVM_25_10 evaluation criteria specified by NHTSA in the CIB NCAP test procedure is crash avoidance.*
- The range of speed reductions recorded for the Mercedes C300 for the LVM_25_10 scenario performed without ACC or LCC was 8.4 to 14.6 mph. One SV-to-POV impact occurred during this series, and it occurred at a relative speed of 6.4 mph.
- For the remainder of the LVM_25_10 scenarios, speed reductions of 14.4 to 14.8 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 13.8 to 14.6 mph.
- For the LVM_35_10 scenario, speed reductions of 21.8 to 25.5 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 24.6 to 25.4 mph.
- For the LVS_35_20 scenario, speed reductions of 14.2 to 15.6 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 14.0 to 15.3 mph.
- For the LVS_45_20 scenario, speed reductions of 23.9 to 25.1 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 24.6 to 25.4 mph. *The LVM_45_20 evaluation criteria specified by NHTSA in the CIB NCAP test procedure is a speed reduction ≥9.8 mph.*

3.1.3. Lead Vehicle Decelerates

3.1.3.1. LVD_15_15 Trials

The Tesla Model S and Mercedes C300 both achieved the speed reductions needed to realize crash avoidance in the LVD_15_15 scenario. Speed reductions of 14.5 to 15.2 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 14.4 to 15.5 mph.

3.1.3.2. LVD_25_25 Trials

In the LVD_25_25 scenario, the Tesla Model S and Mercedes C300 achieved the speed reductions needed to realize crash avoidance in the ACC on/LCC off and ACC on/LCC on test conditions. Both vehicles had at least two SV-to-POV impacts during the LVD_25_25 tests performed with ACC off/LCC off.

- For the LVD_25_25 tests performed with ACC on/LCC off, and LVD_25_25 tests performed with ACC on/LCC on, speed reductions of 24.8 to 25.4 mph were recorded for the Tesla Model S. The range of speed reductions recorded for the Mercedes C300 was 24.8 to 25.7 mph.
- For the LVD_25_25 tests performed with ACC off/LCC off, speed reductions of 1.0 to 18.5 mph were recorded for the Tesla Model S. Impacts occurred during each trial performed in this test series, and impact speeds of 4.9 to 20.0 mph were realized. No CIB activations were observed during two of the three trials, and the FCW failed to present an alert during one of them. This test series is discussed in greater detail in S3.4 “FCW Non-Activations” and S3.5 “CIB Non-Activations.”
- The range of speed reductions recorded for the Mercedes C300 in the LVD_25_25 scenario performed without ACC or LCC was 12.1 to 25.3 mph. Two SV-to-POV impacts occurred during this series, with relative speeds of 6.3 and 9.8 mph.

3.1.3.3. LVD_35_35 Trials

The Mercedes C300 achieved the speed reductions needed to realize crash avoidance during each trial performed in the LVD_35_35 scenario. The overall range of speed reductions for the trials performed without ACC or LCC was 24.5 to 24.8 mph. Higher speed reductions were realized during the trials LVD_35_35 performed with ACC on (regardless of whether LCC was enabled or not), where a range of 30.7 to 32.5 mph was observed. The reason for this difference has to do with when the minimum SV-to-POV range occurred with or without ACC enabled. Without ACC, minimum range occurred between 1.7 to 2.0 seconds before the POV had braked to a stop, when the SV speed was still between 10.2 and 11.0 mph. From that point, although both the SV and POV continued to brake to a stop, the SV did so with a higher deceleration, causing the SV-to-POV headway to increase until both vehicles had stopped, as shown on Figure 10. When ACC was enabled, the SV not only initiated braking from a further distance[10], but it kept braking with the POV until it (i.e., the SV) had stopped completely. The minimum SV-to-POV range observed during the Mercedes C300 LVD_35_35 tests performed with ACC on occurred when both the SV and POV had stopped.

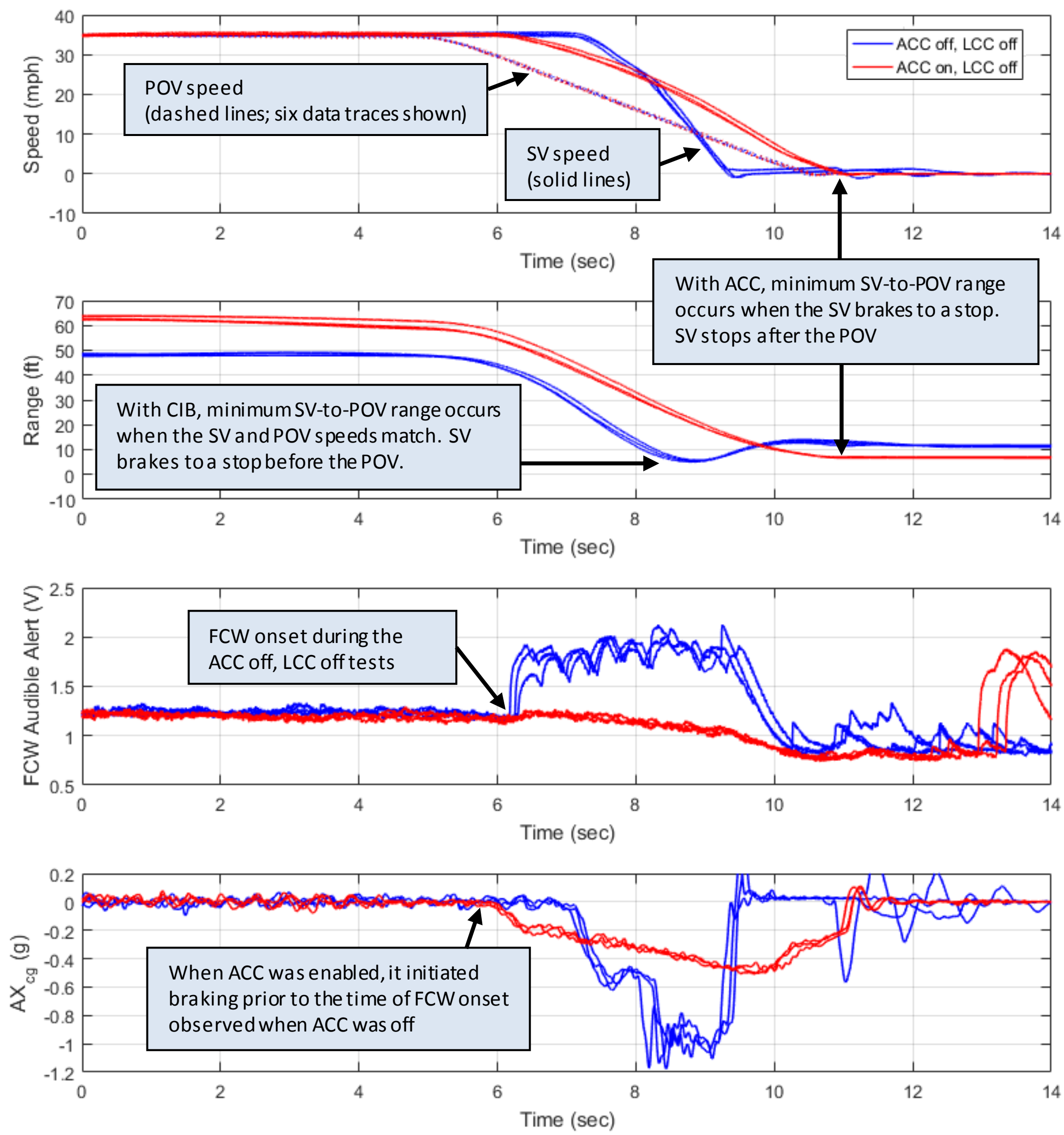

Figure 10. Mercedes C300 LVD_35_35 tests performed with ACC on and off.

The speed reductions recorded for the Tesla Model S during the LVD_35_35 trials varied depending on the test condition performed.

- Speed reductions of 15.5 to 20.1 mph were recorded for the tests performed with ACC off and LCC off. Impacts occurred during each of these trials. The range of impact

[10] Even with the shortest possible headways specified, enabling the Mercedes C300 ACC extended the SV-to-POV range observed during the LVD_35_35 tests beyond the maximum allowance specified in NHTSA's CIB NCAP test procedure (45.3 ± 8 ft, therefore the maximum allowable headway is 53.3 ft). Headways of 59.1 to 63.7 ft were observed during the validity period.

speeds was 3.7 to 6.8 mph. *The LVD_35_35 evaluation criteria specified by NHTSA in the CIB NCAP test procedure is a speed reduction ≥10.5 mph.*

- Crash avoidance was realized during each of the three trials performed with ACC on and LCC off. Speed reductions of 31.3 to 31.7 mph were recorded for these trials.
- When ACC and LCC were both on, speed reductions of 30.8 to 31.8 mph occurred. An SV-to-POV impact occurred during one of the three trials performed in this condition, and it occurred at relative speed of 2.1 mph.

3.2. FCW Activation and Crash Avoidance

The ability of the Tesla Model S and Mercedes C300 to avoid impacts with the POVs is shown in Tables 4 and 5, respectively. In each table, the color convention used to describe the outcome of a given scenario, speed, and configuration was mostly identical to that used in S3.1; the main difference being that Tables 4 and 5 also contain an FCW activation summary, whereas Tables 2 and 3 did not.

In each table, the following color convention was used to describe the FCW alerts for a given test condition:

- Darker green means that FCW alerts were presented for each of the three trials performed within that combination of test conditions.
- Orange indicates that within that test condition, an FCW alert was expected to have occurred during each trial, but did not occur during at least one of three trials performed (in the context of FCW operation, this is a negative outcome).
- Darker blue indicates that within that test condition, an FCW alert occurred during at least one trial, but only because ACC did not respond to the test condition in a way it was expected to and an SV-to-POV impact became imminent (in the context of FCW operation, this is a positive outcome).
- Red indicates that within that test condition, an FCW alert was not presented prior to an SV-to-POV impact.

3.2.1. Lead Vehicle Stopped

The Tesla Model S and Mercedes C300 both avoided the POV during every LVS trial performed in this study. For both vehicles, FCW alerts occurred during every LVS trial performed with ACC and LCC both being disabled.

For the LVS trials performed with ACC on, the Tesla Model S did not present FCW alerts during any trial (regardless of whether LCC was on or off), whereas they were present during each trial performed with the Mercedes C300. The origin of this difference is believed to be in how the respective systems are designed to operate, and not indicative of poor performance by either

Table 4. Tesla Model S FCW Activation and Crash Avoidance Summary.

Test Conditions				Test Summary					
Pre-Crash Scenario	Scenario Severity	Test Speeds (mph)		ACC off, LCC off		ACC on, LCC off		ACC on, LCC on	
		SV	POV	FCW	Avoidance	FCW	Avoidance	FCW	Avoidance
Lead Vehicle Stopped (LVS)	Crash Imminent	15	0	3 / 3	3 / 3	Not performed		Not performed	
		20	0	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		25	0	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
Lead Vehicle Moving (LVM)	Crash Imminent	25	10	3 / 3	0 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		35	10	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		35	20	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		45	20	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
Lead Vehicle Decelerates (LVD)	Crash Imminent	15	15	3 / 3	3 / 3	Not performed		Not performed	
		25	25	2 / 3	0 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		35	35	3 / 3	0 / 3	0 / 3	3 / 3	1 / 3	2 / 3
Left Turn Across Path (LTAP)	Near Miss	25	15	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
		25	25	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
	Crash Imminent	25	15	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1
		25	25	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1
Straight Across Path (SAP)	Near Miss	15	15	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
		25	15	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
		35	15	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
	Crash Imminent	15	15	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1
		25	15	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1
		35	15	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1

Table 5. Mercedes C300 FCW Activation and Crash Avoidance Summary.

Test Conditions				Test Summary					
Pre-Crash Scenario	Scenario Severity	Test Speeds (mph)		ACC off, LCC off		ACC on, LCC off		ACC on, LCC on	
		SV	POV	FCW	Avoidance	FCW	Avoidance	FCW	Avoidance
Lead Vehicle Stopped (LVS)	Crash Imminent	15	0	3 / 3	3 / 3	Not performed			
		20	0	3 / 3	3 / 3	3 / 3	3 / 3	3 / 3	3 / 3
		25	0	3 / 3	3 / 3	3 / 3	3 / 3	3 / 3	3 / 3
Lead Vehicle Moving (LVM)	Crash Imminent	25	10	3 / 3	2 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		35	10	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		35	20	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		45	20	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
Lead Vehicle Decelerates (LVD)	Crash Imminent	15	15	3 / 3	3 / 3	Not performed			
		25	25	3 / 3	1 / 3	0 / 3	3 / 3	0 / 3	3 / 3
		35	35	3 / 3	3 / 3	0 / 3	3 / 3	0 / 3	3 / 3
Left Turn Across Path (LTAP)	Near Miss	25	15	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
		25	25	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
	Crash Imminent	25	15	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1
		25	25	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1
Straight Across Path (SAP)	Near Miss	15	15	0 / 1	1/1	Not performed			
		25	15	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
		35	15	0 / 1	1/1	0 / 1	1/1	0 / 1	1/1
	Crash Imminent	15	15	0 / 1	0 / 1	Not performed			
		25	15	0 / 1	0 / 1	1/1	0 / 1	0 / 1	0 / 1
		35	15	1/1	0 / 1	1/1	0 / 1	1/1	0 / 1

vehicle. In the case of the Model S, ACC is used to initiate braking in response to the POV, and it occurred from a TTC of approximately 3.11 to 4.18 seconds depending on the initial SV speed, as shown in Table 6. When the SV speed was nominally 20 mph, the TTCs at the onset of ACC deceleration[11] occurred 0.61 to 0.70 seconds earlier than the FCW alert onset TTCs observed during the tests performed with ACC and LCC off initiated from the same nominal speed. When results from similar LVS_25_0 tests were compared, the range of differences was 1.04 to 1.44 seconds.

Conversely, the Mercedes C300 did not use ACC to reduce speed during the LVS scenario. Rather, it achieved crash avoidance via the automatic braking provided by CIB. For every scenario evaluated in this study, the Mercedes C300 presented an FCW alert prior to the onset of CIB activation.

Table 6. TTCs Associated with FCW Alert Onset and ACC Deceleration During LVS Tests Performed with the Tesla Model S

Pre-Crash Scenario	TTC @ FCW Alert Onset (s)			TTC @ Onset of ACC Deceleration (s)		
	ACC off, LCC off	ACC on, LCC off	ACC on, LCC on	ACC off, LCC off	ACC on, LCC off	ACC on, LCC on
LVS_15_0	2.06 – 2.16	n/a[1]	n/a[1]	n/a[2]	n/a[3]	n/a[3]
LVS_20_0	2.44 – 2.50	n/a[1]	n/a[1]	n/a[2]	3.11 – 3.14	3.11 – 3.14
LVS_25_0	2.74 – 2.81	n/a[1]	n/a[1]	n/a[2]	3.85 – 3.94	3.95 – 4.18

[1]No FCW alert presented
[2]ACC not enabled
[3] SV speed must be ≥18 mph for ACC to be enabled

3.2.2. Lead Vehicle Moving

With the exception of the LVM_25_10 scenario performed without ACC or LCC, the Tesla Model S and Mercedes C300 both achieved crash avoidance during each LVM trial performed. In the LVM_25_10 scenario performed without ACC or LCC, the Tesla Model S impacted the POV during each of the three trials performed, whereas an SV-to-POV impact occurred once with the Mercedes C300 in this condition.

For both vehicles, FCW alerts were presented during each LVM trial performed without ACC or LCC. However, neither vehicle presented an FCW alert during any LVM trial performed with ACC braking, regardless of whether LCC was on or off. The absence of an FCW alert in these conditions was not believed to be indicative of poor system performance by either vehicle, but rather an indication of how capable ACC was in mitigating the severity of the test conditions. For the tests where no FCW alert was presented, the early braking initiated by the vehicles' respective ACC systems was capable of achieving crash avoidance without relying on CIB interventions late in the pre-crash timeline.

[11] The onset of ACC was taken to be when an SV deceleration of approximately 0.05g was first realized.

3.2.3. Lead Vehicle Decelerates

The Tesla Model S and Mercedes C300 both achieved crash avoidance in the LVD_15_15 scenario. In the LVD_25_25 scenario, the Tesla Model S and Mercedes C300 realized crash avoidance during each of the ACC on/LCC off and ACC on/LCC on test trials. Both vehicles had at least two SV-to-POV impacts during the LVD_25_25 tests performed with ACC off/LCC off.

The Mercedes C300 achieved crash avoidance during each trial performed in the LVD_35_35 scenario. The Tesla Model S also achieved crash avoidance during the LVD_35_35 trials performed with ACC on and LCC off, however SV-to-POV impacts occurred during each of the three LVD_35_35 trials performed with ACC and LCC both being disabled, and during one of the three LVD_35_35 trials performed with both ACC and LCC on.

FCW alerts were presented during most LVD trials performed without ACC or LCC with the Tesla Model S, however one FCW non-activation occurred in the LVD_25_25 test condition (this is discussed more thoroughly in S3.4 "FCW Non-Activations"). In the case of the Tesla Model S LVD_35_35 trials performed with ACC and LCC on, an FCW alert was presented during one of the three trials. This was a true positive alert and occurred because the vehicle's ACC did not automatically apply the brakes as the SV approached the POV (this trial is discussed more thoroughly in S3.5 "CIB Non-Activations").

FCW alerts were presented during each LVD trial performed without ACC or LCC with the Mercedes C300. No FCW alerts were presented during any Mercedes C300 LVD trial performed with ACC, regardless of whether LCC was on or off.

As mentioned in S3.2.2, the absence of an FCW alert during the LVD tests performed with ACC enabled was not believed to be indicative of poor system performance by either vehicle, but rather an indication of how capable ACC was in mitigating the severity of the test conditions. For the tests where no FCW alert was presented, the early braking initiated by the vehicles' respective ACC systems was capable of achieving crash avoidance without relying on CIB interventions late in the pre-crash timeline.

3.2.4. Left Turn Across Path

For both the Tesla Model S and Mercedes C300, every LTAP trial performed with near miss choreography concluded with the POV completing its turn in front of the SV without an SV-to-POV impact. Conversely, an SV-to-POV impact occurred during each trial performed with crash imminent timing. No FCW alerts were observed during any LTAP test (i.e., with either vehicle, regardless of near miss or crash imminent timing). Videos of the two LTAP_25_25 test variants, performed with the Tesla Model S with both ACC and LCC on, are provided in Figures 11 and 12. Tests performed with the Mercedes C300 had the same test outcome. A real-world example of an LTAP is available online at https://www.youtube.com/watch?v=9X-5fKzmy38, and provides an interesting basis for comparison with the test track based emulations.

Tesla Model S LTAP_25_25 (near miss Test 184).wmv

Figure 11. LTAP_25_25 "near miss" scenario performed with the Tesla Model S. ACC and LCC were both on during this trial.

Tesla Model S LTAP_25_25 (crash imminent Test 198).wmv

Figure 12. LTAP_25_25 "crash imminent" scenario performed with the Tesla Model S. ACC and LCC were both on during this trial.

3.2.5. Straight Across Path

For both the Tesla Model S and Mercedes C300, every SAP trial performed with near miss choreography concluded with the POV completing its drive across the front of the SV without an SV-to-POV impact. Conversely, an SV-to-POV impact occurred during each trial performed with crash imminent timing. Sample videos of the two SAP_25_15 test variants, as performed with the Tesla Model S with both ACC and LCC on, are provided in Figures 13 and 14.

Tesla Model S SAP_25_15 (near miss test 0173).wmv

Figure 13. SAP_25_15 "near miss" scenario performed with the Tesla Model S. ACC and LCC were both on during this trial.

Tesla Model S SAP_25_15 (crash imminent test 0190).wmv

Figure 14. SAP_25_25 "crash imminent" scenario performed with the Tesla Model S. ACC and LCC were both on during this trial.

No FCW alerts were observed during any SAP test performed with the Tesla Model S, regardless of near miss or crash imminent timing. This was not the case for the Mercedes C300 however, as auditory FCW alerts were presented during four SAP trials performed with crash imminent timing:

- During one SAP_25_15 trial performed with ACC on and LCC off (although the TTC at FCW alert onset was only negligible at 23 ms)
- During all three SAP_35_15 trials (TTCs ranged between 736 to 866 ms at alert onset depending on the test condition)

No instances of CIB braking or automated braking were observed with either the Tesla Model S or Mercedes C300.

3.3. Operational Consistency

Operational consistency was assessed in three ways, and by determining how many of the three trials performed per test condition (i.e., test series performed with the same pre-crash scenario, speed combinations, and ACC/LCC setting) behaved similarly.

- FCW consistency was assessed by determining how many of the three trials per test condition contained an alert.
- Crash avoidance consistency was assessed by determining how many of the three trials per test condition concluded with the SV avoiding the POV.

- CIB operational consistency was assessed by assessing the presence and magnitude of the CIB interventions observed in each of the three trials per test condition.

Note: C*rash avoidance consistency* should not be confused with *CIB operational consistency*. The tests performed with ACC enabled did not typically require CIB intervention to achieve crash avoidance since the braking commanded by the ACC occurred so early in the pre-crash timeline (lower deceleration magnitudes, such as those within the operational authority provided by an ACC system, can be used to achieve crash avoidance if they are applied early enough).

3.3.1. FCW Consistency

3.3.1.1. Tesla Model S

Generally speaking, operation of the Tesla Model S FCW was consistent within a given test condition. Two exceptions were observed:

- During LVD_25_25 tests performed without ACC or LCC enabled
- During LVD_35_35 tests performed with ACC and LCC enabled

Additional details pertaining to these trials are discussed in S3.4 "FCW Non-Activations."

3.3.1.2. Mercedes C300

Without exception, operation of the Mercedes C300 FCW was consistent within a given test condition. For the test conditions where three trials were performed, all three trials either included an FCW alert or none were presented within that test series.

3.3.2. Crash Avoidance Consistency

3.3.2.1. Tesla Model S

The ability for the Tesla Model S to achieve crash avoidance <u>within a given test condition</u> was also largely consistent (i.e., each of the three trials performed per condition produced the same outcome), with one exception:

- During LVD_35_35 tests performed with ACC and LCC enabled

In this test condition, the first of three valid tests (Test 156) produced an SV-to-POV impact at a relative velocity of 2.1 mph, whereas the latter two trials concluded with crash avoidance. Relevant data from these three trials is provided in Figure 15.

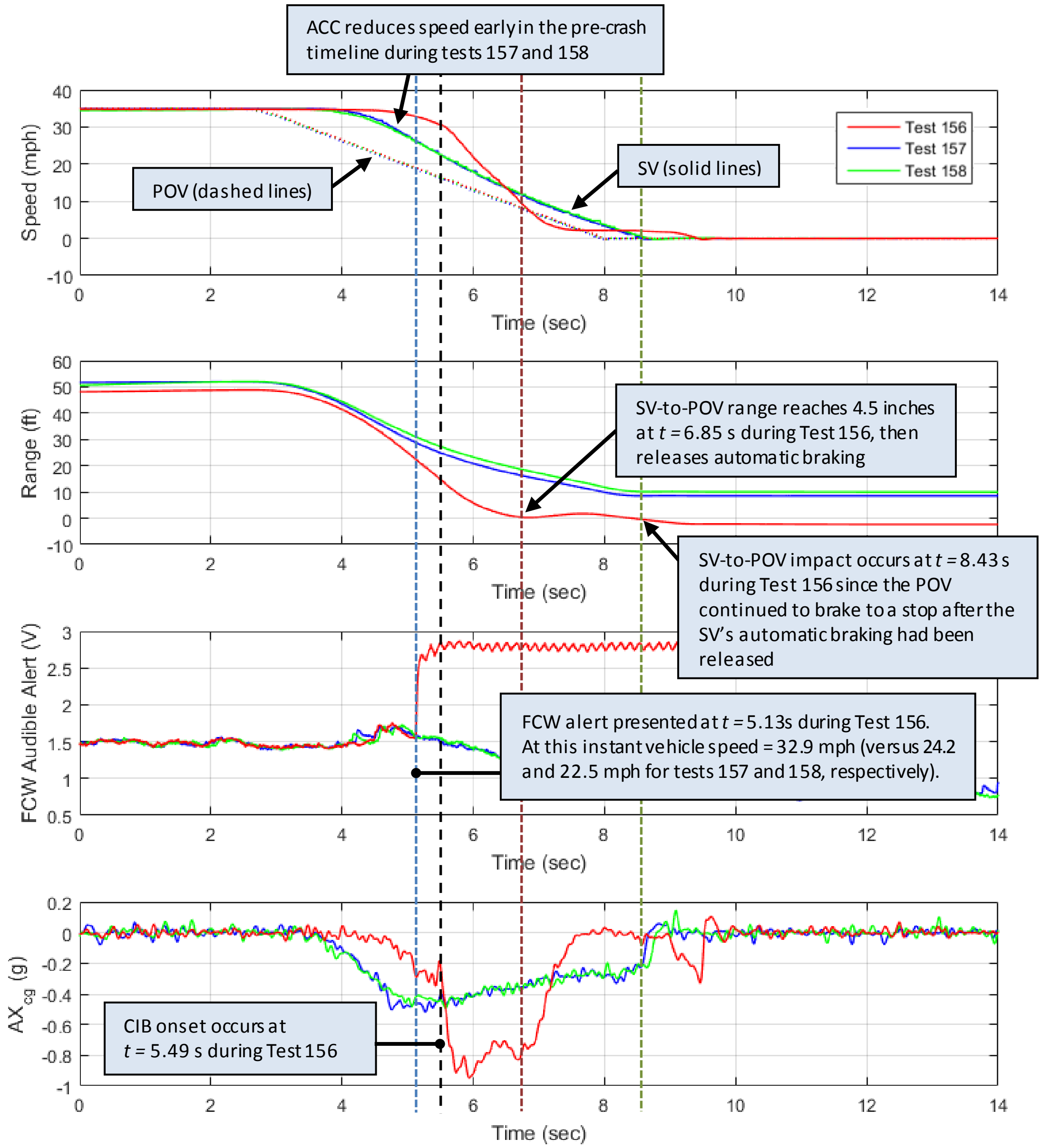

Figure 15. Tesla Model S LVD_35_35 tests performed with ACC and LCC enabled.

The key differences between Test 156 and the two others performed in this condition are twofold. First, ACC did not initiate speed reduction until just before the onset of the FCW alert during Test 156, which was much later in the pre-crash timeline than observed for Tests 157 and 158. As shown in Figure 15, the vehicle speeds of these tests were 26.4 and 31.6 percent lower, respectively, than that observed during Test 156 at the onset of the FCW alert during Test 156. Second, the delayed ACC-based speed reduction present in Test 156 required the vehicle to activate CIB in an attempt to avoid an impact with the POV. This intervention was initiated approximately 360 ms after the onset of the FCW, and was released approximately 1.4 seconds later when the front of the SV was 4.5 inches from the rear of the POV. However, since the POV has not yet completed its braking maneuver (it was traveling at 7.5 mph), and the Tesla

Model S CIB was no longer commanding deceleration, an SV-to-POV impact occurred 1.6 seconds later. The relative impact speed was 2.1 mph.

The reason for the Tesla Model S releasing the automated braking provided by CIB while the POV was still braking are unknown, and this behavior appears to differ from that observed during similar tests performed with the Mercedes C300 (i.e., the LVD_35_35 tests performed with ACC on and LCC off, previously shown in Figure 10).

Note: An additional discussion of this test series is provided in S3.5 "CIB Non-Activations."
The ability for the Tesla Model S to achieve crash avoidance within a given pre-crash scenario was scenario-dependent.

- With no ACC or LCC, each trial concluded with crash avoidance for three of the four LVM test speed combinations. Each of the three trials performed in the LVM_25_10 test condition concluded with an impact, and impact speeds of 2.3, 3.0, and 5.6 mph were observed[12].
- With no ACC or LCC, each trial concluded with crash avoidance for one of the three LVD test speed combinations. Each of the three trials performed in the LVD_25_25 test condition concluded with an impact, where impact speeds of 4.9, 15.9, and 20.0 mph were observed. Each of the three trials performed in the LVD_35_35 test condition[13] concluded with an impact, where impact speeds of 5.9, 6.8, and 3.7 mph were observed.
- With ACC and LCC enabled, each trial concluded with crash avoidance for one of the two LVD test speed combinations. One of the two LVD test speed combinations concluded with crash avoidance (discussed previously). One of the three trials performed in the LVD_35_35 test condition concluded with a relative impact speed of 2.1 mph.

3.3.2.2. Mercedes C300

The ability for the Mercedes C300 to achieve crash avoidance within a given test condition was largely consistent, with two exceptions performed with no ACC or LCC:

- During the LVM_25_10 test series, shown in Figure 16, an SV-to-POV impact occurred during one of the three trials performed (at a relative speed of 6.4 mph).
- During the LVD_25_25 test series, shown in Figure 17, an SV-to-POV impact occurred during two of the three trials performed, and impact speeds of 6.3 and 9.8 mph were observed.

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[12] The evaluation criteria specified in NHTSA's CIB NCAP test procedure requires at least 5 of 7 trials performed in the LVM_25_10 test condition achieve crash avoidance to be awarded CIB NCAP credit.

[13] The evaluation criteria specified in NHTSA's CIB NCAP test procedure requires at least 5 of 7 trials performed in the LVD_35_35 test condition achieve a speed reduction of at least 10.5 mph to be awarded CIB NCAP credit.

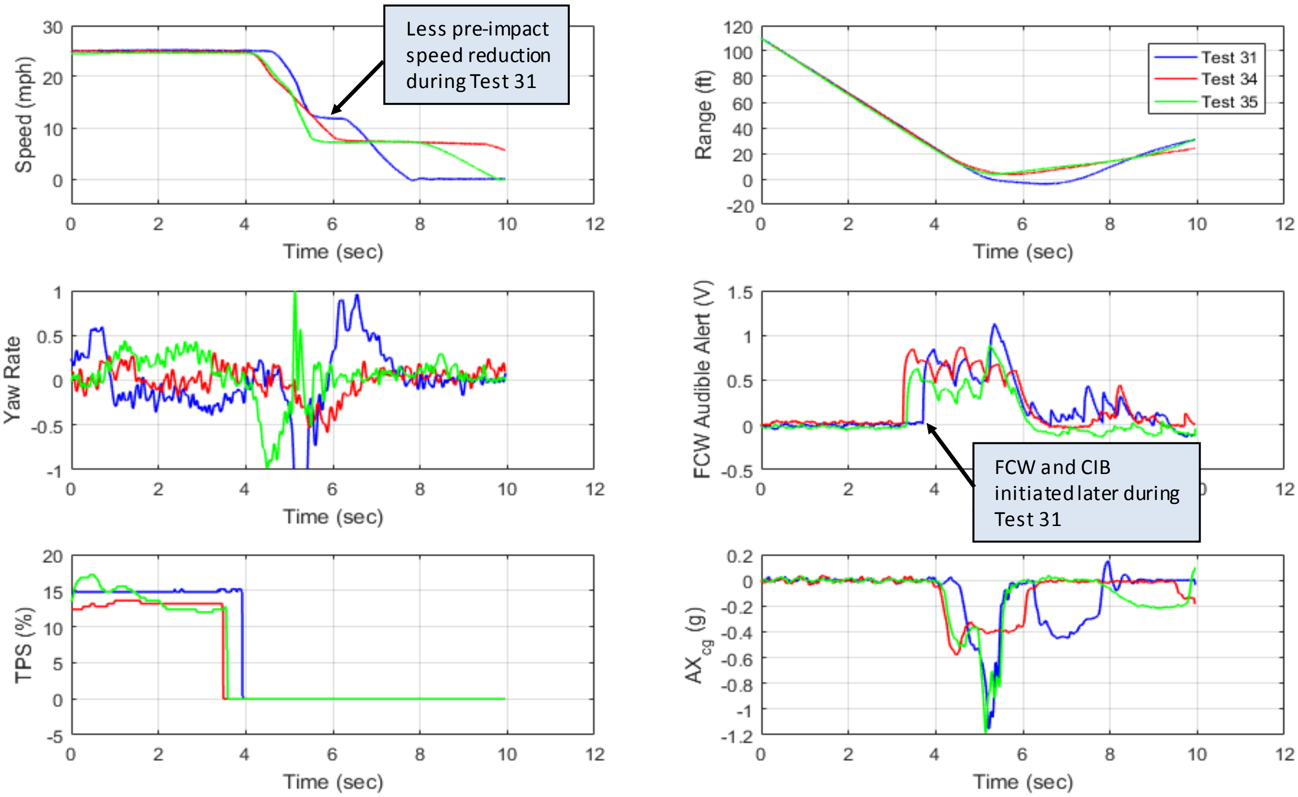

Figure 16. Mercedes C300 LVM_25_10 tests performed with no ACC or LCC.

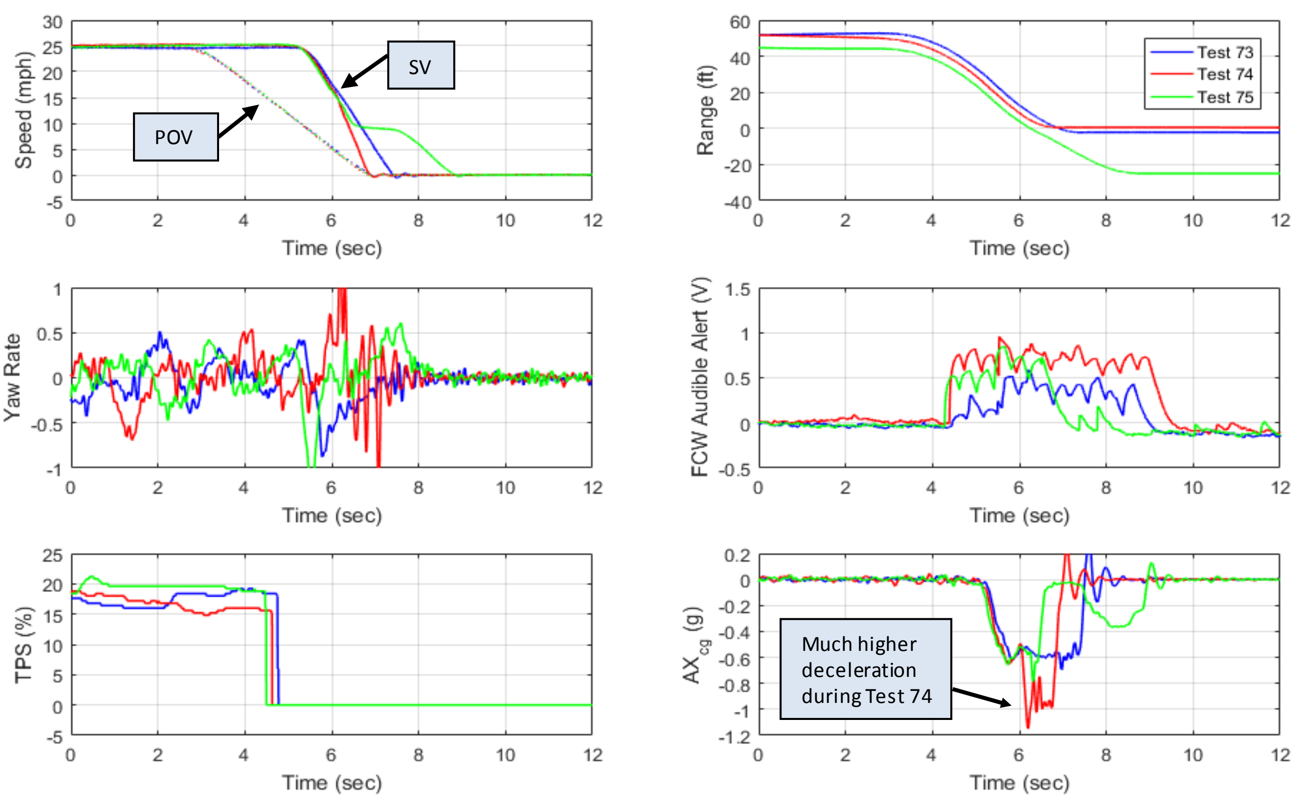

Figure 17. Mercedes C300 LVD_25_25 tests performed with no ACC or LCC.

In the case of the LVM_25_10 test condition performed with no ACC or LCC, the onset of the FCW and CIB intervention during Test 31 occurred at TTCs of 1.48 seconds and 450 ms, respectively. These values were both later in the pre-crash timeline than those associated with Tests 34 and 35, where the TTCs at the onset of FCW ranged between 1.76 and 1.93 seconds, and were between 0.830 and 928 ms at the onset of the respective CIB interventions. The reasons for these differences are not known.

The FCW alert and CIB intervention onsets were nearly identical for the LVD_25_25 tests performed with no ACC or LCC. However, much higher deceleration magnitude was realized during Test 74, the only test to achieve crash avoidance. The reasons for these differences are also unknown.

3.3.3. CIB Operational Consistency

3.3.3.1. Tesla Model S

The assessment of the Tesla Model S CIB operational consistency was based on tests performed *without ACC or LCC enabled*. For the test conditions performed without ACC or LCC, the ability for the Tesla Model S to achieve crash avoidance depended on the speed reduction realized by the combination of post-FCW regenerative braking and the vehicle's CIB-based braking. Regenerative braking occurred each time the driver released the throttle pedal, and was capable of producing a deceleration of approximately 0.14g.

3.3.3.1.1. Lead Vehicle Stopped

Key data collected during each LVS test performed with the Tesla Model S are presented in Figure 18. In the LVS scenario, CIB braking occurred during each trial performed with each of the three SV test speeds: 15, 20, and 25 mph. Regardless of the initial speed, each trial included an FCW alert followed by strong CIB braking shortly thereafter. The timing of the FCW alerts and onsets of CIB braking were largely consistent for a given initial speed condition. Each LVS trial concluded with the SV successfully avoiding the POV.

The final SV-to-POV headway ranges, assessed from the front-most location of the SV front bumper to the rear-most location of the POV, were as follows:

- LVS 15_0: 0.95 to 1.86 ft
- LVS 20_0: 0.96 to 2.84 ft
- LVS 25_0: 2.46 to 2.81 ft

Note that these values are provided to further quantify CIB consistency, and should not be considered in a "more is better" context. Although it may provide a greater crash avoidance "cushion" at the end of the braking maneuver, achieving an excessively large final headway is not necessarily desirable since the associated intervention must be initiated earlier and/or include a greater deceleration magnitude. Multiple vehicle manufacturers have indicated to NHTSA that driver acceptance of such operation can vary.

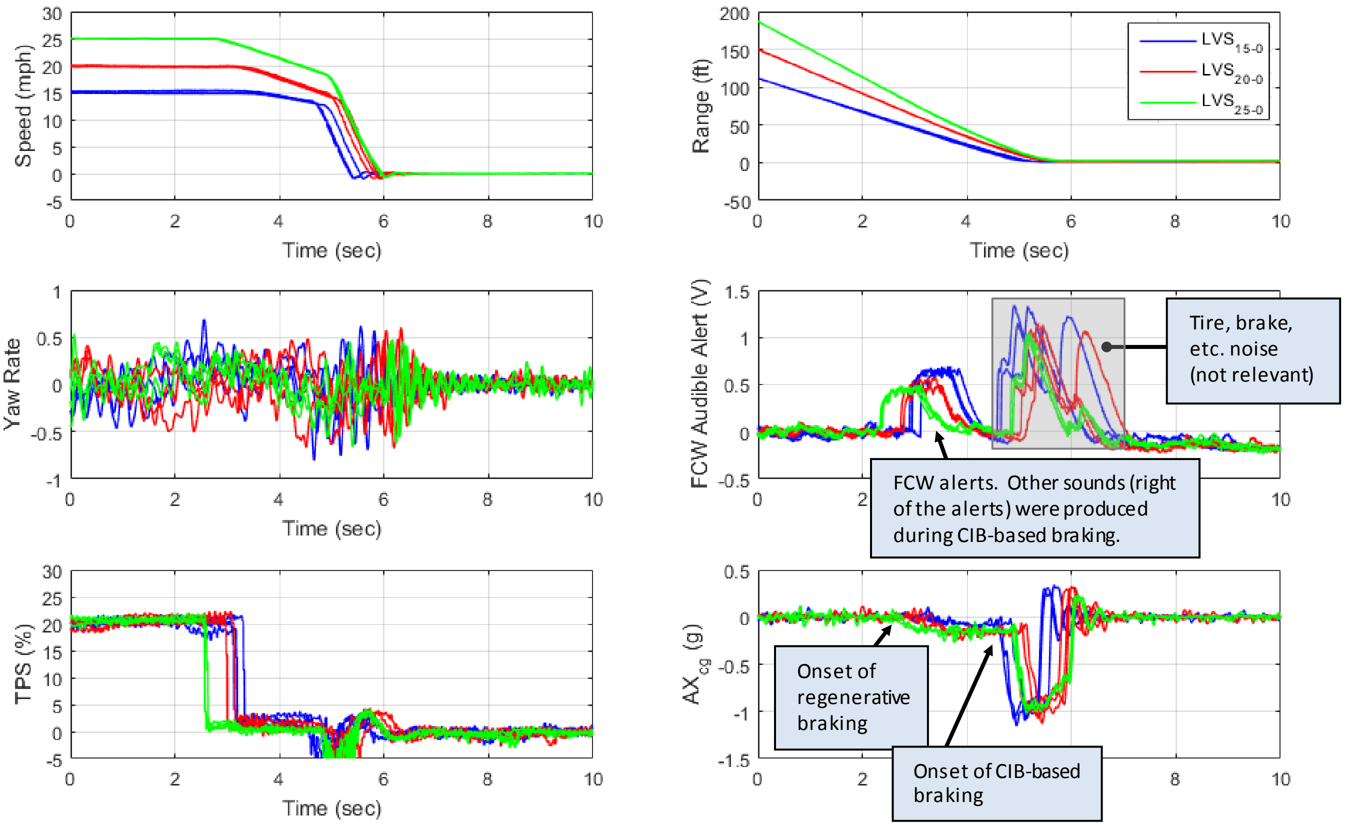

Figure 18. LVS tests performed with the Tesla Model S.

3.3.3.1.2. Lead Vehicle Moving

Figure 19 presents key data collected during each LVM test performed with the Tesla Model S. In the LVM scenario, an FCW was presented during all trials, however CIB braking only occurred during each trial performed with the nominal 25 mph SV-to-POV initial speed differential (i.e., the 35_10 and 45_20 mph test speed combinations). For these tests, each trial included an FCW alert followed by strong CIB braking shortly thereafter. The timing of the FCW alerts and onsets of CIB braking were largely consistent for each test performed with the 35_10 and 45_20 mph test speeds, and each of these trials concluded with crash avoidance. The final SV-to-POV headway ranges were as follows:

- LVM 35_10: 1.15 to 2.64 ft
- LVM 45_20: 0.48 to 1.25 ft

No LVM test performed with the nominal 15 mph SV-to-POV initial speed differential (i.e., the 25_10 and 35_20 mph test speed combinations) included a CIB intervention; all speed reductions that occurred after the driver released the throttle pedal were the result of regenerative braking. Each of the three LVM_25_10 tests concluded with an SV-to-POV impact, whereas those performed with the 35_20 mph speed combinations achieved crash avoidance and a final SV-to-POV headway range of 2.12 to 8.01 ft.

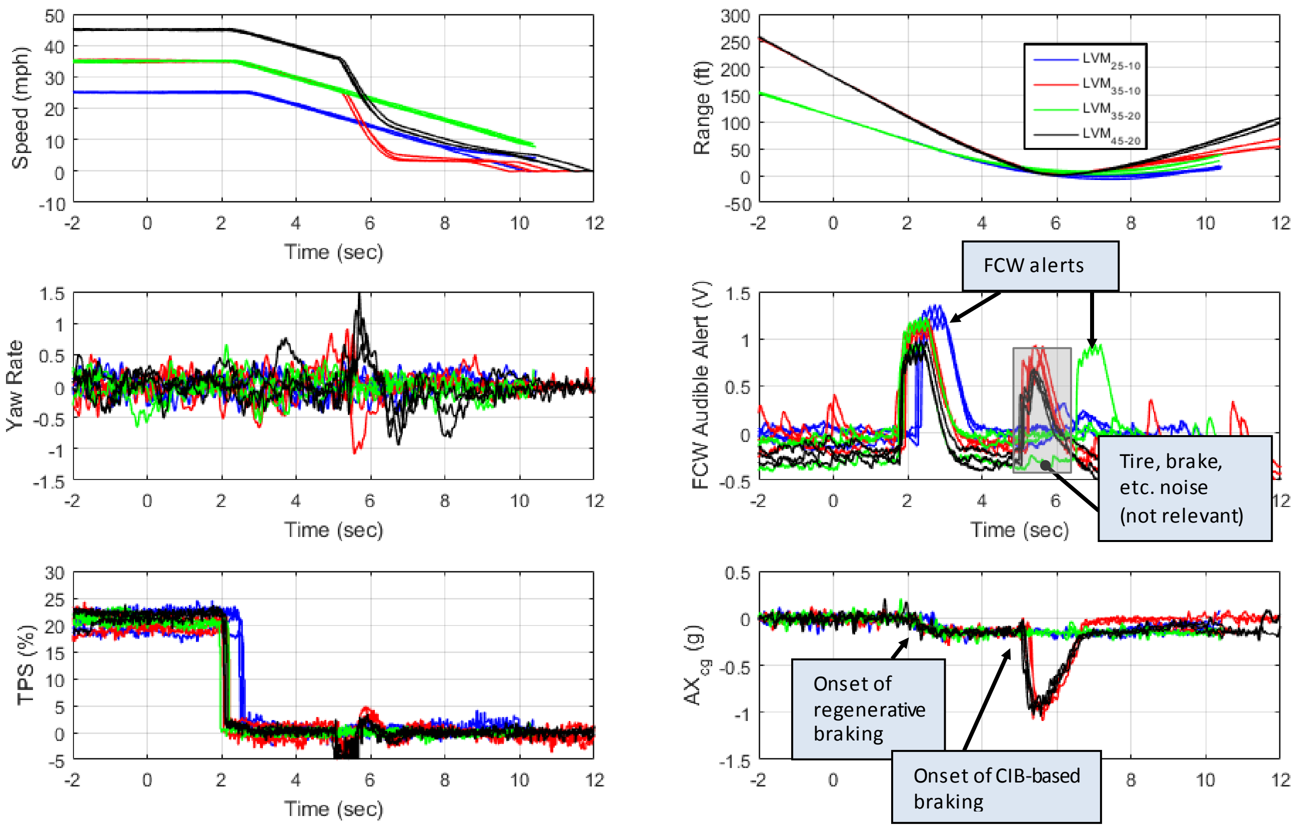

Figure 19. LVM tests performed with the Tesla Model S. Multiple FCW alerts occurred during one of the LVM_35_20 trials.

For each test performed without ACC and LCC, the driver was required to fully release the throttle pedal within 500 ms of being presented with the FCW alert. Once the throttle pedal is released, regenerative braking is activated, thereby slowing the vehicle. The deceleration magnitude associated with regenerative braking was not observed to differ as a function of whether the vehicle's initial speed was 25 or 35 mph. Therefore, two factors can influence the ability for the vehicle to slow during these tests: FCW alert timing and driver response time.

With regards to response time, the driver was required to fully release the throttle pedal within 500 ms of being presented with the FCW alert[14]. For the 35_20 mph tests, the actual release times were 295, 385, and 490ms, which were nearly equivalent to the 330, 375, and 385 ms release times measured during the 25_10 mph tests. For this reason, differences in driver response time are not believed to have been responsible for the crash outcome observed for these two test conditions.

Therefore, the reason for each 35_20 mph test being able to achieve crash avoidance, whereas those performed in the 25_10 mph condition were not, is believed to be attributable to the

[14] This requirement is defined in the CIB test procedure used by NHTSA's NCAP.

differences in the Tesla Model S FCW alert timing observed during the 35_20 and 25_10 mph tests. Although the same driver-selectable FCW headway setting was selected for all LVM tests (i.e., the one configured to present the earliest FCW alert), the FCW times-to-collision (TTC) at alert onset were 3.10, 3.20, and 3.22 seconds during the 35_20 mph tests, but were 2.71, 2.79, and 2.80 seconds during the 25_10 mph tests.

In other words, the earlier alerts presented during the 35_20 mph tests allowed regenerative braking to have approximately 300 to 647 ms more time to slow the vehicle[15]; enough time to ultimately prevent the crash from occurring. For the sake of clarity, Figure 20 presents some of the information previously shown in Figure 19, but is more narrowly focused on the most relevant test trials and data channels.

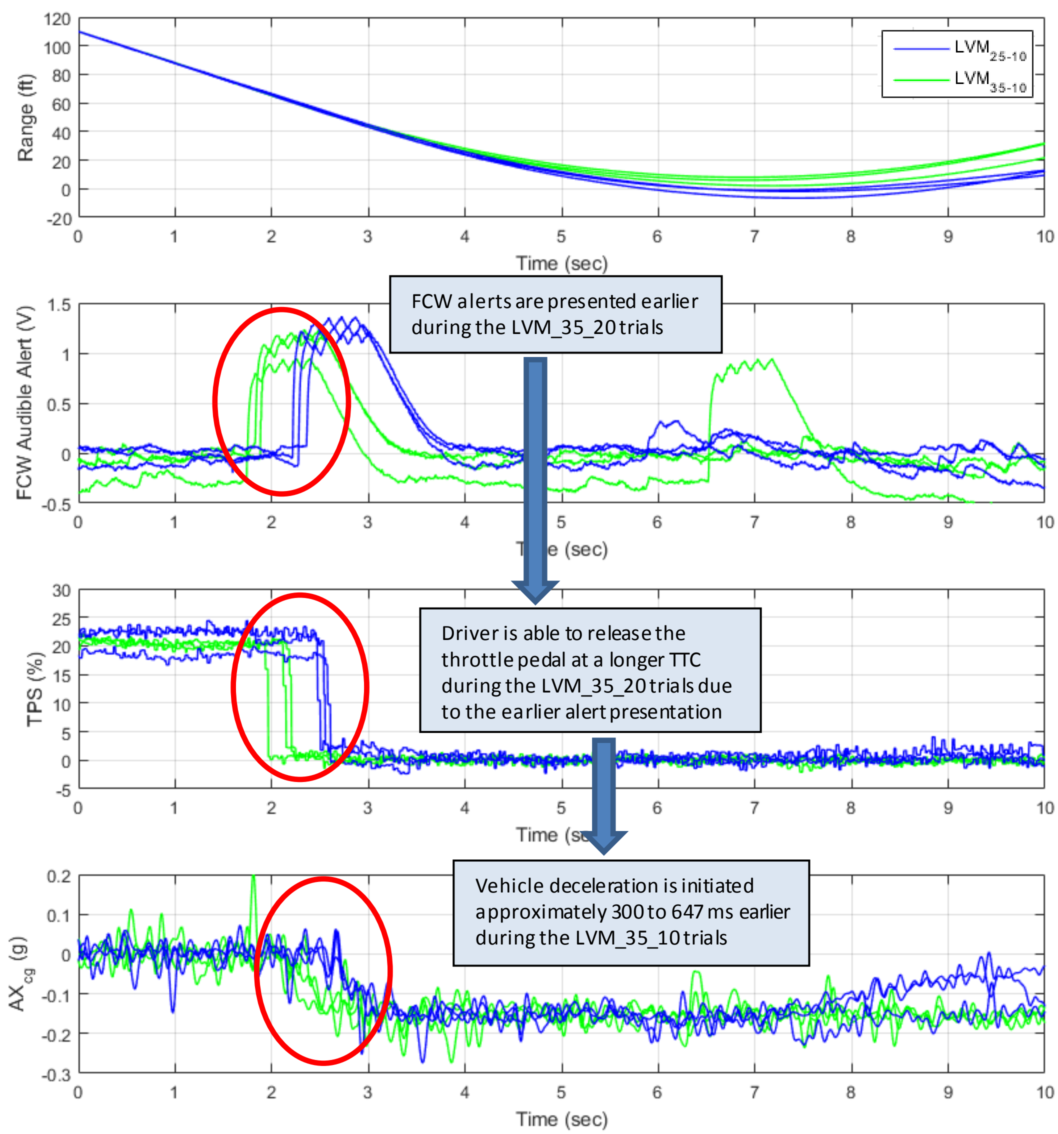

Figure 20. LVM tests performed with the Tesla Model S and a 15 mph relative SV-to-POV speed.

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[15] Calculated by comparing minimum and maximum times at the instant the throttle pedal was fully released.

Note: The third of three LVM_35_20 tests included two FCW alerts. The first occurred at an SV-to-POV range of 72.5 ft (where TTC≈3.22 seconds), and the second at 6.3 ft (just prior to minimum SV-to-POV range of 5.9 ft). The reason for the second alert is unknown, especially since it occurred so late in the pre-crash timeline and no CIB intervention occurred. As previously stated, this test concluded with crash avoidance.

3.3.3.1.3. Lead Vehicle Decelerates

Figures 21 and 22 present key data collected during each LVD trial performed with the Tesla Model S from 15 and 35 mph, with no ACC or LCC, respectively. For these test series, each trial included an FCW alert followed by strong CIB braking shortly thereafter. The within-series timing of the FCW alerts was largely consistent during the 15 mph tests (more so than the onset of the CIB braking). For the tests performed from 35 mph, the onset of the FCW alerts was more variable; however the onset timing of the CIB braking was very consistent.

Figure 23 presents key data collected during each LVD trial performed with the Tesla Model S from 25 mph without ACC or LCC. Unlike those performed from 15 or 35 mph, this series had one trial where no FCW alert was presented, and two trials were CIB did not intervene. An additional discussion of this test series is provided in S3.4 “FCW Non-Activations” and S3.5 “CIB Non-Activations.”

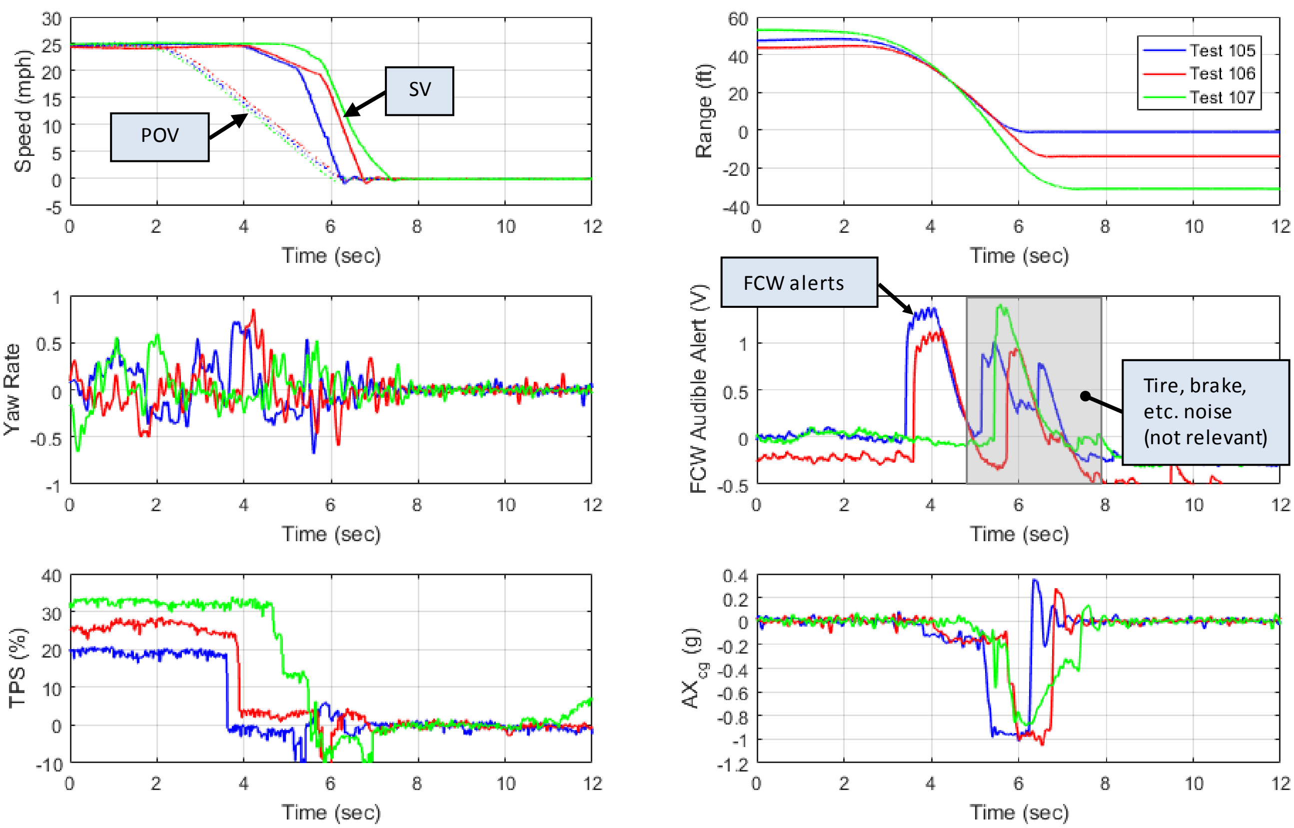

Figure 21. LVD_25_25 tests performed with the Tesla Model S.

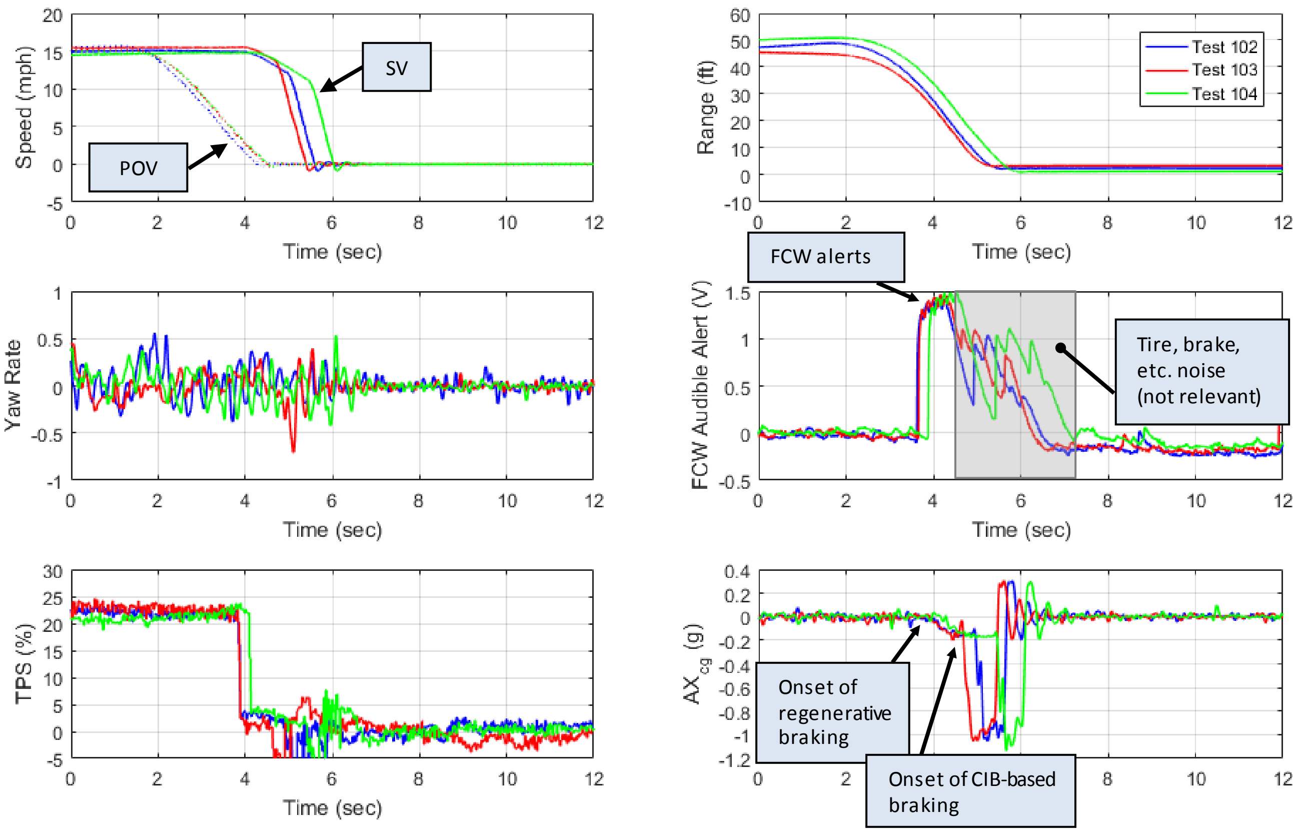

Figure 22. LVD_15_15 tests performed with the Tesla Model S.

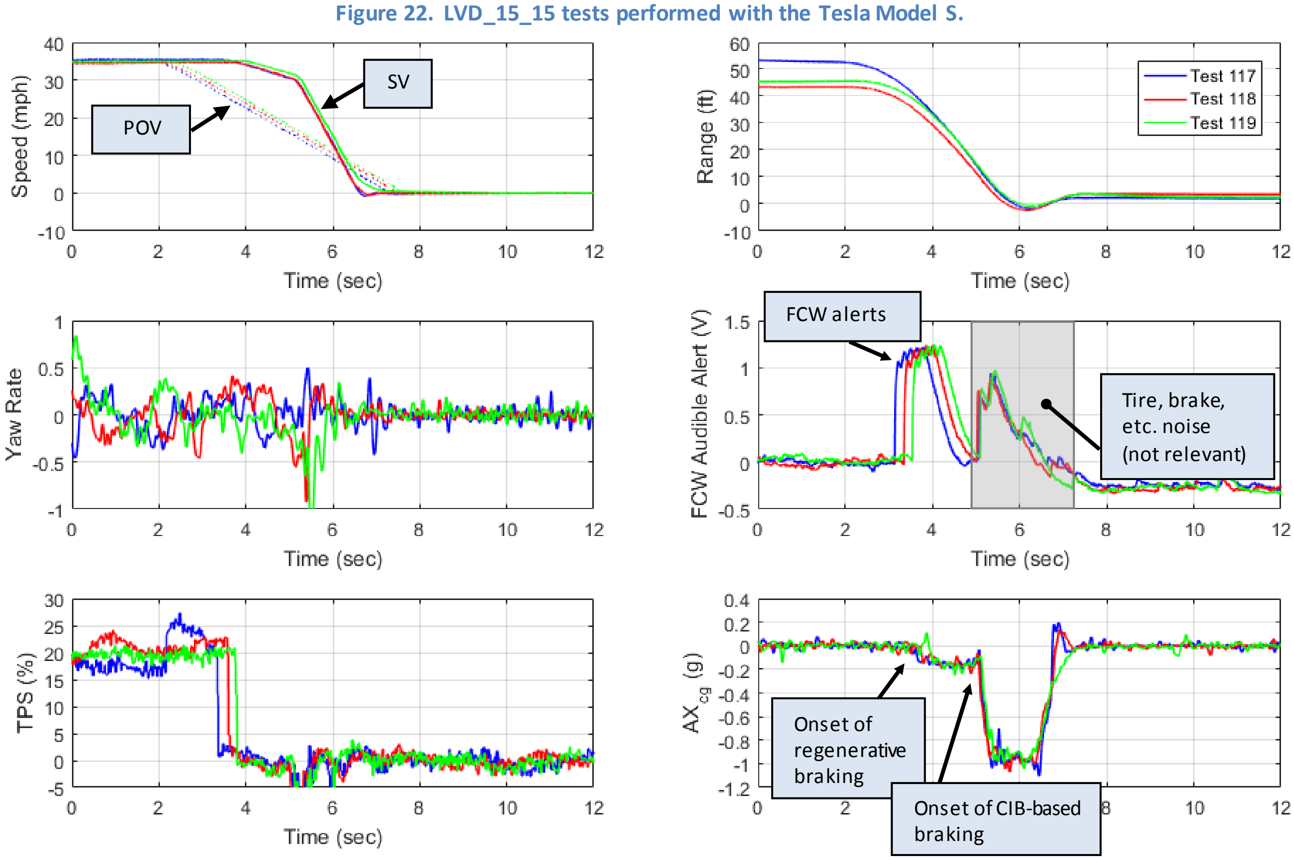

Figure 23. LVD_35_35 tests performed with the Tesla Model S.

The final SV-to-POV headway ranges for the LVD tests performed with the Tesla Model S without ACC or LCC were as follows:

- LVD 15_15: 1.07 to 3.33 ft
- LVD 25_25: Not applicable (relative impact speeds of 4.9, 15.9, and 20.0 mph)
- LVD 35_35: Not applicable (relative impact speeds of 3.7, 5.9, and 6.8 mph)

3.3.3.2. Mercedes C300

Like that performed for the Tesla Model S, assessment of the Mercedes C300 CIB operational consistency was only based on tests performed *without ACC or LCC enabled*. For the test conditions performed without ACC or LCC, the ability for the Mercedes C300 to achieve crash avoidance depended on the speed reduction realized by the combination of post-FCW engine braking and the vehicle's CIB-based brake interventions. The Mercedes C300 was not equipped with a regenerative brake system.

3.3.3.2.1. Lead Vehicle Stopped

Key data collected during each LVS test performed with the Mercedes C300 are presented in Figure 24. Regardless of the initial speed, each LVS trial included an FCW alert followed by CIB braking shortly thereafter. The timing of the FCW alerts and onsets of CIB braking were largely consistent for a given initial speed condition, and each LVS trial concluded with the SV successfully avoiding the POV.

The final SV-to-POV headway ranges for LVS tests performed with the Mercedes C300 without ACC or LCC, assessed from the front-most location of the SV front bumper to the rear-most location of the POV, were as follows:

- LVS 15_0: 2.12 to 3.04 ft
- LVS 20_0: 1.42 to 1.88 ft
- LVS 25_0: 1.36 to 1.91 ft

3.3.3.2.2. Lead Vehicle Moving

Figure 25 presents key data collected during LVM trials performed with each of the four SV-to-POV speeds combinations for the Mercedes C300 (without ACC or LCC). FCW alerts and CIB brake interventions occurred during all of these trials, and only one impact occurred overall (during a LVM_25_10 test).

The timing of the FCW alerts and onsets of CIB braking were largely consistent for a given initial speed condition, with the most variability observed during the trials performed in LVM_25_10 scenario where one of the three trials concluded with an SV-to-POV impact. In this scenario, the TTCs at the onset of the FCW alerts and CIB brake interventions differed by up 446 and 477 ms, respectively (see Table 7). The TTCs of the other speed combinations differed by 55 to 86 ms, and 67 to 79 ms, respectively.

Table 7. FCW Alert Onset and CIB Deceleration TTCs During LVM Tests Performed with the Mercedes C300 (No ACC or LCC)

Pre-Crash Scenario	TTC @ FCW Alert Onset		TTC @ Onset of CIB Deceleration	
	Range (s)	Max Difference (ms)	Range (s)	Max Difference (ms)
LVM_25_10	1.48 – 1.93	**446**	0.450 – 0.928	**477**
LVM_35_10	2.28 – 2.37	**86**	1.13 – 1.20	**68**
LVM_35_20	2.20 – 2.26	**55**	1.15 -- 1.21	**67**
LVM_45_20	2.41 – 2.45	**41**	1.15 – 1.23	**79**

The final SV-to-POV headway ranges for the LVM tests performed with the Mercedes C300 and no ACC or LCC were as follows:

- LVM_25_10: 3.63 to 3.79 ft (an impact speed of 6.4 mph occurred during one trial)
- LVM 35_10: 5.52 to 6.68 ft
- LVM_35_20: 3.72 to 4.71 ft
- LVM 45_20: 5.82 to 6.93 ft

3.3.3.2.3. Lead Vehicle Decelerates

Key data collected during the LVD_15_15 and LVD_35_35 test series performed with the Mercedes C300 are presented in Figures 26 and 27, respectively. Similar data collected during the LVD_25_25 tests were previously shown in Figure 17. Regardless of the test speeds, each trial included an FCW alert followed by CIB braking shortly thereafter. The timing of the FCW alerts and onsets of CIB braking were largely consistent for a given initial speed condition. With the exception of one LVD_25_25 test, each LVD trial concluded with the SV successfully avoiding the POV.

The final SV-to-POV headway ranges for the LVD tests performed with the Mercedes C300 without ACC or LCC were as follows:

- LVD 15_15: 1.20 to 2.20 ft
- LVD 25_25: 0.53 ft (during one trial; relative impact speeds of 6.3 and 9.8 mph occurred during the other two trials)
- LVD 35_35: 5.14 to 5.75 ft

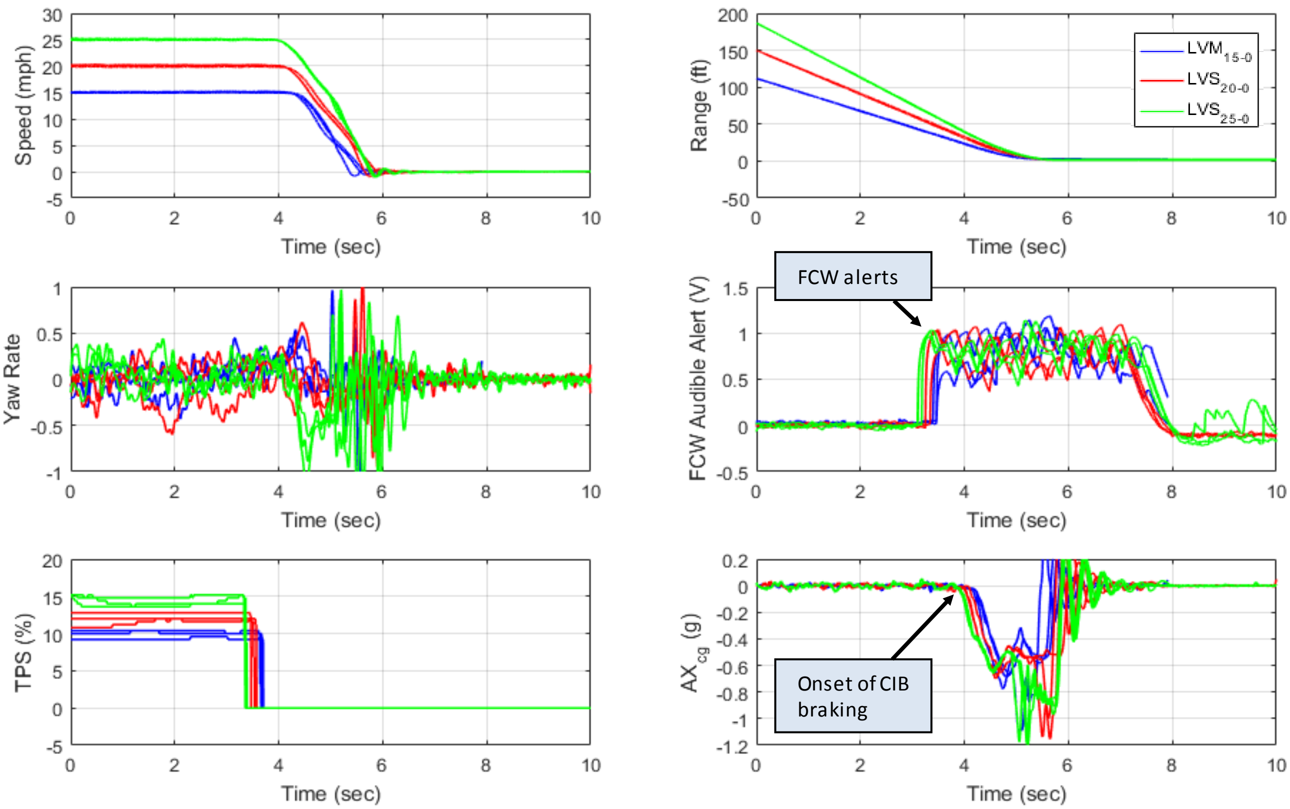

Figure 24. LVS tests performed with the Mercedes C300.

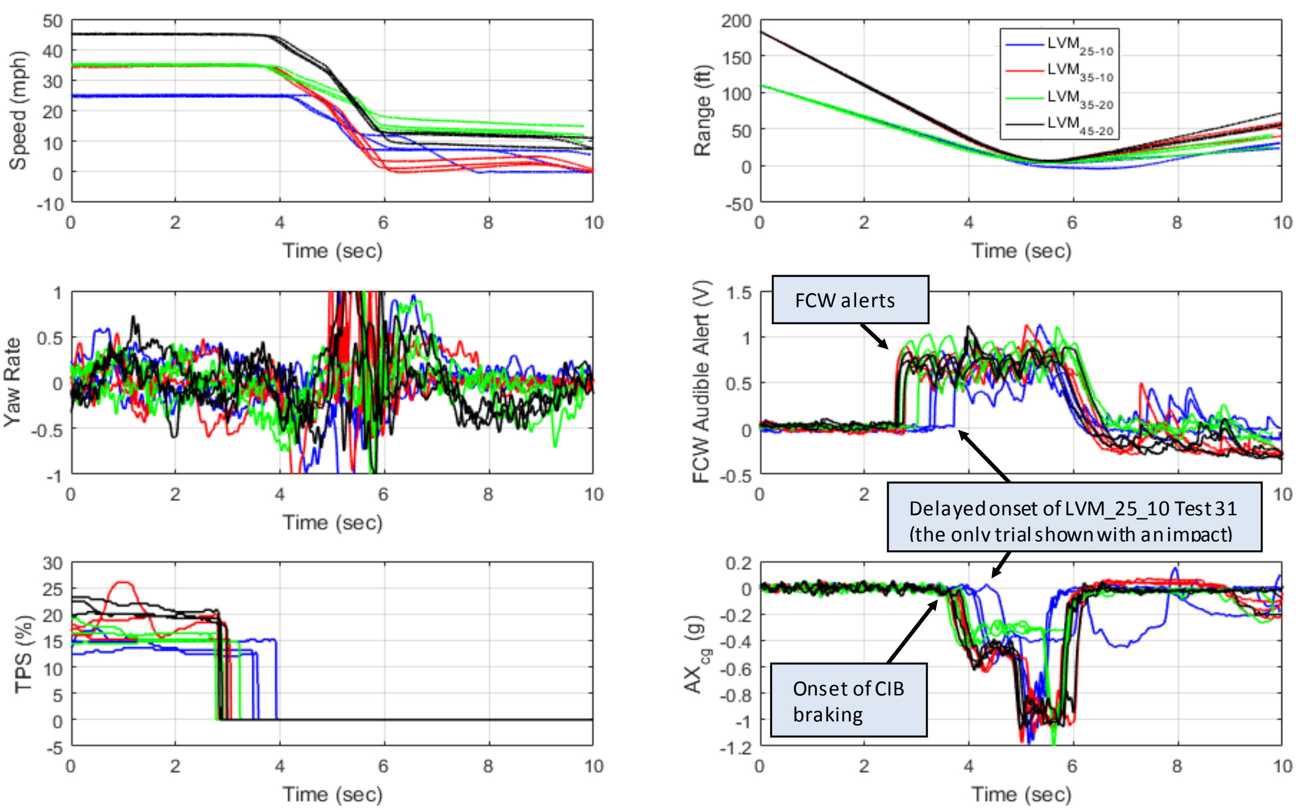

Figure 25. LVM tests performed with the Mercedes C300.

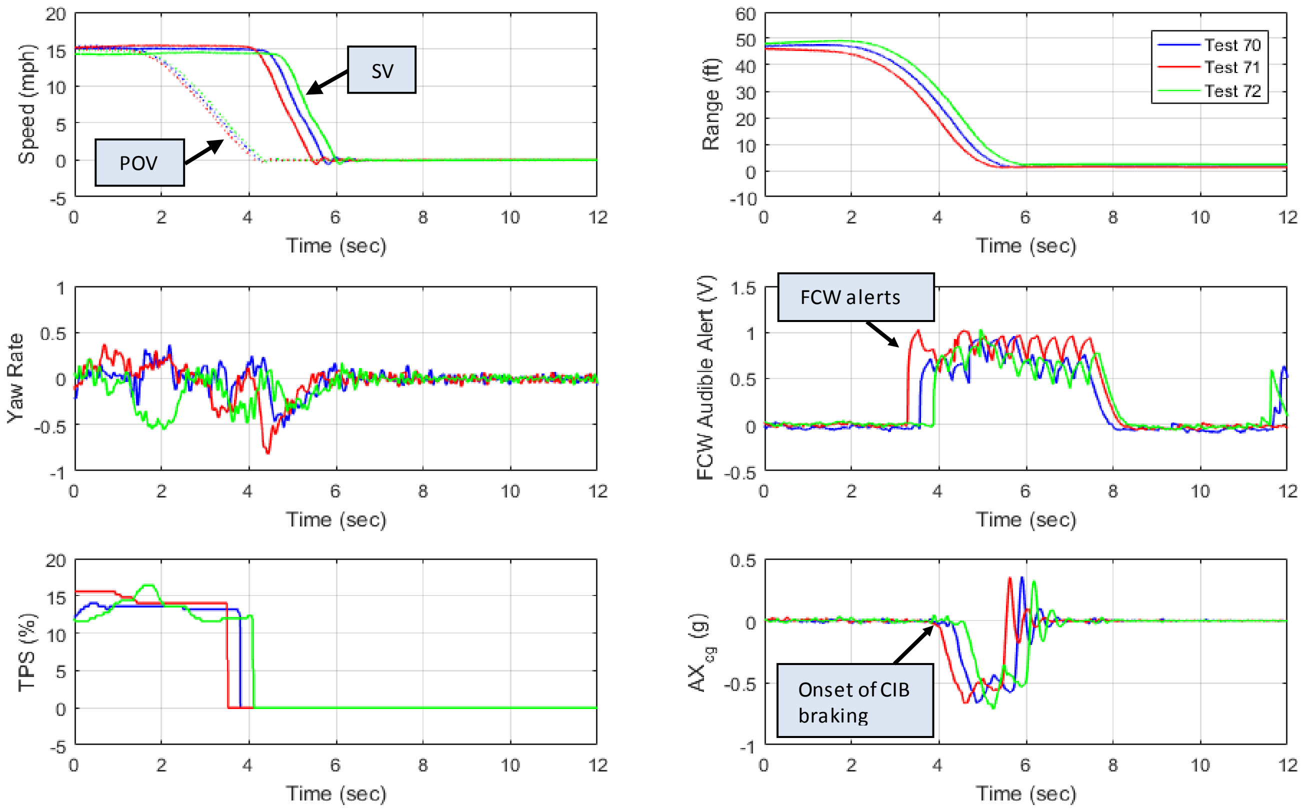

Figure 26. LVD_15_15 tests performed with the Mercedes C300.

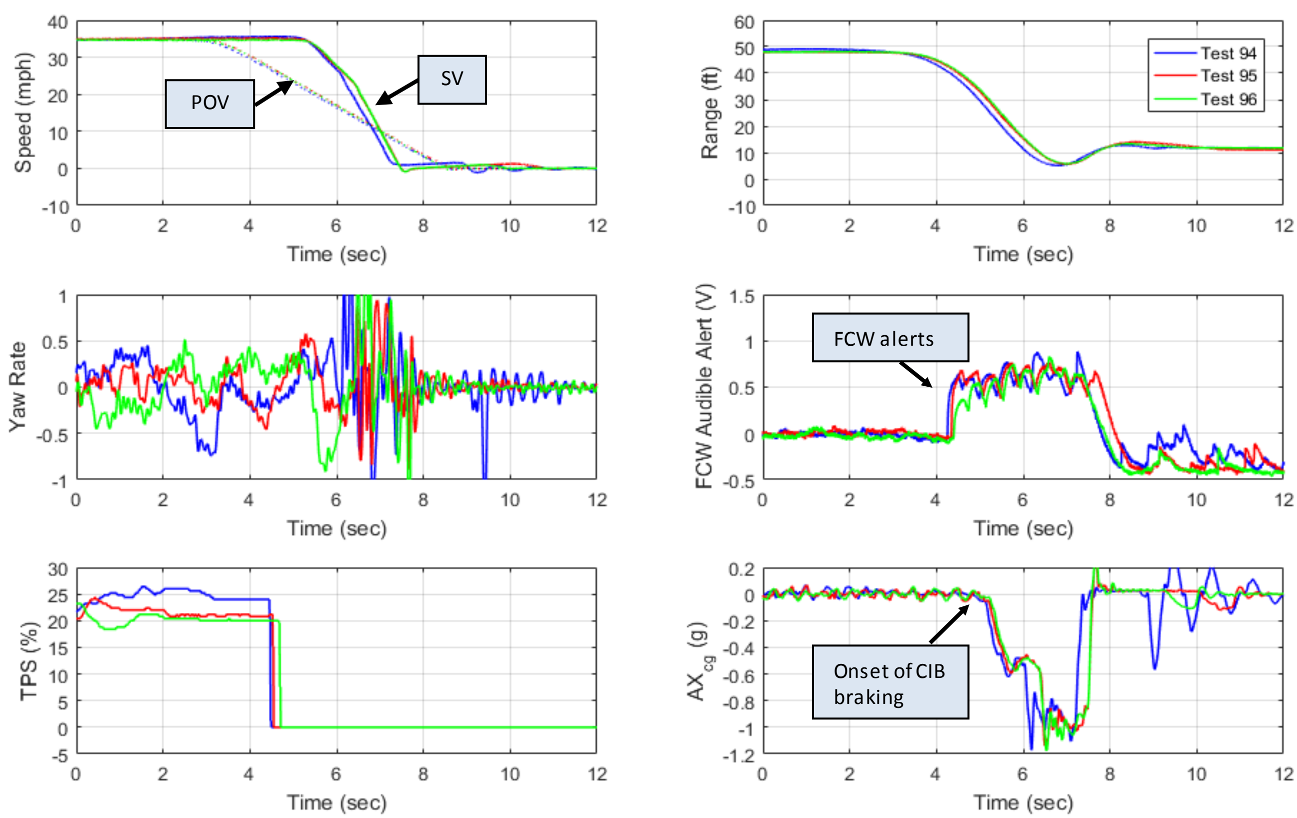

Figure 27. LVD_35_35 tests performed with the Mercedes C300.

3.4. FCW Non-Activations

3.4.1. Tesla Model S

When neither ACC nor LCC were enabled, an FCW alert was not presented during the third of three trials performed with the Tesla Model S in the LVD_25_25 scenario. Although each of these three trials concluded with an SV-to-POV impact, the relative impact speed recorded during the test without the FCW (20.0 mph) was greater than those recorded during the trials where the FCW alert was presented (4.9 and 15.9 mph). An additional discussion of these tests is provided in S3.5 "CIB Non-Activations."

With ACC enabled (with or without LCC also enabled), the Tesla Model S did not present an auditory FCW alert during any LVS, LVM, and LVD test trial. For these test conditions, this behavior is not believed to be problematic, however, since extended periods of low-magnitude deceleration, initiated at an early TTC, were used to achieve crash avoidance in each case.[16]

3.4.2. Mercedes C300

With ACC enabled (with or without LCC also enabled), the Mercedes C300 did not present an auditory FCW alert during any LVM or LVD test trial. As was the case for the Tesla Model S, extended periods of low-magnitude deceleration initiated at an early TTC, were used by the Mercedes C300 to achieve crash avoidance in each LVM and LVD test trial.[13]

Note: FCW alerts were presented during each Mercedes C300 LVS test performed with ACC enabled (with or without LCC also enabled), however CIB appears to have been solely responsible for reducing the vehicle speed needed to achieve crash avoidance. Figures 28 and 29 present representative trials from each test LVS_20_0 and LVS 25_0 test condition, respectively the onsets of (1) the FCW alerts, and (2) the CIB-based decelerations occurred at nearly equivalent times regardless of whether the vehicle was operated with or without ACC and/or LCC enabled.

3.5. CIB Non-Activations

3.5.1. Tesla Model S

3.5.1.1. LVM_25_10 Tests Performed Without ACC or LCC

As previously indicated in S3.3.2.2 and S3.3.3.1.2, CIB non-activations occurred during each of the three LVM_25_10 trials performed with the Tesla Model S and no ACC or LCC. Although

[16] It is believed that FCW activation was not deemed necessary by the vehicle since ACC alone was able to avoid the crash. However, this could not be objectively and absolutely quantified since neither the onset of the throttle release or brake intervention commanded by the vehicle's ACC, nor the commanded onset of the vehicle's AEB, were directly recorded from the vehicle itself (e.g., from an applicable electronic control unit or module).

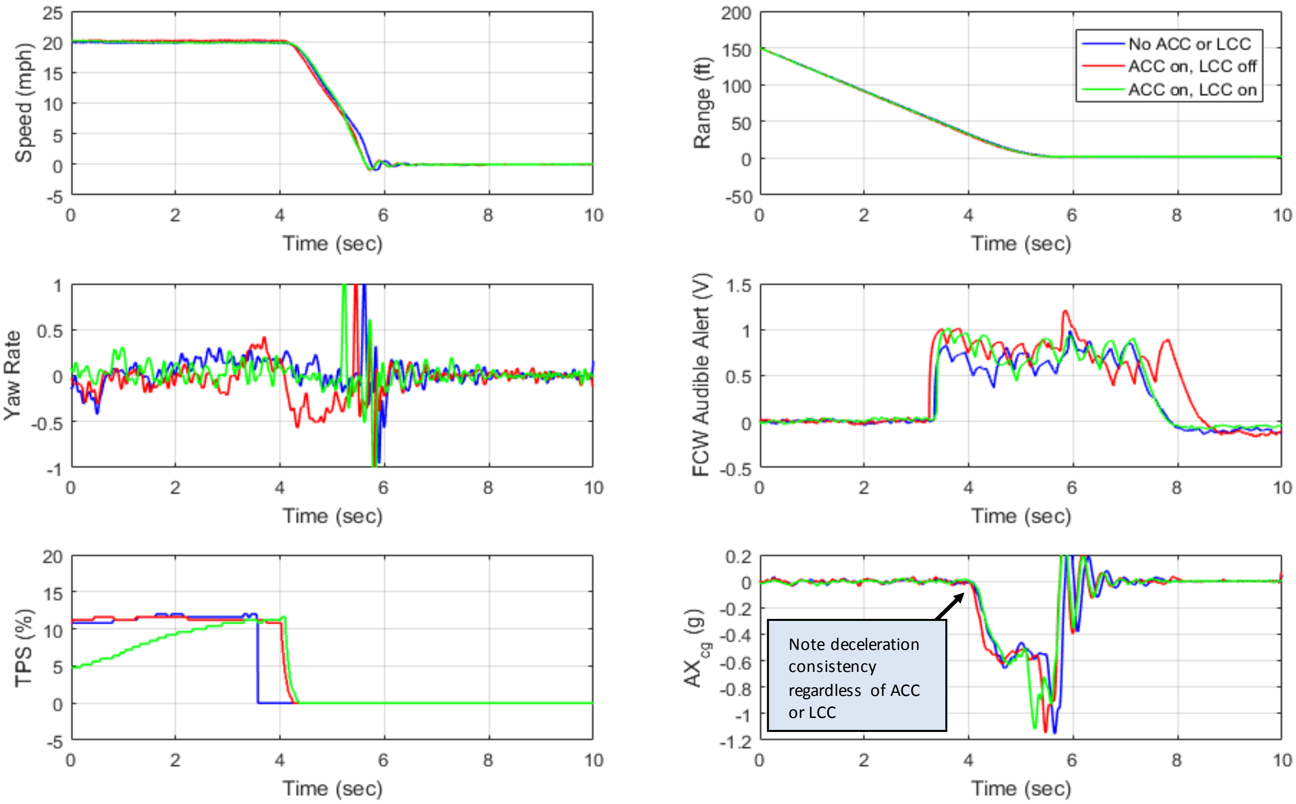

Figure 28. LVS_20_0 tests performed with the Mercedes C300.

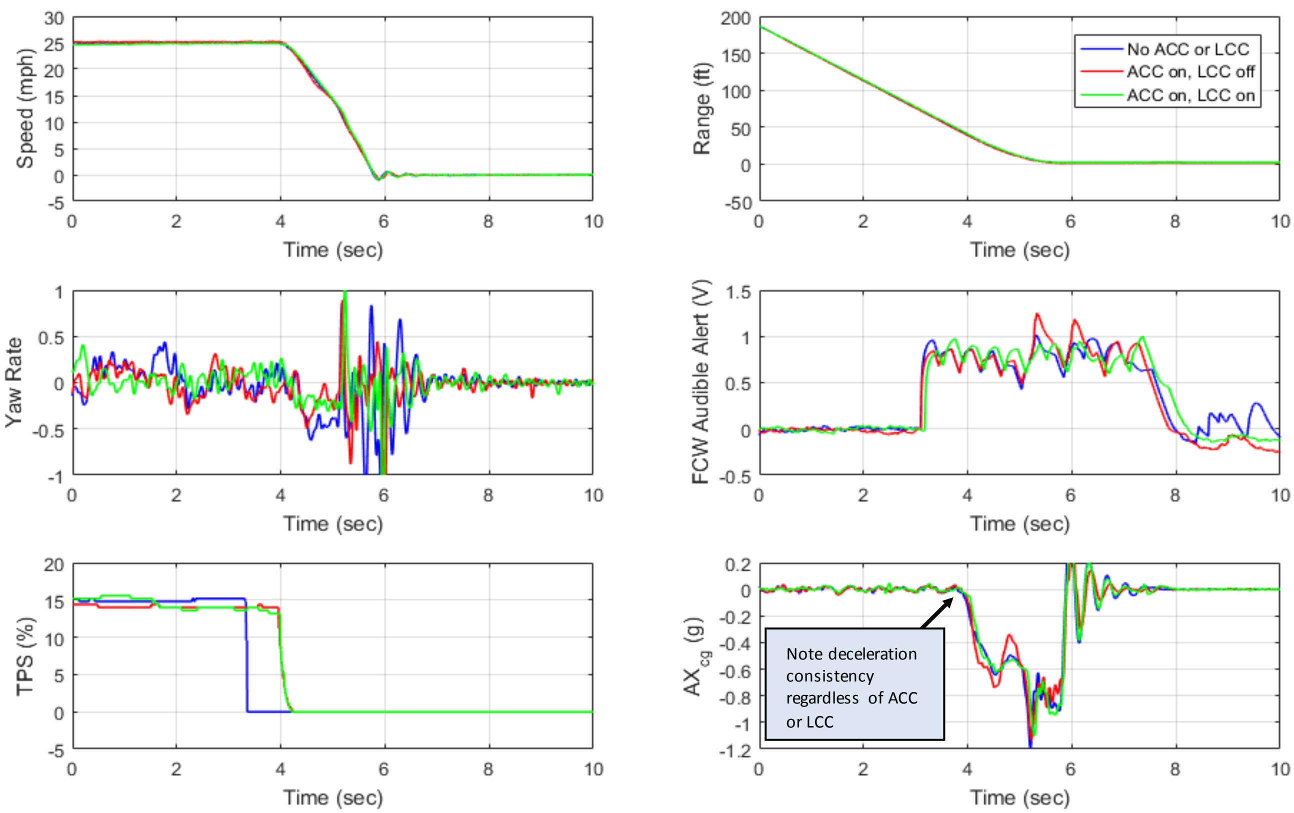

Figure 29. LVS_25_0 tests performed with the Mercedes C300.

FCW alerts were presented in each of these trials, only the regenerative braking that occurred after the SV driver released the throttle pedal (in response to the FCW alert) was responsible for the pre-impact speed reduction observed during these trials, and impact speeds of 2.3, 3.0, and 5.6 mph were ultimately realized.

It is beyond the scope of this report to speculate why the Tesla Model S did not activate CIB during the LVM tests where regenerative braking alone was unable to achieve crash avoidance. However, the result is noteworthy because CIB interventions did occur during the LVM trials performed with higher relative velocities (i.e., LVM_35_10 and LVM_45_20 scenarios used a 20 mph speed differential, and regenerative braking alone was able to prevent SV-to-POV impacts during each LVM_35_30 trial.

3.5.1.2. LVD_25_25 Tests Performed Without ACC or LCC

When neither ACC nor LCC were enabled, CIB did not intervene during the second and third of three trials performed with the Tesla Model S in the LVD_25_25 scenario (Tests 106 and 107, with the later also being the trial where an FCW alert did not occur). During these trials, relative impact speeds of 15.9 and 20.0 mph were realized versus the 4.9 mph impact speed recorded during the first trial (Test 105), where CIB intervention was apparent.

Identifying the specific reason why the Tesla Model S FCW and CIB operated inconsistently in the LVD_25_25 test series performed without ACC or LCC was beyond the scope of the work described in this report. However, a high-level assessment of whether environmental factors may have contributed to the test variability was made. To maximize the data available for this assessment, four trials were considered: the three tests reported in the tables previously discussed, and one "extra" trial performed to insure adequate data were available for analysis in the event post-processing identified one of the first three trials was not performed correctly (Test 108). Data from this fourth trial was later deemed unnecessary and is only discussed in this section of the report.

All tests in the series were performed on August 11, 2016 with the same test equipment and driver, on the same day, and within 21 minutes of each other (from 8:50 to 9:11 am). All tests were performed within the test tolerances specified in NHTSA's CIB test procedure[17]. However, review of video collected from a camera positioned on the vehicle's dashboard revealed clouds were present in the sky during this test series, and that they prevented the sun from shining directly on the POV during two of the four test trials. This is important because when the sun shined directly on the POV, it cast a shadow to the right of it. When the sun was obscured, the shadow was not present. The relative SV-to-POV impacts during the tests where a shadow was

[17] The SV driver released the throttle pedal without being presented with an FCW alert during one trial, which violates a requirement that the driver released the throttle pedal within 500 ms after the alert onset. Since the alert was never presented, the driver should not have released the throttle pedal. Given that this occurred so late in the pre-crash timeline, and since all other validity criteria were satisfied during this trial, the trial was not discarded and the data retained for analysis and discussion.

not present, the first and last tests performed in the series, were 4.9 and 4.4 mph. When shadows were present, the relative impact speeds were 15.9 to 20.0 mph.

Figures 30 through 33 present screen captures from the video collected during this test series. Test videos from the third and fourth tests are also provided.

Figure 30. 25_25 LVD Test 105 performed with the Tesla Model S. Note the absence of a shadow on the passenger side of the surrogate vehicle.

Figure 31. 25_25 LVD Test 106 performed with the Tesla Model S. Note the presence of a shadow on the passenger side of the surrogate vehicle.

Tesla Model S Test 107 (no FCW or CIB).wmv

Figure 32. 25_25 LVD Test 107 performed with the Tesla Model S. Note the presence of a shadow on the passenger side of the surrogate vehicle.

Tesla Model S Test 108 (FCW and CIB).wmv

Figure 33. 25_25 LVD Test 108 performed with the Tesla Model S. Note the absence of a shadow on the passenger side of the surrogate vehicle.

Data from the Tesla Model S LVD_25_25 tests performed without ACC or LCC are shown in Figure 34. For the tests performed without a POV shadow (Tests 105 and 108), an FCW was presented at TTCs of 2.04 and 2.8 seconds, respectively. For these tests, a CIB intervention occurred 1.8 and 1.5 seconds later, respectively, and peak decelerations of 0.98 and 1.05g were produced. The SV-to-POV impacts occurred 730 and 785 ms after the onset of CIB, and the decelerations at the time of impact were 0.95 and 0.98 g.

Tests 106 and 107 were performed when a POV shadow was apparent. In the case of Test 106, an FCW was presented at a TTC of 2.03 seconds; an interesting result because while the FCW alert timing for Tests 105, 106, and 108 was similar, the CIB did not intervene during Test 106. For this trial, the only pre SV-to-POV impact speed reduction that occurred was the result of regenerative braking initiated after the driver released the throttle pedal at a TTC = 1.68 seconds.

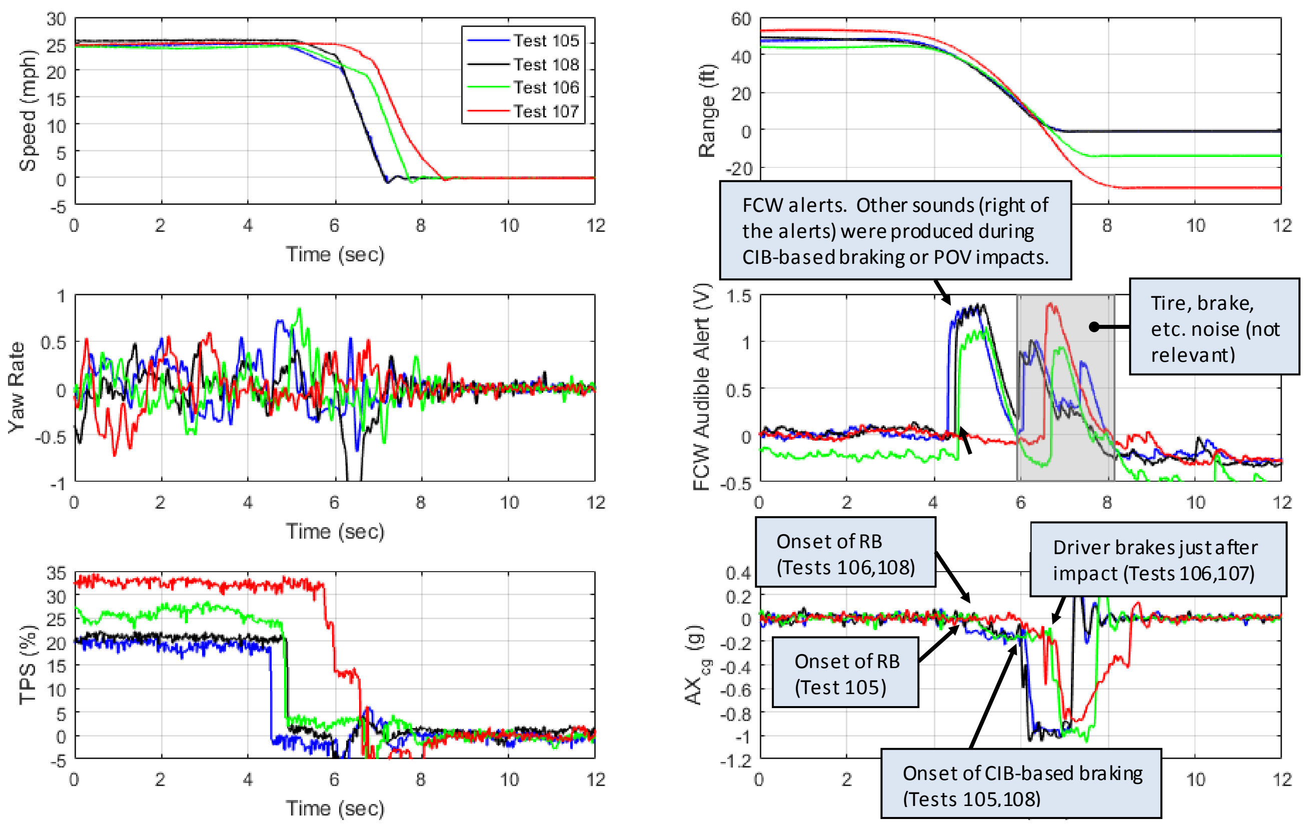

Figure 34. LVD_25_25 tests performed with the Tesla Model S (no ACC or LCC). Note: "RB" = regenerative braking.

No FCW alert or CIB intervention occurred during Test 107. The only pre SV-to-POV impact speed reduction that occurred during this trial was the result of regenerative braking initiated after the driver released the throttle pedal at a TTC = 0.75 seconds.

3.5.1.3. LVD_35_35 Tests Performed With ACC and LCC

The effect of POV shadows on the Tesla Model S AEB system was not as clearly defined as the LVD_25_25 tests performed without ACC or LCC may imply. The LVD_35_35 tests performed with ACC and LCC occurred on August 23, 2016 at a similar time of day as the LVD_25_25 tests performed without ACC or LCC (from 9:59 to 10:12 am; within 13 minutes of each other), and all test tolerances capable of being affected by the driver were as specified in NHTSA's CIB test procedure[18]. However, unlike the LVD_25_25 without ACC or LCC tests, a POV shadow was

[18] The SV speed, headway, lane position, and throttle release timing were controlled by the combination of ACC and LCC during this test series.

present during each of the three LVD_35_35 tests performed with ACC and LCC enabled. As seen in Figures 35 and 36, and the corresponding videos below them, the size and orientation of the POV shadows from each test series were similar, but not identical. The within-series shadows were largely consistent, however.

Tesla Model S Test 156 (no ACC braking present).wmv

Figure 35. 35_35 LVD Test 156 performed with the Tesla Model S. Note the presence of a shadow on the passenger side of the surrogate vehicle.

Tesla Model S Test 157 (ACC braking present).wmv

Figure 36. 35_35 LVD Test 157 performed with the Tesla Model S. Note the presence of a shadow on the passenger side of the surrogate vehicle.

Data from LVD_35_35 tests performed with ACC and LCC enabled were previously shown in Figure 15, and discussed in S3.3.2.1, so the specific differences between the trials will not be reiterated here. With respect to the effect of POV shadows, the importance of this series is that the POV shadow did not appear to adversely affect the ACC operation during two of the three trials. Whether the POV shadow was responsible for ACC not providing any speed reduction during Test 156 is unknown. Also unknown is how ACC could be so adversely affected without also having FCW and/or CIB be similarly compromised (i.e., unresponsive) within the same test trial.

3.5.2. Mercedes C300

Although some of the test trials resulted in SV-to-POV impacts, no CIB non-activations were observed during any LVS, LVM, or LVD test trials performed with the Mercedes C300. In other words, CIB activations occurred during each trial they were expected to.

4.0 CONCLUDING REMARKS

Generally speaking, the AEB performance of the Tesla Model S and Mercedes C300 was largely comparable.

4.1. Overall Observations

- Both vehicles were able to achieve crash avoidance in a majority of the rear-end scenarios discussed in this report.
- For both vehicles, ACC generally provided enough braking to achieve crash avoidance without also requiring CIB to intervene.
- Neither vehicle effectively responded to the POV in the LTAP or SAP scenarios.

4.2. Conditions Resulting In SV-to-POV Impacts For Both Vehicles

The LVM_25_10 test group performed with no ACC or LCC was the most challenging lead vehicle moving series for both vehicles. This test scenario is specified in NHTSA's NCAP CIB test procedure, which requires a vehicle achieved crash avoidance during at least 5 of 7 trials performed.

- Each of the three trials performed with the Tesla Model S concluded with an SV-to-POV impact. The range of impact speeds was 2.3 to 5.6 mph.
- One of the three trials performed with the Mercedes C300 concluded with an SV-to-POV impact. The impact speed observed during this trial was 6.4 mph.

The LVD_25_25 test group performed with no ACC or LCC was the most challenging lead vehicle decelerating series for both vehicles.

- Each of the three trials performed with the Tesla Model S concluded with an SV-to-POV impact. The range of impact speeds was 4.9 to 20.0 mph.
- Two of the three trials performed with the Mercedes C300 concluded with an SV-to-POV impact. The impact speeds observed during these trials were 6.3 and 9.8 mph.

4.3. Tesla Model S-Specific Observations

Each of the three LVM_25_10 trials performed with the Tesla Model S and no ACC or LCC concluded with an SV-to-POV impact because of CIB non-activations. Only the regenerative braking that occurred after the SV driver released the throttle pedal (in response to the FCW alert) was responsible for the pre-impact speed reduction observed during these trials.

Two of the three impacts observed during the LVD_25_25 tests performed with the Tesla Model S and no ACC or LCC occurred because of CIB non-activations (i.e., the CIB system did not automatically apply the brakes when necessary). One of these trials also included an FCW non-activation. Identifying the specific reason(s) for these non-activations was beyond the scope of the test-track evaluations described in this report. However, review of the video and sensor-based data collected during these trials at least indicate the potential of shadows cast to the side of the POV as being a contributing factor for the poor performance.

SV-to-POV impacts occurred during each LVD_35_35 trial performed without ACC or LCC. CIB activated during each of the three trials performed in this condition, and the range of impact speeds was 3.7 to 6.8 mph. This test scenario/condition is specified NHTSA's NCAP CIB test procedure, which requires an SV speed reduction ≥10.5 mph for at least 5 of 7 trials performed. The Tesla Model S realized impact speed reductions of 15.5 to 20.1 mph in this test condition.

An SV-to-POV impact also occurred during one LVD_35_35 trial performed with ACC or LCC both enabled. In this trial, ACC did not automatically reduce vehicle speed when the POV began to brake, but an FCW alert was presented and CIB braking was initiated. Interestingly, the Tesla Model S released the CIB-based braking just after avoiding the POV, but while it was still decelerating. Shortly thereafter, the POV stopped and the test concluded with a relative impact speed of 2.1 mph. This characteristic was not present during the other LVS_35_35 tests performed with the Tesla Model S without ACC or LCC enabled, and was not observed during similar tests performed with the Mercedes C300.

5.0 REFERENCES

[1] "*NHTSA Federal Automated Vehicles Policy*," September 2016

[2] "*Model_S_Owners_Manual_Touchscreen_DAS_NA_R20160317_en_US*"

[3] "*Laboratory Test Procedure for Federal Vehicle Motor Safety Standard (FMVSS) No. 135 Light Vehicle Brake Systems*," TP-135-01, December 2005

[4] "*C-Class Operator's Manual*," Part no. 2055844601, Edition C-2015

[5] "*Laboratory Test Procedure for Federal Vehicle Motor Safety Standard (FMVSS) No. 126, Electronic Stability Control Systems*," TP-126-03, September 2011

[6] "*US DOT/NHTSA - Forward Collision Warning Confirmation Test - 2015 Mercedes Benz C300*," November 2015

[7] "*Forward Collision Warning System Confirmation Test*," February 2013

[8] "*Crash Imminent Brake System Performance Evaluation for the New Car Assessment Program*," Docket No. NHTSA-2015-0119-0026

[9] Federal Register Vol. 80, No. 214 from November 5, 2015, Docket No. NHTSA-2015-0006-0024

[10] "*Radar Measurements of NHTSA's Surrogate Vehicle SSV*," Docket No. NHTSA-2012-0157-0034

6.0 APPENDICES

6.1. Additional Test Vehicles Specifications

Table A-1. Test Vehicle Weight Information.

Vehicle	Vehicle Weight Information (lbs)			
	Baseline[1]	Overall[2] (GVWR)	Front Axle[2] (GAWR)	Rear Axle[2] (GAWR)
2015 Tesla Model S 85D (5YJSA1H2XFFxxxxxx)	4848[3]	5,321 (5820)	2,655 (2813)	2,666 (3307)
2015 Mercedes C300 4MATIC (55SWF4KB3FUxxxxxx)	3,594[3]	4,180 (4,773)	2,142 (2,348)	2,038 (2,480)

[1]Fully-fueled test vehicle without driver, experimenter, or instrumentation
[2]Includes the combination of a fully-fueled test vehicle plus driver, experimenter, and instrumentation
[3]Estimated

6.2. Sun Angles During Certain LVD Tests Performed With The Tesla Model S

The U.S. Naval Observatory's Department of Astronomical Applications maintains a website[19] that allows users to calculate the sun's position in the sky for a given time, date, and location on earth. Position is described using altitude and azimuth angles. Altitude is the angle up from the horizon and includes the effect of standard atmospheric refraction when the object is above the horizon. Zero degrees altitude means exactly on the local horizon, and 90 degrees is "straight up." Azimuth is the angle along the horizon, with zero degrees corresponding to true north (not magnetic), and increases in a clockwise fashion when looking down at the earth. Thus, 90 degrees is east, 180 degrees is south, and 270 degrees is west. Using these two angles, one can describe the apparent position of the sun at a given time.

The two cities closest to the Transportation Research Center, Inc. (TRC) proving grounds with tabular USNO sun-angle calculations were Bellefontaine and Marysville, Ohio. Since East Liberty is located approximately halfway between Bellefontaine and Marysville, and 1.2 miles at 170°N from Lane 4 of the skid pad where the AEB tests were performed with the GST surrogate vehicle (as shown in Figure A-1), the sun's position was estimated by averaging the data from both locations.[20] The times used in the calculations mentioned in this section were taken from the computer time stamp associated with each test file.

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[19] http://aa.usno.navy.mil/data/docs/AltAz.php

[20] The direct distance between downtown Bellefontaine, OH (the intersection of Sandusky Ave. and Main St. Bellefontaine: 40.362610, -83.759579) and downtown Marysville, OH (the intersection of 5th St. and Main St. Marysville: 40.236413, -83.366942) is 22.4591 miles at 112.85°N. The line connecting these 2 points also intersects the outside blacktop radius on TRC's Winding Road Course (40.2918, -83.53858), a distance of 12.63 miles from downtown Bellefontaine, and 1.2 miles at 170°N from Lane 4 of the skid pad where the AEB tests were performed with the GST surrogate.

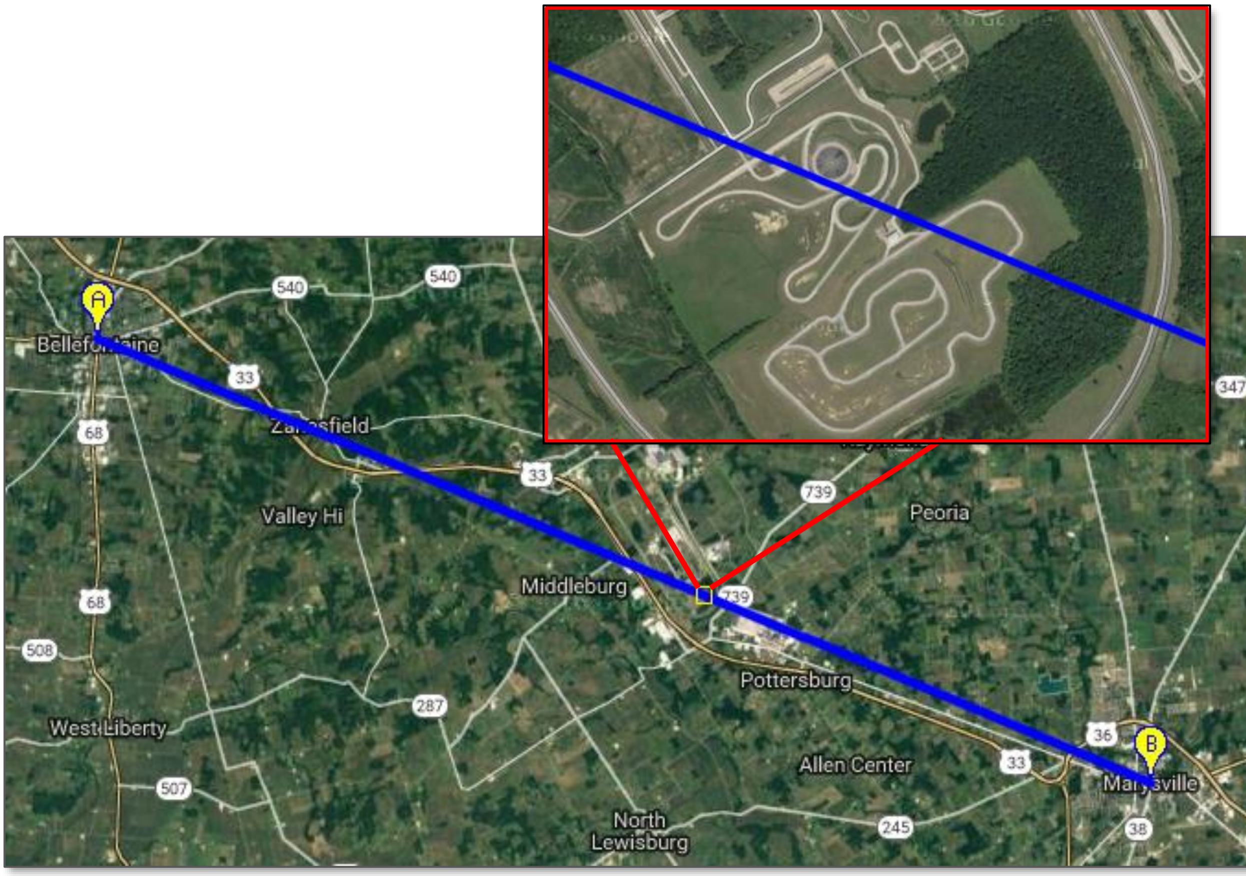

Figure A-1. Location of TRC proving grounds relative to nearby cities with USNO sun angle information.

To describe the sun's position relative to the forward direction of the vehicle, a bearing angle of zero degrees was taken to be straight ahead (12 o'clock), 90 degrees was right (3 o'clock), 180 degrees was straight back (6 o'clock), and 270 degrees was left (9 o'clock).

The LVD tests of interest, previously described in S3.5 "CIB Non-Activations," were performed on the TRC Skid Pad North Loop and Skid Pad Lane 4 (previously shown in Figure 2). Since all LVD tests described in this report were performed with the SV and POV being driven "south," and the azimuth of the skid pad is 148.45°N, the equation used to translate the sun's position relative to the vehicle was:

$$\text{Bearing} = \text{Azimuth} + (360 - 148.45) \text{ degrees}$$

Figure A-2 depicts this transformation. Table A-2 presents a summary of the sun's altitude, azimuth, and bearing angles for the LVD tests where CIB or ACC performance was different from that observed during similar tests performed minutes apart within the same series (i.e., during certain LVD_25_25 and LVD_35_35 tests, respectively).

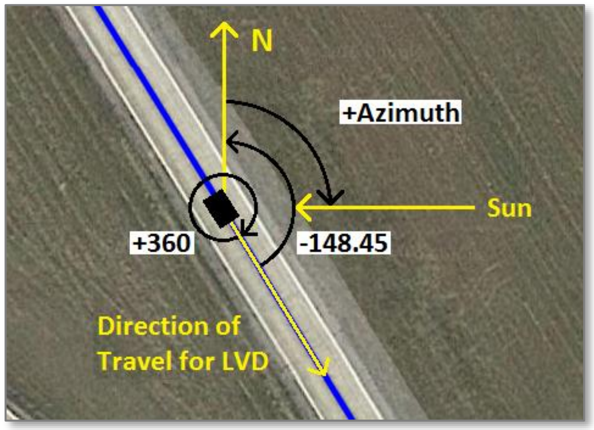

Figure A-2. Coordinate transformations used for LVM and LVD tests performed on the TRC Skid Pad.

As previously described in S3.5.1.2, no CIB intervention occurred during two of the four LVD_25_25 trials performed with the Tesla Model S and no ACC or LCC. During this test series, the sun's altitude and bearing ranged from 23.05 to 27.05 degrees and 301.05 to 304.45 degrees, respectively. A sun bearing of 300° is equivalent to the 10 o'clock position. This means the sun was slightly ahead and to the left of the SV and POV for these tests, and moved further ahead as testing progressed.

No ACC braking occurred during one of the three LVD_35_35 trials performed with the Tesla Model S and both ACC and LCC enabled (previously described in S3.5.1.3). During this test series, the sun's altitude and bearing ranged from 34.15 to 36.45 degrees and 317.05 to 319.65 degrees, respectively. This means the sun was slightly ahead and to the left of the SV and POV for these tests, and moved further ahead as testing progressed.

Table A-2. USNO Sun Position Data (Bearing Angle has been translated into Vehicle Coordinates).

Maneuver	Test #	Date	Time	Altitude (degrees)	Azimuth (degrees)	Bearing (degrees)
LVD_25_25	105	8/11/2016	8:50 AM	23.05	89.5	301.05
	106*	8/11/2016	8:57 AM	24.40	90.6	302.15
	107*	8/11/2016	9:02 AM	25.35	91.4	302.95
	108	8/11/2016	9:11 AM	27.05	92.9	304.45
LVD_35_35	156*	8/23/2016	9:59 AM	34.15	105.5	317.05
	157	8/23/2016	10:06 AM	35.40	106.9	318.45
	158	8/23/2016	10:12 AM	36.45	108.1	319.65

*Tests where performance differed from comparable tests.