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Traffic Jam Assist Test Development Considerations

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16. Abstract

This report summarizes the use of three preliminary TJA test scenarios, discusses the results from testing three commercially available vehicles equipped with TJA, and provides general assessments of the scenarios used.

The three test scenarios were intended to emulate driving situations commonly encountered during real-world driving, and consider the performance capabilities of the TJA systems presently available in the United States market. The first scenario involved a lead vehicle accelerating to the desired speed and braking to a stop. In the second scenario, a lead vehicle abruptly changed lanes to suddenly reveal a stopped vehicle. The final scenario used a cut-in and deceleration maneuver performed at close range to the subject vehicle. The three vehicles tested were a 2017 Mercedes E300, a 2017 Tesla Model S 90D, and a 2017 BMW 540i xDrive.

The performance of the three vehicles was analyzed and comments regarding test conduct, test parameters, and metrics are provided.

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GLOSSARY

ACC	Adaptive Cruise Control
AEB	Automatic Emergency Braking
DPD	Distance Pilot DISTRONIC
FC1	Foam Car 1
GPS	Global Positioning System
GST	Guided Soft Target
LPRV	Low Profile Robotic Vehicle
LVLCB	Lead Vehicle Lane Change with Braking
LVAD	Lead Vehicle Accelerates then Decelerates
OXTS	Oxford Technical Solutions
POV	Principal Other Vehicle
RTK	Real-Time Kinematic
SLCA	Steering and Lane Control Assistant
SOV	Secondary Other Vehicle
SP	Steering Pilot
SRSV	Suddenly Revealed Stopped Vehicle
SV	Subject Vehicle
TACC	Traffic Aware Cruise Control
TJA	Traffic Jam Assist
TTC	Time-to-Collision

EXECUTIVE SUMMARY

The primary objective of the work described in this report was to evaluate test methods and metrics appropriate for the evaluation of traffic jam assist (TJA) system performance. Three US-specification production light vehicles were used (a 2017 Mercedes E300 4matic, a 2017 Tesla Model S 90D, and a 2017 BMW 540i xDrive), however given the exploratory nature of this work, not all vehicles were evaluated with each test scenario. At the time this study was conducted, TJA systems did not have steer-to-avoid or other automated lateral control capabilities, hence the tests designed for this work focused on evaluating the longitudinal capabilities of the systems. Since TJA systems are designed to operate in low speed traffic conditions, test speeds were limited to a maximum of 25 mph (40 km/h).

Three maneuvers that emulate basic, albeit challenging, longitudinal traffic scenarios were used: lead vehicle accelerates then decelerates (LVAD), suddenly revealed stopped vehicle (SRSV), and lead vehicle lane change with braking (LVLCB). Use of these scenarios provided a way to examine the limits of TJA system capabilities and data useful for test procedure refinement.

The LVAD tests emulate stop and go traffic where the subject vehicle (SV) accelerates to a position behind a lead vehicle (LV), and follows it with a headway determined by the SV TJA setting. After a short while, the LV brakes to a stop and the response of the SV is observed. Initially a human-driven LV was used, but it was later replaced by a realistic-looking surrogate known as the guided soft target (GST) to improve the accuracy and repeatability of the tests. Deceleration levels of 0.3 and 0.6 g were used with the GST as the LV. The BMW 540i and Tesla Model S were tested with the GST, and crashes were observed only for the 0.6 g deceleration case with the TJA systems set to the closest following distance setting. It is therefore recommended that use of this combination of LVAD test parameters be retained for future TJA evaluations.

The SRSV test emulates a scenario where a stopped vehicle is revealed to the SV after the LV makes an abrupt lane change around it. The Mercedes E350 and Tesla Model S were tested with this scenario, and the results revealed that crashes occurred only for the combination of the highest test speed of 25 mph (40 km/h) and the closest following distance setting for both vehicles. It is therefore recommended that this combination of SRSV test parameters be retained for future TJA evaluations.

The LVLCB test emulates a scenario where an LV, traveling in an adjacent lane and in front of the SV, cuts-in at close proximity to the SV and decelerates. The BMW 540i and Tesla Model S were evaluated with this maneuver, and the GST served as the LV. Various combinations of LV decelerations were used during and/or after its lane-changes. Although several of these ultimately produced SV-to-POV impacts, some of the most challenging deceleration combinations, quantified by impact speed magnitude, were occurred when the LV performed a lane-change (without decelerating) followed by 0.6 g straight-line deceleration, and when the LV used a within lane-change deceleration of 0.1g followed by either 0.3 or 0.6 g straight-line deceleration. It is therefore recommended that these deceleration combinations be retained for future TJA evaluations using the LVLCB maneuver.

1 INTRODUCTION

Traffic Jam Assist (TJA) is an advanced driver assistance system designed to automatically maintain the lateral position of a driver's vehicle within its travel lane while simultaneously establishing and maintaining a constant longitudinal headway between it and the vehicle immediately ahead. The system is intended to function as a comfort-and-convenience feature and, should a crash-imminent driving situation arise, to prevent a rear-end crash while the driver's vehicle is operating in SAE automation level 2 or 3, at low speed.

1.1 Objectives

The objective of the work described in this report was to evaluate test methods and metrics suitable for objectively quantifying TJA system performance at a test track. The process used to perform this work included the following steps:

- Perform a literature review to understand the functionality (i.e., capability) of currently-available TJA systems
- Design tests to challenge the TJA systems
- Instrument test vehicles
- Conduct preliminary tests to evaluate test performability
- Iteratively refine TJA test scenarios as needed, and incorporate refinements into a draft test procedure
- Summarize test results from the final iterative refinement

1.2 Test Methodology

The evaluations described in this report used TJA-relevant crash-imminent test scenarios designed to emulate situations present in real-world driving. Since TJA systems are designed to operate in low-speed traffic conditions, the test speeds contained within each scenario were limited to a maximum of 25 mph (40 km/h). At the time this study was conducted, TJA systems did not have steer-to-avoid or other automated lateral control capabilities, hence the tests designed for this work focused on evaluating the longitudinal capabilities of the systems.

1.2.1 Test Vehicles

Three vehicles equipped with TJA were chosen for this study:

1. 2017 Mercedes E300 4matic
2. 2017 Tesla Model S 90D
3. 2017 BMW 540i xDrive

A brief description of each vehicle and their respective TJA systems is provided in the following subsections. Due to vehicle and test equipment availability constraints, all three vehicles could not be tested with each test scenarios. Details about which vehicle/scenario combinations were used for the work described in this report are provided in Section 2.

1.2.1.1 2017 Mercedes E300

The 2017 Mercedes E300, shown in Figure 1, TJA system is named Drive Pilot. To enable TJA, the vehicle's Distance Pilot DISTRONIC (DPD) and Steering Pilot (SP) systems must both be enabled. The Mercedes E300 TJA activates at low speed, if and only if there is another vehicle in front of it. DPD must be activated to utilize SP. The Mercedes E300 was equipped with three forward-facing radars and two forward-facing cameras.

Figure 1. 2017 Mercedes E300.

A combination switch on the left-hand side of the steering wheel, shown in Figure 2, activates the DPD. The combination switch can be moved horizontally to set the current vehicle speed (2) or to deactivate DPD (1). If moved vertically, the switch either increases (3) or decreases (4) speed. To increase or decrease following distance, the end of the switch can be rotated backward (6) or forward (5) respectively. The driver may select one of seven headway settings with the Mercedes E300 DPD.

Figure 2. Mercedes E300 Distance Pilot DISTRONIC combination switch [2].

The driver activates (or deactivates) SP by pressing a button located to the left of the steering wheel (Figure 3). The activation status is shown by the indicator light (1). The instrument panel indicates three distinct TJA system statuses:

1. TJA turned on
2. TJA on and available
3. TJA on, available, and active

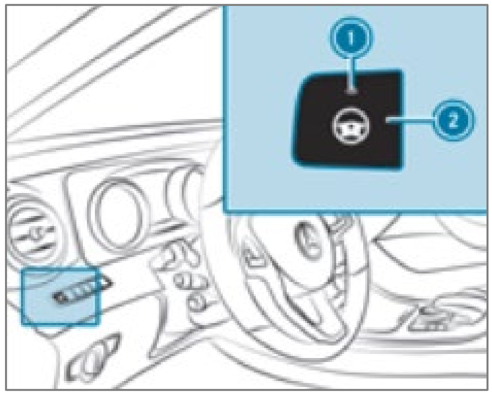


Figure 3. Mercedes E300 Steering Pilot on/off button and button location [2].

1.2.1.2 2017 Tesla Model S 90D

The 2017 Tesla Model S 90D, shown in Figure 4, also combines the functionality of two systems to implement TJA: Traffic Aware Cruise Control (TACC) and Autosteer. The TACC functions as the vehicle's adaptive cruise control, while the Autosteer system provides lane centering functionality. With the firmware used during the tests described in this report (v8.1 build 17.11.10), TACC activates at speeds lower than 5 mph (8 km/h) only if a lead vehicle is detected. The Tesla Model S was equipped with eight cameras (located around the vehicle) and one forward facing radar.

Figure 4. 2017 Tesla Model S.

The control lever shown in Figure 5 is used to activate TACC. To set the TACC speed to the current driving speed, or to adjust the travel speed when TACC is active, the lever is moved either up or down (1). One of seven different headway settings can be chosen by rotating the cruise control lever (2). TACC is deactivated by pushing the cruise control lever away from the driver or activating the brakes (3). TACC can be activated at its last set speed by pulling the lever once toward the driver (4).

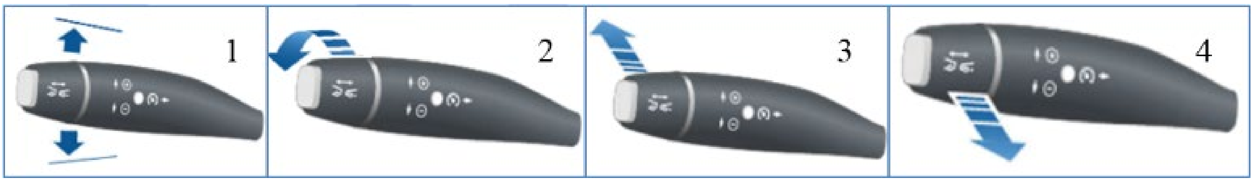


Figure 5. Tesla Model S cruise control lever.

Autosteer is enabled within the vehicle control driver assistance menu. The instrument panel indicates two distinct Autosteer system statuses:

1. Autosteer turned on only: If Autosteer is turned on, but not actually steering the vehicle, the steering wheel icon appears gray next to the vehicle speed as shown in Figure 6.

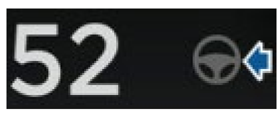


Figure 6. Tesla Model S TJA Autosteer dash display (Autosteer On, but inactive).

2. Autosteer turned on, available and active: When Autosteer is active, the steering wheel icon turns blue as shown below in Figure 7.

Figure 7. Tesla Model S TJA Autosteer dash display (Autosteer active).

2017 BMW 540i

The 2017 BMW 540i, shown in Figure 8, uses the vehicle's Active Cruise Control (ACC) and Steering and Lane Control Assistant (SLCA) systems to implement TJA. The minimum ACC set speed is 20 mph (32 km/h), but the system is designed to follow a lead vehicle below this threshold; all the way to zero speed if necessary. The driver may select one of four ACC headway settings with the BMW 540i. The vehicle was equipped with a forward-facing radar and two forward-facing cameras.

Figure 8. BMW 540i.

The BMW 540i driver controls, located on the left side of the steering wheel, are shown in Figure 9. The buttons and their functions are listed in Table 1.1. The driver presses the ACC button (1), to activate or deactivate ACC. Pressing the rocker switch (5) changes the user's travel speed by increments of either 1 mph (1.6 km/h) if pressed to the resistance point, or 5 mph (8.0 km/h) if pressed past the resistance point. If the rocker is held in either the up or down positions the vehicle will accelerate or decelerate until the switch is released.

Figure 9. BMW 540i steering wheel controls (see Table 1.1 for details)

Table 1.1. BMW 540i Steering Wheel Controls Functions.

No.	Button	Function
1		Adaptive Cruise Control → On/Off
2		Set/maintain speed
3		→ Pause ACC → Continue ACC with last setting
4		→ Adjust following distance Choose from 4 settings
5		Rocker switch: → Increase set speed → Decrease set speed Each time the rocker switch is pressed to the resistance point, the desired speed increases or decreases by 1 mph/1 km/h. Each time the rocker switch is pressed past the resistance point, the desired speed changes by a maximum of 5 mph (10 km/h).
6		Steering and lane control assistant including TJA → On/Off

The instrument panel indicates the ACC speed setting and status on the speedometer as shown in Figure 10;

1. ACC turned on and interrupted: When the system is on but interrupted, an orange arrow indicates the selected speed.

2. ACC turned on and active: When the system is on and active, the arrow turns to green and indicates the selected speed (as shown in Figure 10).

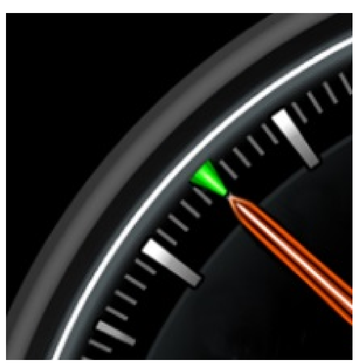


Figure 10. BMW 540i ACC speed and status display.

The following distance button ("4" in Table 1.1), can be pressed repeatedly until the desired following distance is selected. The distance setting is indicated by the number of green bars shown on the display (Figure 11). Four bars indicate the furthest setting.

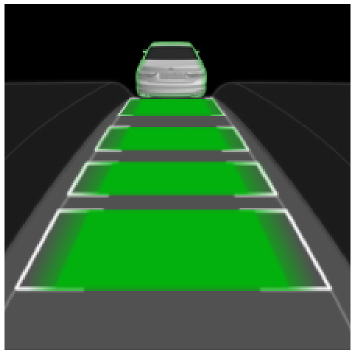
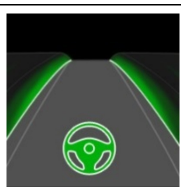
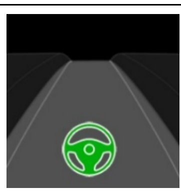


Figure 11. BMW 540i ACC heading setting display (farthest headway shown).

The SLCA button (6 in Table 1.1) can be pressed to activate SLCA. This system can be activated between 43 and 130 mph (209 km/h) if lane markings are detected, or under 43 mph (69 km/h) if a lead vehicle is detected. The SLCA status displays shown on the instrument panel are described in Table 1.2.

Table 1.2. BMW 540i SLCA Status Indication Icons.

Symbol	Description
	Gray steering: SLCA is on standby
	SLCA is activated
	Green Steering with green lane marking: SLCA is active, lane lines detected.
	Green Steering with gray lane marking: No lane marking detected or vehicle outside of lane marking. If outside of lane marking, steering support continues toward the center of the lane. If a lane marking is not detected, the vehicle follows the vehicle ahead

1.2.2 Surrogate Vehicles

Most of the test scenarios used for the work described in this report contained crash-imminent driving situations. To allow these tests to be performed safely, and to prevent damage to the test vehicles, one of two realistic-looking surrogate vehicles was used in lieu of an actual vehicle.

1.2.2.1 Guided Soft Target

The Guided Soft Target (GST) system, developed and manufactured by Dynamic Research Inc., was used for the scenarios described in Sections 2.1.2, and 2.3. The two main components of the system, shown in Figure 12, are the Soft Car 360 Micro (Soft Car) surrogate vehicle and the Low Profile Robotic Vehicle (LPRV).

Figure 12. Soft Car 360 Micro (left) and Low Profile Robotic Vehicle (right).

The Soft Car is dimensionally similar to a Smart Fortwo car, and is secured to the LPRV using Velcro. Internally, the Soft Car consists of a vinyl-covered foam structure. If a test vehicle impacts the target at low speed, it is typically pushed off and away from the platform and then the platform is pushed against the ground and stops as the test vehicle drives over it. At higher impact speeds, the Soft Car breaks apart as the test vehicle essentially drives through it. Reassembling the Soft Car on top of the LPRV takes a team of 3 to 5 people approximately 7 to 10 minutes to complete. The LPRV is preprogrammed, and allows the Soft Car's movement to be accurately and repeatedly choreographed with the test vehicle using closed-loop control.

1.2.2.2 Foam Car 1

NHTSA's "Foam Car 1" (FC1), surrogate vehicle, shown in Figure 13, was used for the Suddenly Revealed Stopped Vehicle (SRSV) test scenario described in Section 2.2. Unlike the Soft Car, FC1 is only designed to emulate the rear of an actual vehicle, and unlike the tests using the GST system, FC1 remained stationary during each SRSV trial.

Figure 13. NHTSA's Foam Car 1 surrogate vehicle.

1.2.3 Measurement and Data Acquisition Systems

An Intrepid Systems neoVI ION data acquisition system was used to collect instrumentation data (sensor and video) for the tests conducted. Data were logged at a frequency of 100 Hz. Vehicle GPS position and inertial measurements were generated using Oxford Technical Solutions (OXTS) RT3002 units. This system uses real-time kinematic (RTK) corrections to improve GPS accuracy to within 0.8 in (2 cm). Relative distances and velocity between test actors were measured using an OXTS RT-Range S system.

2 TEST SCENARIOS

The test scenarios developed for this study were based on real-world traffic scenarios believed to be applicable to the TJA system operational domain. TJA systems are generally designed to operate in low-speed traffic conditions, hence the test speeds were limited to 25 mph (40 km/h) for the tests described in this report. At the time this study was conducted, TJA systems did not have steer-to-avoid or other automated lateral control capabilities, hence the tests designed for this work focused on evaluating the longitudinal capabilities of the systems. Three basic scenarios were designed and are described in detail in this chapter.

2.1 Lead Vehicle Accelerates Then Decelerates

The Lead Vehicle Accelerates Then Decelerates (LVAD) scenario was used to emulate stop-and-go traffic where the subject vehicle (SV) accelerates to a position behind a lead vehicle, and follows it with a headway determined by the SV TJA setting. After a short while, the lead vehicle brakes to a stop and the response of the SV is observed. Both vehicles reside in the same travel lane throughout each test. The scenario is shown in Figure 14.

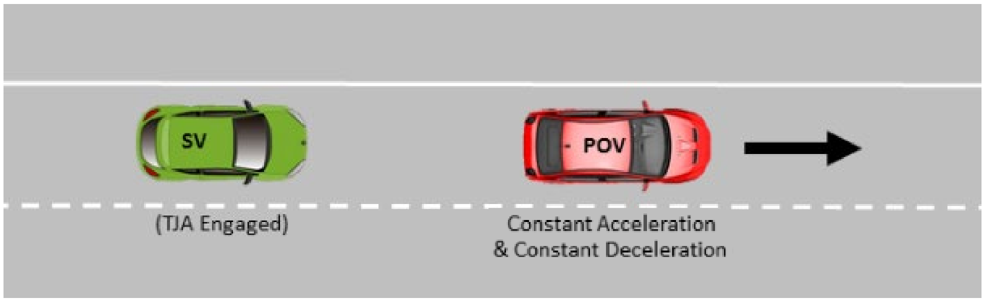


Figure 14. LVAD test.

Initial Conditions: The SV TJA system was activated and set to the desired headway setting. The TJA preset speed was set between 5 to 10 mph (8 to 16 km/h) over the desired test speed. The SV was then driven towards a stationary principal other vehicle (POV) and, using TJA, allowed to come to rest behind it (i.e., TJA automatically braked the SV to a stop behind the POV).

Test Conduct: The POV was accelerated to, and then retained at, the desired test speed until the SV had established a steady state following distance behind it (i.e., the headway was being maintained by the TJA). The POV then decelerated to a stop. A sample POV speed profile is shown in Figure 15.

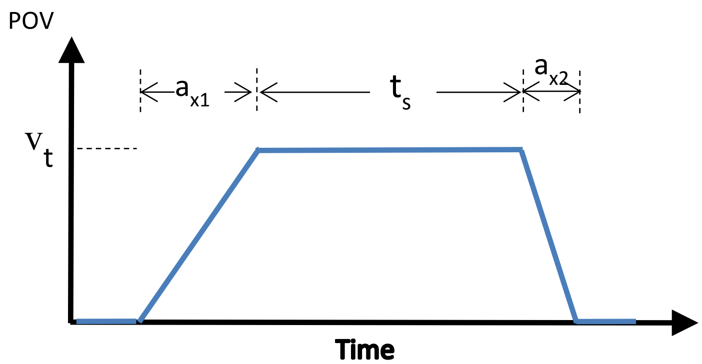


Figure 15. POV speed profile for LVAD test.

This test was performed using two different POVs, a 2015 Lexus LS500 (i.e., a real passenger car) or the GST (a surrogate vehicle)

The test methods used for each of the POVs is described in Sections 2.1.1 and 2.1.2.

Analysis: This test was used to study how the SV TJA responded to stop-and-go traffic. Crash avoidance capability was of particular interest.

2.1.1 LVAD With Lexus LS500 as POV – Preliminary Test Matrix

Since the acceleration authority of the TJA systems discussed in this report was unknown at the beginning of this study, and the GST acceleration was limited to ≈0.12g, the LVAD tests were initially performed with a driver-operated Lexus LS500 as the POV. However, because it was driven by a human and not a robot, the POV accelerations and decelerations could not be closely controlled during these trials. Therefore, for these tests, the POV driver was simply told to accelerate smoothly and decelerate aggressively (but not with full braking), and to do so as consistently as possible.

All LVAD tests performed with the Lexus LS500 as the POV were conducted with the closest SV headway setting. The LVAD with Lexus LS500 POV test matrix is shown in Table 2.1. The magnitudes of the SV-to-POV headways observed during these tests are detailed in Section 3.1.

Table 2.1. LVAD with Lexus LS500 as POV - Test Matrix.

Vehicle	Acceleration a_{x1}	Deceleration a_{x2}	Test Speeds V_t (mph)	SV Headway Setting	Repetitions for Each Test Speed
BMW 540i	Driver Controlled	Driver Controlled	10, 15, 20, 25	Closest	5
Tesla Model S	Driver Controlled	Driver Controlled	10, 15, 20, 25	Closest	5
Mercedes E300	Driver Controlled	Driver Controlled	10, 15, 20, 25	Closest	10

2.1.2 LVAD With GST as POV – Test Matrix

To evaluate the effect of more severe POV deceleration, the LVAD tests were rerun using the GST as the POV (i.e., since there was a greater risk of an SV-to-POV impact). The GST-based tests were conducted with POV decelerations of 0.3 and 0.6 g, and tests were performed using both the closest and farthest SV headway settings. Since the GST acceleration and deceleration profiles were robotically controlled, input repeatability was improved over that achieved by the human driver. The LVAD with GST POV test matrix is presented in Table 2.2.

Table 2.2. LVAD With GST as POV - Test Matrix.

Vehicle*	Acceleration a_{x1}	Deceleration a_{x2}	Test Speeds V_t (mph)	SV Headway Setting	Repetitions for Each Test Speed
BMW 540i	0.12g	0.3g	10, 15, 20, 25	Closest	2
			10, 15, 20, 25	Farthest	2
	0.12g	0.6g	10, 15, 20, 25	Closest	2
			10, 15, 20, 25	Farthest	2
Tesla Model S	0.12g	0.6g	10, 15, 20, 25	Closest	2
			10, 15, 20, 25	Farthest	2

*Due to the limited availability of the GST for this test program, only the BMW 540i and Tesla Model S were tested with the GST as the LV.

2.2 Suddenly Revealed Stopped Vehicle

As shown in Figure 16, the SRSV scenario emulates a driving situation where a stopped vehicle is suddenly revealed to the SV after a lead vehicle makes an abrupt lane change around it.

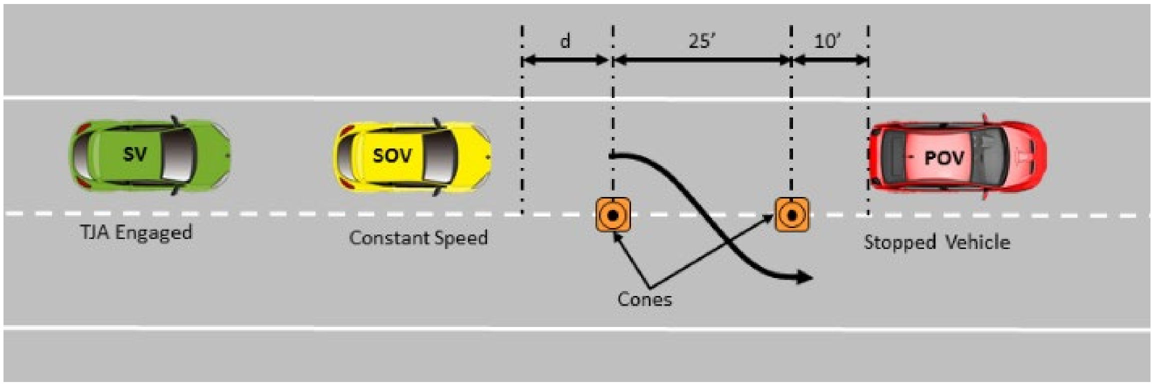


Figure 16. SRSV test.

Initial Conditions: For this test, FC1 (described previously in Section 1.2.2.2) was used as the stopped POV depicted in Figure 16, and was positioned in the center of the SV travel lane. To assist the driver of the lead vehicle (the secondary other vehicle, or SOV), pylons were placed 10 and 35 ft (3 and 11 m) behind the POV to define the window within which the SOV was to perform the lane change. While staging, the SOV was positioned at a distance of at least 200 ft (61 m) from the closest pylon and in the center of the SV travel lane. This distance "d" (see Figure 16) was adjusted so that it was large enough to allow the SV driver to activate the vehicle's TJA <u>and</u> reach a steady state following distance behind the SOV before the SOV reached the first pylon. The SV TJA speed was set 5 to 10 mph (8 to 16 km/h) over the SOV test speed.

Test Conduct: The SV, with TJA enabled and active, was driven towards, and allowed to stop behind the SOV. The SOV was then accelerated to, and then retained at, the desired test speed. The SV's TJA was used to accelerate the SV to the SOV speed, and to maintain a constant headway by restricting the SV speed to that of the SOV. While maintaining the desired test speed, the SOV performed a single lane change between the course pylons to reveal the stationary POV to the SV. The SOV driver braked the vehicle to a stop after it had passed the POV.

Analysis: This test was used to study how the SV TJA responded to suddenly revealed stationary POV. Crash avoidance capability was of particular interest.

Test Matrix: The Tesla Model S and Mercedes E300 were tested with this maneuver. The BMW 540i was unavailable due to it being used by another test program. The SRSV test matrix is shown in Table 2.3.

Table 2.3. SRSV Test Matrix.

Vehicle	Test Speeds V_t (mph)	SV TJA Headway Setting	Repetitions for Each Test Speed
Tesla Model S	10, 15, 20, 25	Closest	5
Mercedes E300	10, 15, 20, 25	Closest	5

2.3 Lead Vehicle Lane Change With Braking

The Lead Vehicle Lane Change with Braking (LVLCB) test emulates a scenario where a POV being operated in an adjacent lane cuts-into a space between the SV and a SOV traveling ahead of it. During some trials, the POV performed the lane change then braked to a stop. Other trials were performed with the POV decelerating during and after the lane change, and then coming to a stop. Figure 17 describes the LVLCB scenario.

Initial Conditions: The SV TJA system was activated and set to the maximum headway setting. With the exception of the tests performed at 10 mph, the SV TJA speed was set 5 to 10 mph (8 to 16 km/h) over the SOV test speed. For the 10 mph tests, even with the maximum headway setting, the steady state headway was insufficient for the POV to perform a cut-in between the SV and SOV. Therefore, for these tests, the SV TJA speed was set to the desired test speed (i.e., 10 mph or 16 km/h) and the SOV accelerated away from the SV just prior to the POV lane change to create enough of a gap between the SV and SOV for the POV to merge between them.

For the LVLCB tests described in this report, the SOV was positioned ahead of the SV in the same travel lane, while the POV was placed in the right adjacent lane between the SV and SOV. The GST was used as the POV for these tests due to the risk of an SV-to-POV collision and the need for precise control of the POV path and deceleration rates during the maneuver, whereas the SOV was a driver-operated Lexus LS500. The LVLCB pretest staging setup is shown in Figure 17.

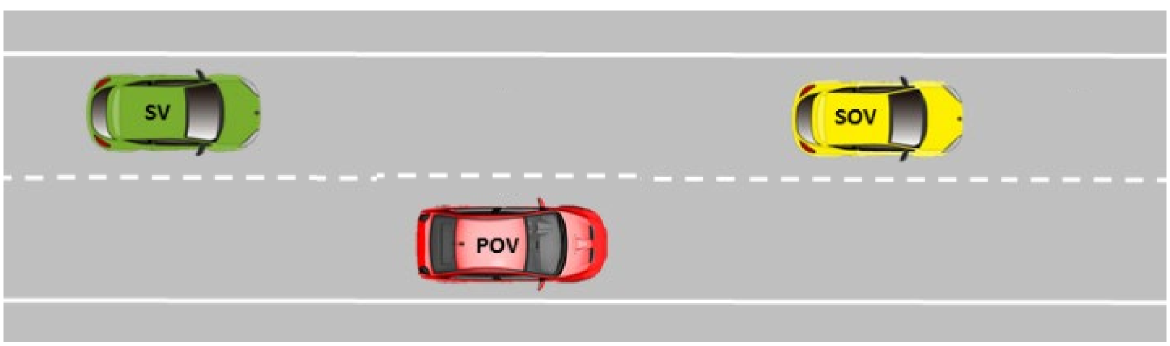


Figure 17. LVLCB pretest staging test setup.

Test Conduct: The SV, with TJA enabled and active, was driven towards, and allowed to stop behind, the SOV, which was at rest in the center of the SV travel lane. The POV and SOV were then accelerated to, and then retained at, the desired test speed. The SV's TJA was used to accelerate the SV to the SOV speed, and to maintain a constant headway. Operating in closed loop, the POV was programed to remain 15 ft (4.5 m) ahead of the SV in the adjacent lane (depicted in Figure 18) as the SV reached its steady state following distance to the SOV.

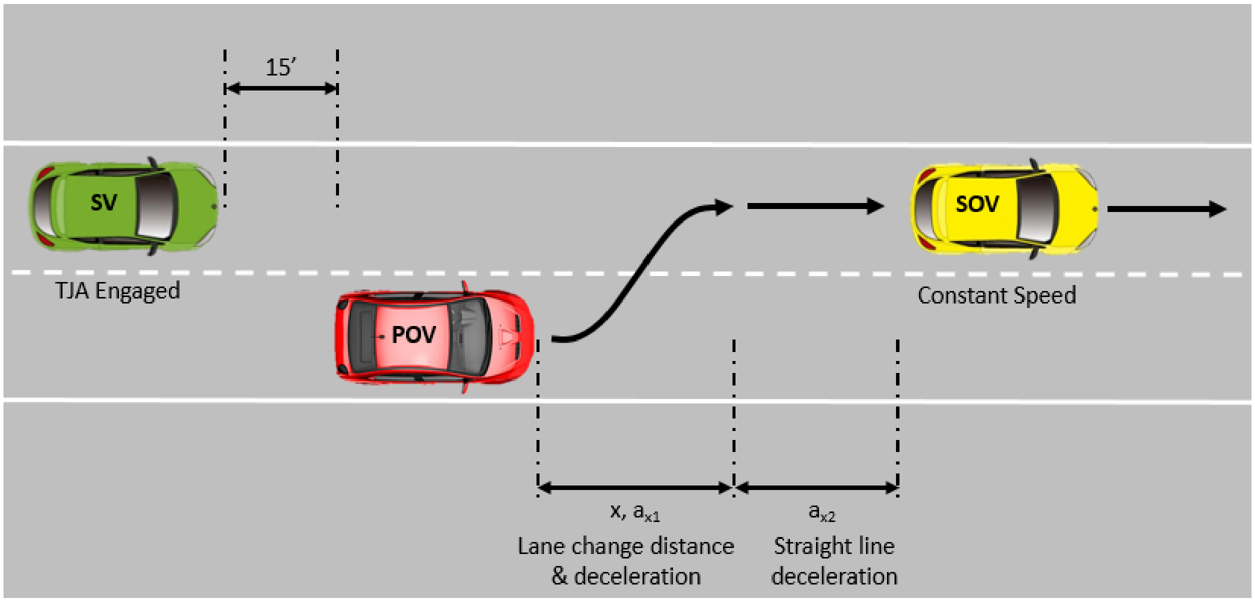


Figure 18. LVLCB test.

Once each of the three actors reached the desired speeds, and while the SV-to-POV longitudinal headway was at the desired magnitude, the POV performed a single lane change between the SV and SOV. Longitudinally, the POV travelled 25 ft (7.6 m) during the lane change (distance “x” in Figure 18). During the lane changes, the POV was decelerated at a_{x1}, henceforth referred to as “lane-change deceleration” in the remainder of the document. As soon as the lane change was completed, POV deceleration was changed to a_{x2}, henceforth referred to as “straight-line deceleration” in the remainder of this document.

Analysis: This test was used to study how the SV’s TJA responded to a POV cut-in performed at close proximity. The manner in which the system attempted to reestablish the desired SV-to-POV separation, and its ability to avoid an SV-to-POV impact was of particular interest.

Test Matrix: The Tesla Model S and BMW 540i were tested with this maneuver. The Mercedes E300 was unavailable due to it being used by another test program. Table 2.4 describes the various combinations of lane-change and straight-line decelerations used to perform the LVLCB tests described in this report. One test was performed for each combination.

Table 2.4. LVLCB Scenario Deceleration Combinations.

Straight-Line Deceleration (g)		0.3								0.6							
Lane-Change Deceleration (g)		0		0.05		0.1		0.2		0		0.05		0.1		0.2	
SV Headway Setting*		Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far
Test Speed (mph)	10	x	x							x	x						
	15	x	x	x	x					x	x	x	x				
	20	x	x	x	x	x	x			x	x	x	x	x	x		
	25	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

* Near → closest setting, far → farthest setting

3 RESULTS

3.1 Lead Vehicle Accelerates Then Decelerates Tests With Real Vehicle as POV

The results from the LVAD tests performed with a Lexus LS500 as the POV are discussed in this section. Specifically, the distances between the SV and POV one second before initiation of POV braking (at a time where the TJA systems were attempting to maintain a constant headway) and at the end of the maneuver (after the POV had braked to a stop) were evaluated. As previously mentioned in Section 2.1.1, the closest headway setting was used for these tests.

The steady state following distance one second prior to the onset of POV braking (i.e., when POV deceleration was > 0.05 g) is plotted as a function of nominal test speed in Figure 19. These results indicate that each of the three vehicles tested had largely comparable steady state following distances when their respective TJA systems used the closest setting. The data also indicate that steady state range increases in a linear fashion with test speed.

For some tests performed with the BMW 540i, the SV driver terminated the maneuver by manually applying the brakes. While it is unclear whether these tests would have concluded with an SV-to-POV impact (i.e., it is possible crash-imminent braking may have intervened at a time later in the pre-crash timeline than when the manual intervention occurred), the driver's precautionary braking assured the tests were safely performed. This did not affect the reporting of the vehicle's steady state following distance, however these trials are marked with a solid yellow triangle in Figure 19.

The SV range to the POV at the end of the maneuver, after the SV and POV had both come to rest, is shown in Figure 20. These results indicate the final SV-to-POV range was largely consistent for the Mercedes E300 tests performed at 10, 15, and 20 mph, after which they decreased slightly (and with more disparity) for the 25 mph trials.

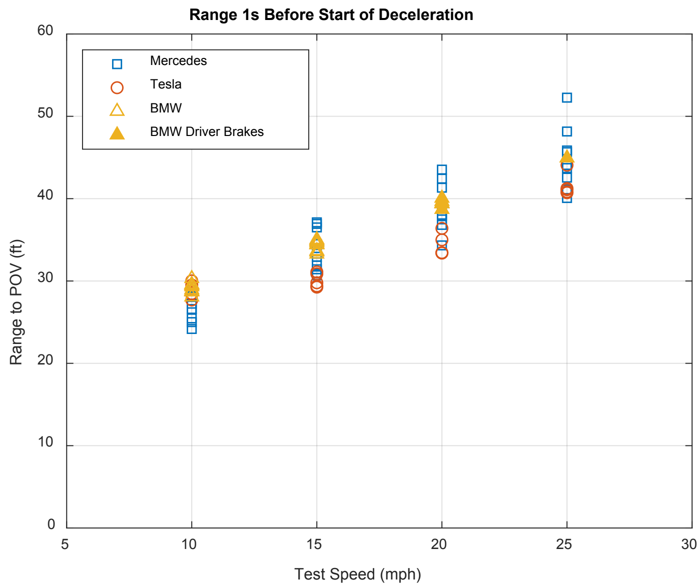


Figure 20. LVAD test steady state following distance.

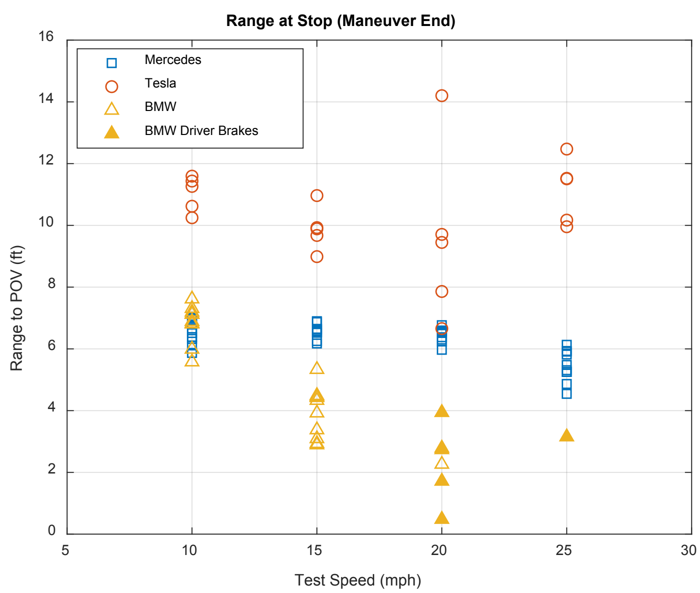


Figure 19. LVAD test range at end of maneuver.

As the nominal test speed increased, the final SV-to-POV range trended downward for the BMW 540i. Trials where the SV driver intervened with manual braking before the respective trial had concluded are indicated using the convention previously defined for use in Figure 19. Only one trial using an actual vehicle as the POV was used to evaluate the BMW 540i from 25 mph.

The final SV-to-POV ranges of the Tesla Model S tests performed from 10, 15, and 20 mph also showed a decreasing trend with increasing test speed. Note that prior to performing the tests from 25 mph with this vehicle, the test engineers reduced the deceleration of the POV for safety reasons (i.e., to reduce the potential for a crash); an adjustment believed to be responsible for the magnitude of the subsequent ranges for the Tesla Model S.

3.2 Lead Vehicle Accelerates Then Decelerates With Surrogate Vehicle as POV

To address the variability associated with having a human driver responsible for operating the POV, accurately assess the effect of deceleration level, and allow each trial to be performed without having the SV driver potentially intervene with manual braking, the actual vehicle POV was replaced with the GST to provide a realistic, yet strikeable, surrogate vehicle. This section describes the test results observed with the GST-based POV tests.

3.2.1 0.6 g POV Deceleration

This section presents results from the tests performed with a POV deceleration of 0.6g. Results for the closest and farthest headway settings are shown side-by-side for ease of comparison. Trials that concluded with crash avoidance are indicated with outlined (empty) data points, whereas those producing an SV-to-POV impact are shaded (solid).

The steady state SV-to-POV following distance observed during tests performed with the closest and farthest headway settings are shown in Figures 21 and 22, respectively. For a given test speed, the BMW 540i had a larger steady state following distance than the Tesla Model S.

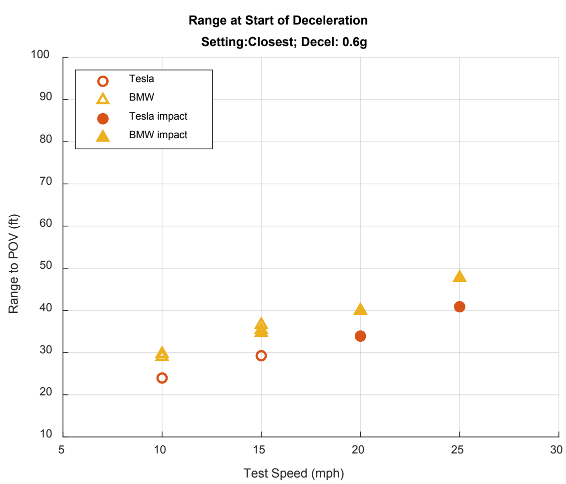


Figure 21. Steady state following distance, closest heading setting, 0.6 g POV deceleration.

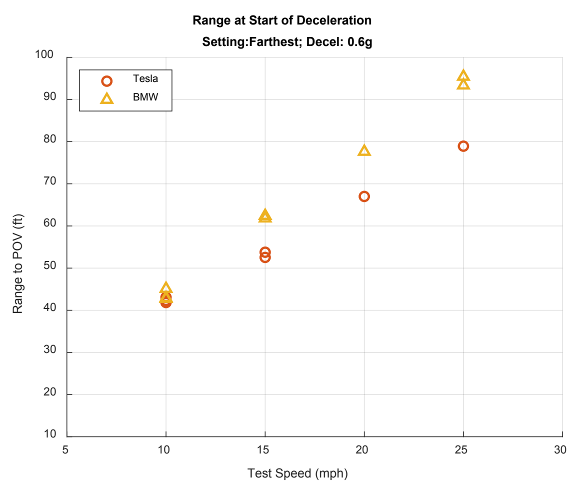


Figure 22. Steady state following distance, farthest heading setting, 0.6 g POV deceleration.

The SV-to-POV ranges observed at the end of each LVAD trial are shown in Figures 23 and 24. For tests where the SV collided with the POV, the range at the end of the maneuver was fixed to a value of -1. Crash avoidance was realized by both vehicles when the farthest TJA setting was used.

When the closest headway setting was used, the Tesla Model S avoided the POV during the trials performed from 10 and 15 mph. The BMW 540i had one impact during conduct of the 15 mph tests. Both vehicles were unable to avoid an SV-to-POV impact during the 20 and 25 mph tests.

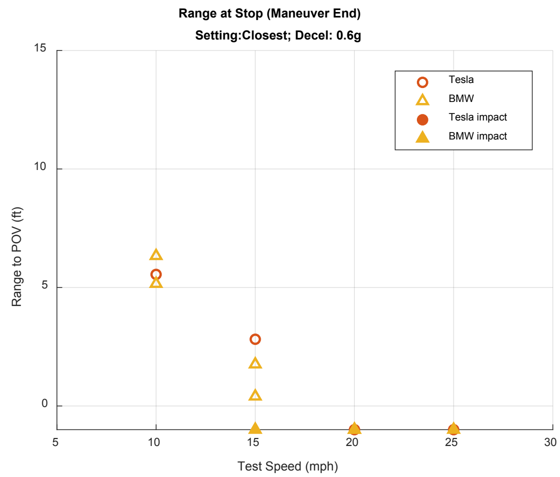


Figure 23. Range at stop, closest TJA setting, 0.6g POV deceleration.

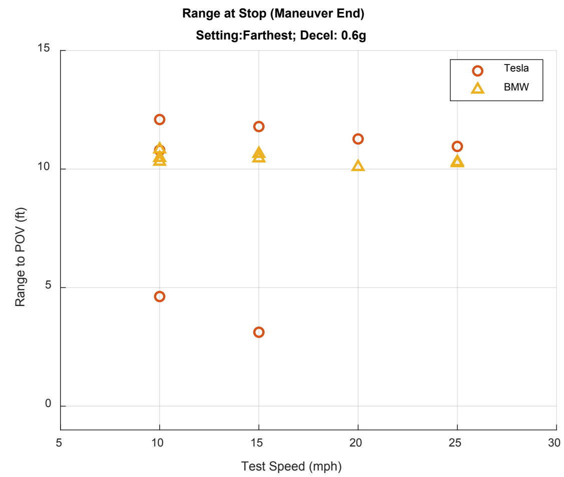


Figure 24. Range at stop, farthest TJA setting, 0.6g POV deceleration.

3.2.2 0.3 g POV Deceleration

This section presents results from tests performed with the BMW 540i and a POV deceleration of 0.3 g (neither the Mercedes E300 nor the Tesla Model S were evaluated in this test condition due to vehicle availability constraints). The steady state SV-to-POV following distance observed during tests performed with the closest and farthest heading settings are shown in Figures 25 and 26, respectively.

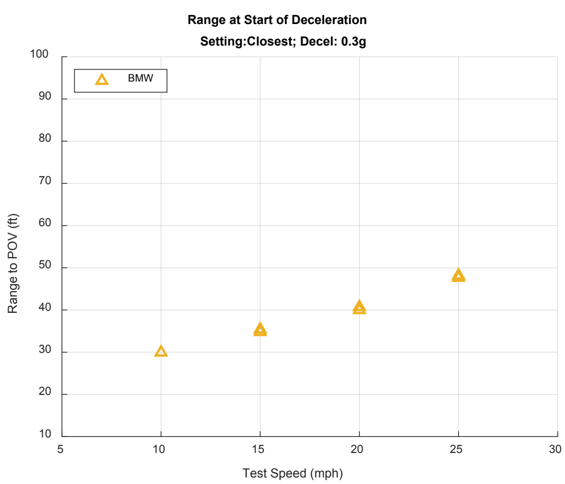


Figure 25. Steady state following distance, closest heading setting, 0.3 g POV deceleration

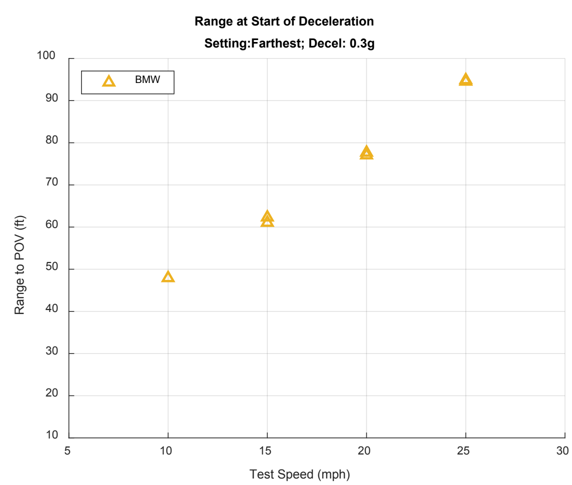


Figure 26. Steady state following distance, farthest heading setting, 0.3 g POV deceleration

Regardless of the test speed, the BMW 540i avoided a POV impact during each trial. Interestingly, the relationship between test speed and the final SV-to-POV range was dependent on the following distance setting used. With the closest following distance, increasing the test speed resulted in a reduction in the final range to the POV (shown in Figure 27). The opposite trend was observed during tests performed with the farthest headway setting, as shown in Figure 28.

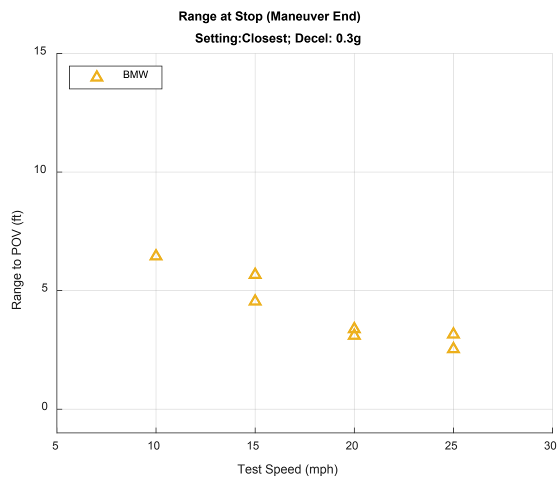


Figure 25. Range at stop, closest heading setting, 0.3 g POV deceleration.

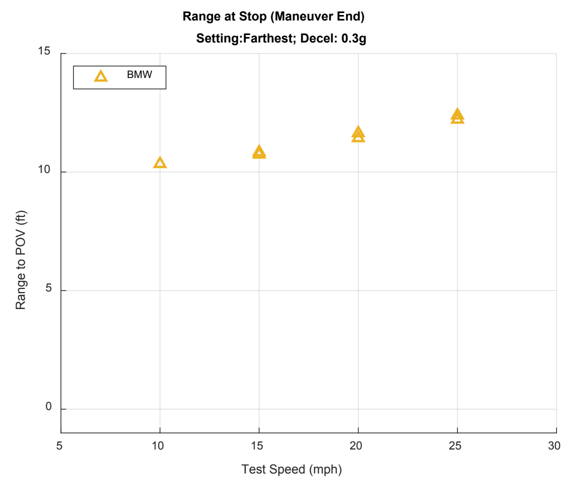


Figure 26. Range at stop, farthest heading setting, 0.3 g POV deceleration.

3.3 Suddenly Revealed Stopped Vehicle Tests

This section discusses the results for tests performed using the SRSV scenario. The SRSV steady state following distance plot is shown in Figure 29.

Figure 27. SRSV tests steady state following distance, closest headway setting.

The range to the stopped vehicle (i.e., the POV) at the end of the maneuver is shown in Figure 30. The range for trials that concluded with an SV-to-POV impact is marked as -1. Both vehicles concluded their respective trials with crash avoidance when test speeds up to 20 mph were used.

For the tests initiated from 25 mph, the POV impacts were observed during 2 of 5 trials performed with the Mercedes E300, and during 3 of 3 trials performed with the Tesla Model S (the test series was aborted after these three trials to reduce the risk of damage to the vehicle and test equipment).

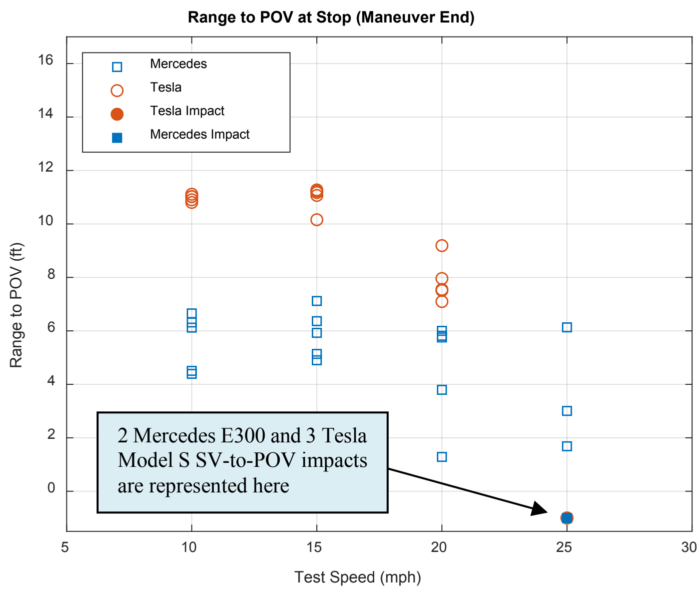


Figure 28. Range to stop for SRSV tests, closest headway setting.

The lateral distance[1] of the SV to the SOV at the onset of braking automatically initiated by the SV's TJA or automatic emergency brake (AEB) system is shown in Figure 31.

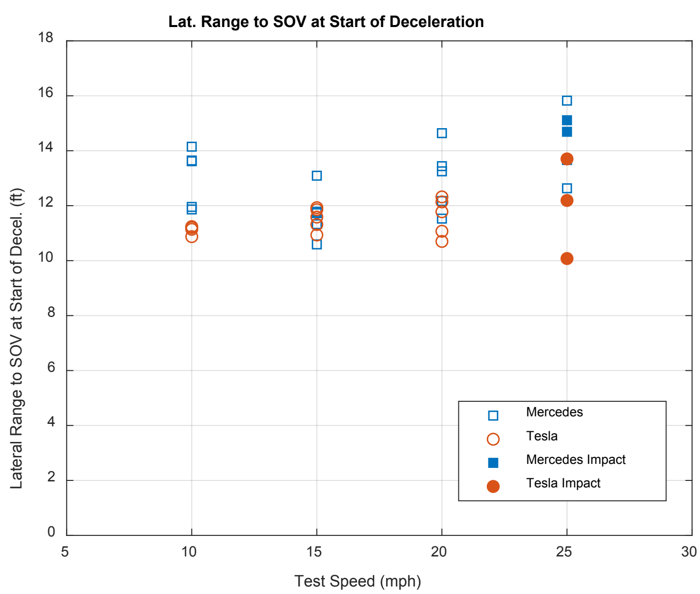


Figure 29. SV Lateral Range to SOV at Onset of SV Deceleration.

[1] Measured from the longitudinal centerline of each vehicle.

Here, onset of braking was taken to occur at the instant when the SV deceleration was > 0.05 g, regardless of how it was achieved.[2] The data indicate how far the SOV had moved into the right adjacent lane when the SV first began braking to avoid the stopped POV centered in its travel lane. For all cases, both SVs began braking only after the SOV had moved at least 9.8 ft (3 m) from the SV's center line (i.e., the SOV was completely in the adjacent lane before the SV reacted to the stationary POV).

The longitudinal range of the SV to the stationary POV at the onset of SV braking is shown in Figure 32. Except for one test performed at 25 mph, the Tesla Model S results were largely consistent across the four test speeds, and exhibited significant overlap. The Mercedes E300 results were more disparate, as the onset of braking during the tests performed at 10 mph occurred a lower headway than observed for the other test speeds. The headways at braking onset exhibited significant overlap during tests performed from 15 to 25 mph with the Mercedes E300.

Figure 30. SV longitudinal range to POV at onset of SV deceleration.

The time-to-collision (TTC) of the SV with respect to the stationary POV at the onset of SV braking is shown in Figure 33. The TTC for the Mercedes E300 generally increased for the 15 mph (24 km/h) compared to the 10 mph (16 km/h). However, the subsequent increases in test speed generally caused the TTC at braking onset to trend downward. For the Tesla Model S, the TTC at braking onset decreased with increasing test speed, with only one instance of overlap between two test speed groups (one trial performed at the 25 mph test speed produced a TTC within the distribution of those associated with the 20 mph group).

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[2] This report is agnostic to the braking method used (regenerative braking following release of the accelerator or application of the foundation brakes) by the SV since either method would have been automatically commanded by the SV's TJA and/or AEB. The onset of braking is established merely by the deceleration level (> 0.05 g).

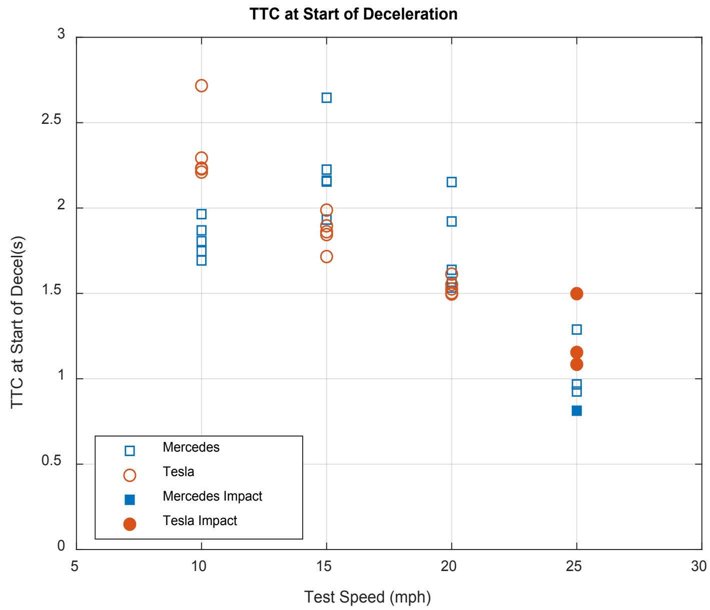

Figure 31. SV-to-POV TTC at onset of SV braking.

3.4 Lead Vehicle Lane Change With Braking Tests

The LVLCB test results for the Tesla Model S and BMW 540i are shown in Table 3.2 and Table 3.3 respectively. The coloring convention used for the information described in these tables is as follows:

- **Black:** The deceleration combinations are not feasible. When these combinations are used, the POV comes to a stop before completing the lane change.
- **Green:** The SV TJA automatically avoided a POV impact. Deceleration values are presented for tests with high deceleration to highlight the severity of the SV's response.
- **Red Shades:** An SV-to-POV impact occurred. The shade of red is used to visually indicate crash severity, with darker shades indicating a more severe crash. The speed bins corresponding to each shade of red are shown in Table 3.1. The relative speed of impact (in mph) also displayed.

Table 3.1. Relative Speed of Impact Color Code.

Speed Bin (mph)	Color
$0 < \Delta V \leq 1$	
$1 < \Delta V \leq 6$	
$6 < \Delta V \leq 10$	
$10 < \Delta V \leq 13$	
$13 < \Delta V$	

- **White:** The test data was either not valid or the test was not performed.

Results from LVLCB tests performed with the Tesla Model S are summarized in Table 3.2. When 0.3 g straight-line deceleration was used, SV-to-POV impacts were observed only for the tests with 0.1 g lane-change braking. For this combination of decelerations, SV-to-POV impact speeds of 9.0 and 9.3 mph were observed for the closest and farthest TJA heading settings, respectively.

Compared to the tests performed with 0.3 g straight-line deceleration, more SV-to-POV impacts were observed during the 0.6 g straight-line deceleration trials. For these tests, the impact severity was highest when no lane-change deceleration was used. The combinations of test speed and TJA headway setting that resulted in crash avoidance during the 0.6 g straight-line deceleration tests also produced crash avoidance during comparable tests performed with the lesser 0.3 g straight-line POV braking.

Table 3.2. Tesla Model S LVLCB SV-to-POV Impact Speed Summary.

Straight-Line Deceleration (g)		0.3								0.6							
Lane-Change Deceleration (g)		0		0.05		0.1		0.2		0		0.05		0.1		0.2	
SV TJA Headway Setting*		Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far
Test Speed (mph)	10																
	15									9.6	5.8						
	20									11	0.1						
	25					9.0	9.3			13.2	14.1	11.1	9.4	9.5	10.8		

* Near → closest setting, far → farthest setting

Results from LVLCB tests performed with the BMW 540i are summarized in Table 3.3. For the 0.3 g straight-line deceleration tests, SV-to-POV impacts were observed during the 20 mph tests performed with 0.1 g lane-change braking, and during all 25 mph tests. For the 25 mph tests, the highest speed impacts of 16.7 and 14.6 mph occurred when 0.1 g lane-change braking was used, during the tests performed with the closest and farthest TJA headway settings, respectively.

With 0.6 g straight-line deceleration, all of the 20 and 25 mph LVLCB tests performed with the BMW 540i produced SV-to-POV impacts. For the 20 mph test speed, impact severity decreased as within lane-change deceleration was increased. This was not the case for the 25 mph tests. Although the lowest impact speeds settings were realized during the tests performed with the highest lane-change deceleration, the highest impact speeds were realized during tests with 0.1 g lane-change deceleration (16.2 and 15.7 mph for the closest and farthest TJA headway settings, respectively); an observation in agreement with the BMW 540i 0.3 g straight-line deceleration tests.

Table 3.3. BMW 540i LVLCB SV-to-POV Impact Speed Summary.

Straight-Line Deceleration (g)		0.3								0.6							
Lane-Change Deceleration (g)		0		0.05		0.1		0.2		0		0.05		0.1		0.2	
SV TJA Headway Setting*		Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far
Test Speed (mph)	10																
	15																
	20					4.6	3.1			14.7	15.1	12.4	12.1	5.6	6.1		
	25	3.6	3.4	7.3	6.7	16.7	14.6	11.1	10.4	15.6	15.2	14.0	12.4	16.2	15.7	9.6	8.3

* Near → closest setting, far → farthest setting

4 CONCLUSIONS

Three production vehicles equipped with TJA were evaluated using three test scenarios developed to emulate driving situations commonly encountered during real-world driving. The performance of these vehicles was objectively quantified using metrics appropriate for the respective test scenarios. Some key observations of each test are listed below.

Overall, the SVs tested responded to the crash-imminent scenarios with braking only; no steer-to-avoid responses were observed. No SV-to-POV impacts occurred during tests performed at 10 mph, regardless of the test scenario.

LVAD Tests:

1. Tests performed with a human driver operating an actual vehicle as the POV were inconsistent and could not be used for high decelerations (>0.5 g) due to the potential of an SV-to-POV impact.

2. Each SV tested avoided the POV during all 0.3 g POV deceleration trials performed for both the far and near TJA following distance settings.

3. For the 0.6 g POV deceleration trials, no crashes occurred with the farthest TJA heading setting. With the closest heading setting, the minimum test speed capable of producing an SV-to-POV impact was vehicle dependent, however both SVs tested impacted the POV with test speeds of 20 and 25 mph.

4. Since SV-to-POV impacts were only observed when 0.6 g POV deceleration was used in conjunction with the closest SV TJA following distance setting, it is recommended that use

of this combination of LVAD test parameters, at a minimum, be retained for future TJA evaluations.

SRSV Tests:

1. The proximity of the SOV to the stopped POV at the time of the SOV lane change challenged the TJA systems tested. Avoiding the suddenly revealed the POV required the SV respond very quickly due to the at a short TTC used at the time of the reveal.

2. For both SVs evaluated with the SRSV scenario, SV-to-POV impacts were only observed for the highest speed tested (25 mph).

3. Replacing the human SOV operator with a path-following steering robot would improve the consistency by which the SOV lane changes may be performed and would eliminate the need for pylons, which are not present on real-world roads.

4. Since SV-to-POV impacts only occurred when the highest test speed of 25 mph (40 km/h) was used in conjunction with the closest SV TJA following distance setting, it is recommended that use of this combination of SRSV test parameters, at a minimum, be retained for future TJA evaluations.

LVLCB Tests:

1. Tests performed with 0.6 g POV straight-line deceleration often, but not always, resulted in higher speed SV-to-POV impacts than otherwise equivalent tests performed with 0.3 g straight-line braking. In many instances, the effect of a particular combination of test conditions depended on the SV being evaluated.

2. 0.1 g lane-change deceleration produced SV-to-POV impacts for both vehicles evaluated regardless of the straight-line deceleration level. The test speed of the trials during which the impact occurred, as well as the impact speed, varied between the vehicles, however.

3. During the tests performed with 0.6 g POV straight-line deceleration, those without lane-change deceleration were generally the most challenging for the Tesla Model S. For the BMW 540i, the severity (quantified by impact speed magnitude or whether crash avoidance was realized) of tests performed without lane-change deceleration were second only to those with lane-change deceleration of 0.1 g.

4. Regardless of the straight-line deceleration level, test severity decreased when the lane-change deceleration was increased from 0.1 to 0.2 g for both SVs evaluated.

5. Both SVs experienced POV impacts during one or more LVLCB tests performed at 25 mph. The BMW 540i impacted the POV during every LVLCB test performed at 25 mph.

6. It is recommended that retaining combinations of 0.3 and 0.6 g straight-line decelerations, no lane-change deceleration, 0.1 g lane-change deceleration, and use of the closest SV TJA

following distance setting, at a minimum, be retained for future TJA evaluations since these are the factors which seem to ensure high test severity.

5 REFERENCES

[1] Daimler AG. (2017). *E-Class operator's manual* (Part number 213 584 78 01). Stuttgart, Germany: Author. Available at www.mbusa.com/content/dam/mb-nafta/us/owners/manuals/2017/operators/MY17_E-Class_Sedan_Operator.pdf

[2] Tesla Motors, Inc. (2016). *Model S owner's manual*. Palo Alto, CA: Author.

[3] Bayerische Motoren Werke. (2017). *The BMW 5 Series Sedan. Owner's manual* (Part number 01 40 2 978 699 ue). Munich, Germany: Author.

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