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16. Abstract

This report summarizes how the suddenly revealed stopped vehicle (SRSV) and lead vehicle lane change with braking (LVLCB) test scenarios defined in NHTSA's traffic jam assist (TJA) draft research test procedure were used to assess the feasibility of increasing the number of actors in each driving situation. Better understanding the technical and logistic factors associated with such additions is of interest to NHTSA, as the expanded capability may improve NHTSA's ability to research system performance involving new and/or more complex real-world driving situations on the test track.

For the SRSV tests, one or two secondary other vehicles (SOVs) were positioned in the subject vehicle (SV) rear blind spots for the duration of each trial, which created a 4- or 5-actor scenario. For the LVLCB tests, one SOV was added to the test choreography (also positioned in an SV rear blind spot), which resulted in a 4-actor scenario. These tests were performed at 25 and 35 mph (40.2 and 56.3 km/h).

The test protocols discussed in this report were generally found to be well-defined and performable; however, some elements of the 35-mph (56.3-km/h) tests require further refinement. This may include some adjustments to the software and configuration settings used by the robotic controllers.

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Executive Summary

The National Highway Traffic Safety Administration's traffic jam assist (TJA) draft research test procedure provides a way to observe how a TJA system responds to three low-speed, car-following, crash-imminent driving scenarios (NHTSA, 2019). The work described in this report used two of these scenarios, but added more vehicles for each test condition to assess the feasability of increasing the number of actors and overall test complexity. Better understanding the technical and logistic factors associated with such additions is of interest to NHTSA, as the expanded capability may improve NHTSA's ability to research the performance of vehicle technologies under new and/or more complex real-world driving situations on the test track.

The suddenly revealed stopped vehicle (SRSV) scenario tests the ability of the TJA system to detect and respond to a stationary principal other vehicle (POV) that is suddenly revealed after a lead vehicle (LV) steers around it. For the tests described in this report, up to two secondary other vehicles (SOV) were added. For some trials, an SOV was positioned in the subject vehicle (SV) right rear blind spot. For other tests, two SOVs were used, and were positioned in the SV left and right rear blind spots. The addition of the SOVs to the SRSV scenario resulted in a 4 or 5 actor test, respectively.

The lead vehicle lane change with braking (LVLCB) scenario assesses the ability of the TJA system to detect and respond to a moving POV that braked during and/or after performing a lane change into a space between the SV and LV. For the tests described in this report, one SOV was used to increase LVLCB test complexity, and it was always positioned in the SV's right rear blind spot. The addition of this SOV resulted in a 4-actor test for the LVLCB scenario.

A 2019 Audi A6 and a 2017 BMW 540i were used as the SVs for testing. All TJA tests were performed with the SV being driven in SAE automation level 2 (SAE International, 2018), where its lateral and longitudinal control are simulaneously maintained by the vehicle for the duration of each test trial. Each test scenario was performed at 25 and 35 mph (40.2 and 56.3 km/h).

The multi-actor test scenarios were generally able to be performed as specified. However, satisfying all validity criteria (i.e., the specifications used to define what constitutes a valid test trial) during the 35-mph (56.3-km/h) tests was not achieved, and further refinement of the control software and configuration settings used by the robotic controllers may be needed to achieve the desired LV lane-change onset timing (for the SRSV scenario), and the proper POV deceleration within an acceptable time (for the LVLCB scenario). These issues are believed to be reconcilable via use of live filtering data and additional path tuning, but these potential solutions were either unavailable or could not be validated with the time and resources that were available for testing.

1 Introduction

Traffic jam assist is an advanced driver-assistance system capable of automatically controlling the lateral position of a driver's vehicle within its travel lane while simultaneously and automatically establishing and maintaining the longitudinal headway to a vehicle immediately ahead of it.

To document the methods used by NHTSA to research TJA system operation and performance on the test track, NHTSA developed a draft research test procedure comprised of three test scenarios intended to represent real-world driving conditions within the system's operational design domain (NHTSA, 2019), as follows.

- **Lead vehicle decelerates, accelerates, then decelerates (LVDAD).** The objective of the LVDAD test is to evaluate the TJA system's ability to detect and respond to a POV that moderately brakes to a stop, pauses, accelerates back to its initial speed, then brakes aggressively to a stop ahead of the SV. In this test, the SV and POV remain in the same lane for the duration of each test trial.
- **Suddenly revealed stopped vehicle.** The objective of the SRSV test is to evaluate the TJA system's ability to detect and respond to a stationary POV that is suddenly revealed after an LV steers around it. In this test, the SV and POV remain in the same lane for the duration of each test trial. The LV begins in the same lane as the SV and POV but performs a single lane change into an adjacent lane before colliding with the POV.
- **Lead vehicle lane change with braking.** The objective of the LVLCB test is to evaluate the TJA system's ability to detect and respond to a moving POV that brakes during and/or after performing a lane change into a space between the SV and LV. In this test, the SV and SOV remain in the same lane for the duration of each test trial. The POV begins in a lane adjacent to the SV and LV but performs a single lane change into the SV and LV travel lane.

The work described in this report details research performed to evaluate the feasibility of incorporating up to two additional SOVs to NHTSA's SRSV and LVLCB test scenarios. Specifically, factors related to the increased test complexity and testing effort are described and quantified.

2 Test Protocol

This section describes the SV, POV, SOV, and LV used in this evaluation. Additionally, a brief description of the equipment used to perform the testing and an outline of the TJA scenarios are presented.

Note: For each test described in this report, the SV adaptive cruise control (ACC) headway was set to the farthest distance (headway) possible.

2.1 Subject Vehicles

Two SVs were used during this evaluation. A 2019 Audi A6 was used initially; however, due to vehicle scheduling conflicts, testing was completed with a 2017 BMW 540i.

2.1.1 2019 Audi A6

The 2019 Audi A6 used ACC with lane guidance to help keep the vehicle centered in the lane and positioned behind the LV for TJA. The ACC automatically adjusted the vehicle's speed and headway in relation to the vehicle in front of it. Lane guidance automatically provided the steering inputs intended to keep the vehicle centered in its lane of travel.

To activate ACC, the driver pulled the lever shown in Figure 2-1 A to position 1 and then set the speed by pressing the button labeled 2 in the same figure. Once ACC was activated and engaged, the driver engaged lane guidance by pressing the button on the stock shown in Figure 2-1 B. Full details on this system can be found in the Audi A6 owner's manual (Audi, 2019).

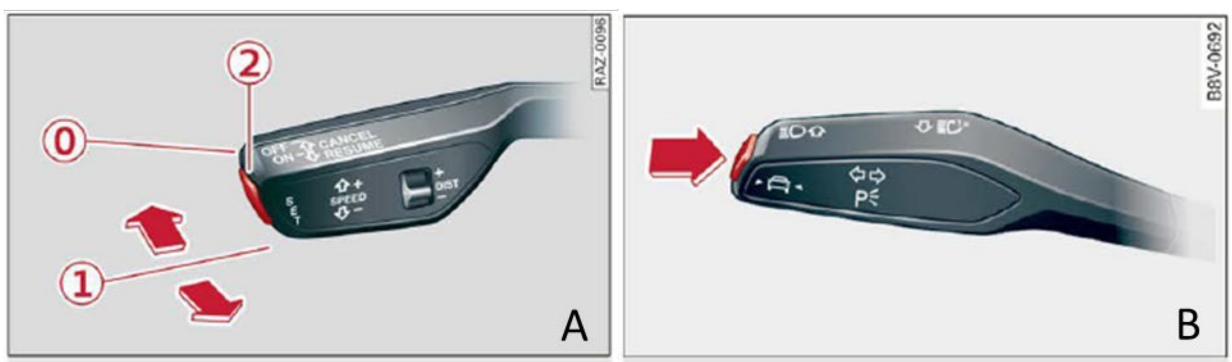

Figure 2-1. ACC and lane guidance system activation

2.1.2 2017 BMW 540i

A 2017 BMW 540i used ACC with steering and lane control assistant for TJA. As with the Audi A6, the BMW 540i ACC automatically adjusted the vehicle's speed and headway to the vehicle in front of it, and lane control assistant provided the steering inputs intended to keep the vehicle centered in the travel lane.

The ACC and lane control assistant control buttons were located on the left-hand side of the steering wheel. To activate ACC, the driver pressed the button labeled B in Figure 2-2 and then set the speed by pressing the button labeled C in the same figure. The speed could be adjusted with the toggle switch also shown in Figure 2-2. Once ACC was activated and engaged, the driver engaged lane control assistant by pressing button A shown in Figure 2-2. Full details on this system can be found in vehicle owner's manual (Bayerische Motoren Werke, 2017).

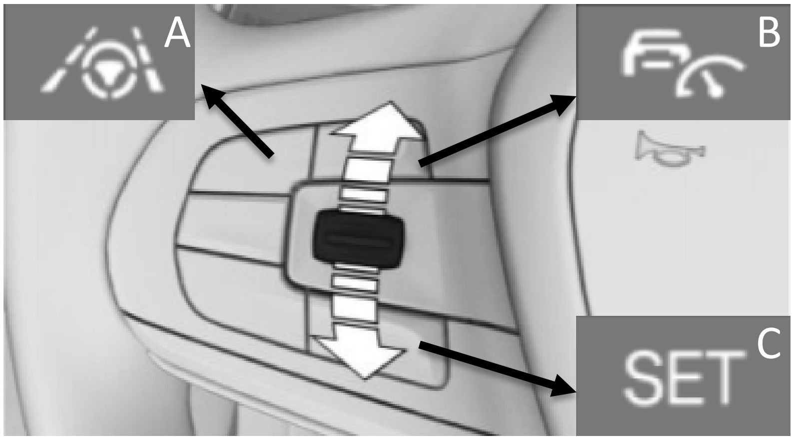

Figure 2-2. ACC and lane control assistant activation

2.2 Principal Other Vehicle

The POV used was a guided soft target (GST) system comprised of a low-profile robotic vehicle (LPRV) that can be driven over by the SV, and a global vehicle target (GVT) consisting of foam panels and skins that are designed to separate upon impact, as shown in Figure 2-3.

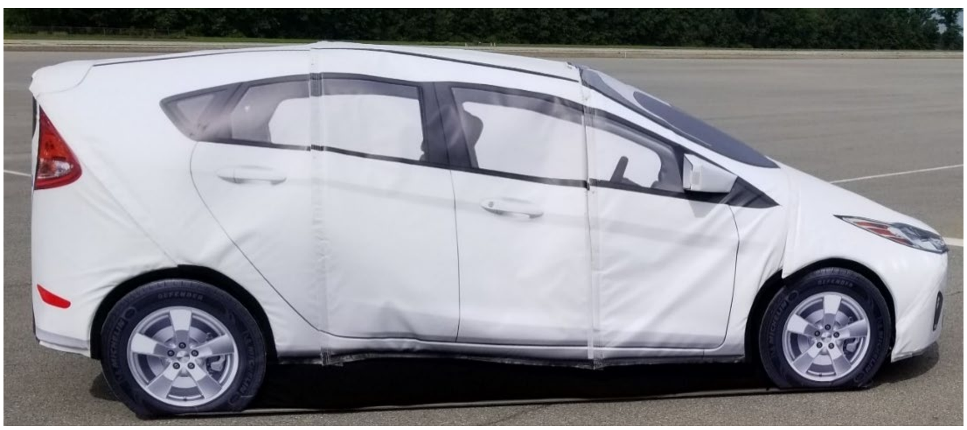

Figure 2-3. GVT Revision F, secured to the top of the LPRV

Extensive collaborative research was performed from 2015 to 2018 to ensure the GVT appears realistic to the vehicle systems designed to respond to it (Euro NCAP, 2018). The LPRV provides accurate closed-loop control of the POV relative to the SV, and because the GST system is strikeable from any approach aspect it can be incorporated into nearly any pre-crash scenario. Multiple fail-safe measures are incorporated to ensure the safe operation of the GST.

For this test program, GVT revision F was used as the POV and the SOV for tests performed with the Audi A6. GVT revision G[1] was used as the SOV for tests performed with the BMW 540i.

2.3 Lead Vehicle

The LV used for all tests was a 2019 Ford Fusion[2]. This vehicle was instrumented with steering, brake, and throttle robots as described in Section 2.5, to provide the inputs needed to achieve accurate and repeatable test maneuvers.

2.4 Secondary Other Vehicles

Up to two SOVs were used for the work described in this report.[2] For the LVLCB tests, one SOV (a 2019 Ford Fusion) was added to the respective scenario defined in the NHTSA TJA draft research test procedure. For the SRSV tests, one or two SOVs were added (a 2019 Ford Fusion or a 2019 Ford Fusion plus a GST). The decision to use two kinds of SOVs during the SRSV tests was made primarily in response to equipment availability; however, this also allowed for a direct observation of how the two could be operated in the same scenario while performing equivalent roles (i.e., an actual vehicle and a surrogate).

Like the LV, the SOV Ford Fusion was instrumented with steering, brake, and throttle robots. When used, the SOV GST was comparable to the POV GST. Each SOV was programmed to adjust their current position and speed relative to the position and speed of the SV.

2.5 Test Equipment

Test equipment consisted of AB Dynamics (ABD) steering, brake, and throttle robots and an Oxford Technical Solutions (OxTS) RT and Range system. These are briefly described in this section. An in-vehicle data acquisition system was installed in the SV to collect data from each actor during test conduct.

2.5.1 Steering Robot

An ABD SR15 Orbit steering robot was installed in both the LV and Ford Fusion SOV for this study. The SR15 Orbit is a lightweight, low-torque robot programmed to travel along a desired path via closed loop control with the SV (see Figure 2-4 for a typical installation example).

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[1] Visually, GVT revisions F and G are nearly equivalent. However, revision G features slightly revised geometry (less rake to the rear) and radar return characteristics. Although these adjustments were performed to make revision G more representative of an actual car than revision F, the differences did not confound the assessment of multi-actor test feasibility.

[2] Additional LV and SOV makes and models were not used or needed for the work described in this report. The study objective was to assess the feasibility of increasing the number of actors used in TJA-based test scenarios, not to assess how the SVs respond to other (alternative) vehicles or objects.

Figure 2-4. Example steering robot installation

2.5.2 Throttle and Brake Robots

Robotic brake and throttle robots were installed in the LV and Ford Focus SOV to accurately and repeatedly provide longitudinal control of these vehicles, where applicable. For this study, ABD CBARs were used (see Figure 2-5 for a typical installation example).

Figure 2-5. Example throttle and brake robot installation

2.5.3 Inertial and GPS Measurements

The SV, POV, LV, and SOVs were each instrumented with OxTS RT 3002 inertial measurement and GPS units to measure the position, orientation, and dynamics of each vehicle or actor. Differential corrections were applied to the GPS data to maximize position accuracy. Paired with an OxTS Range S system, relative ranges and velocities between the SV, LV, POV, SOVs, and permanent lane markings (surveyed points) were also collected.

2.6 Test Scenarios

Section 2.6.1 and 2.6.2 provide an overview of test scenarios and validity criteria developed for SRSV and LVLCB TJA test scenarios described in this report.

2.6.1 Suddenly Revealed Stopped Vehicle With More Actors

As previously mentioned, the objective of the SRSV test described in NHTSA's TJA draft research test procedure is to evaluate the system's ability to detect and respond to a stationary POV that is suddenly revealed after an LV steers around it. For that scenario, the SV can either choose to brake to avoid the stopped vehicle, steer to avoid the stopped vehicle, or use a combination of steering and braking. From an SV perspective,[3] the driving situations used for the work described in this report are more challenging since one or both steer-to-avoid options are effectively removed. In the 4-actor SRSV tests, an SOV resides in the SV right rear blind spot, and in the 5-actor tests, an SOV is present in the SV left and right rear blind spots. In both cases, the SV will impact the SOV if it attempts to perform a lane change around the stopped POV towards an SOV, shown in Figure 2-6.

The SV and POV remained in the same lane for the duration of each SRSV test trial. The LV began in the same lane as the SV and POV but performed a single lane change into an adjacent lane to avoid colliding with the stopped POV. For tests performed with only one SOV, the SOV traveled in the blind spot to the right of the SV (SOV1 in Figure 2-6). For tests performed with both SOVs, SOV1 again traveled in the blind spot to the right of the SV and SOV2 traveled in the blind spot to the left of the SV. For both driving situations, the tests were performed at 25 and 35 mph (40.2 and 56.3 km/h).

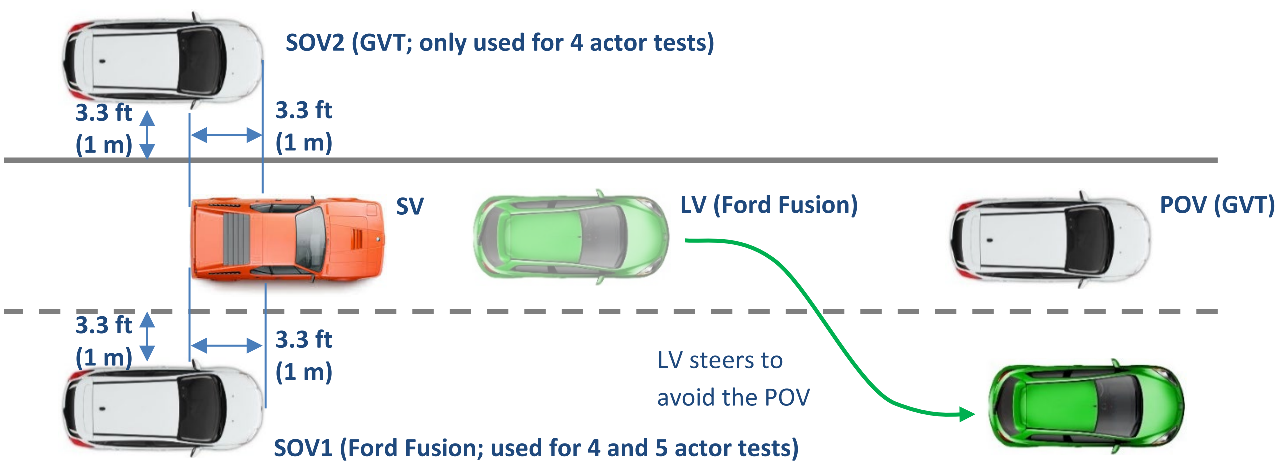

Figure 2-6. SRSV path

Figure 2-7 shows the required LV path, which was achieved via use of a steering robot. This lane change consists of two constant radius curves connected with a straight line as the LV crosses the right lane line. Since the curve radii and LV-to-POV distance at the onset (40 ft or 12.2 m) of the

[3] Although neither of the SVs evaluated in this study had the ability to automatically steer around the POV to avoid, it is conceivable that the future generation vehicles may. Should that occur, SRSV tests performed with one or more SOVs may provide an interesting way to assess SV crash avoidance decision making.

LV lane change remained the same regardless of SV and LV speed, overall maneuver severity increased as a function speed.

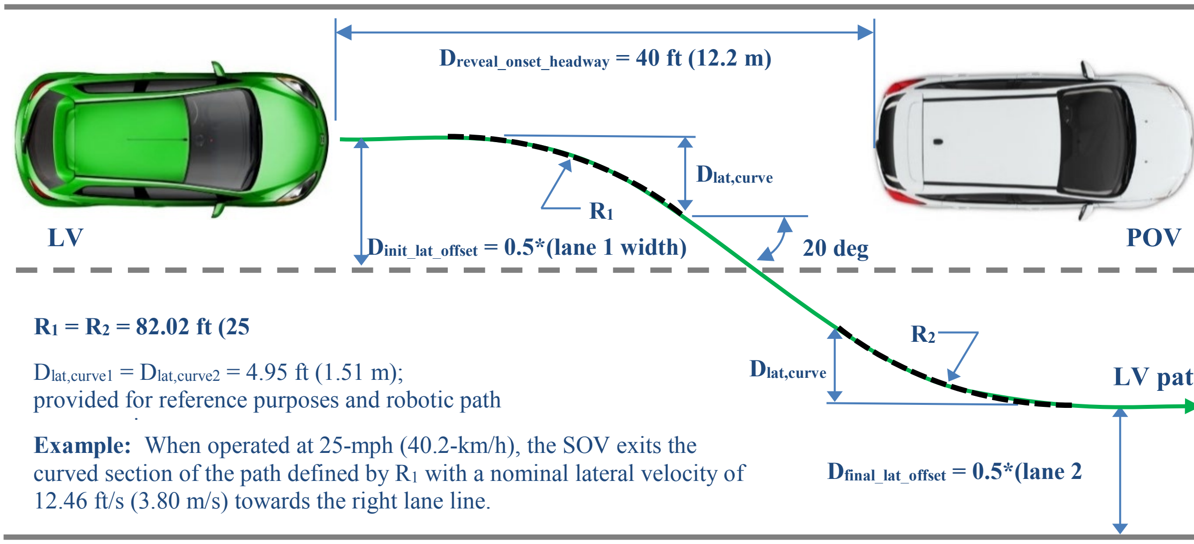

Figure 2-7. SRSV LV path profile

2.6.2 Lead Vehicle Lane Change With Braking With More Actors

The objective of the LVLCB test is to evaluate the TJA system's ability to detect and respond to a moving POV that enters a space between the SV and an LV (see Figure 2-8). For the tests described in this report, the POV began in a lane adjacent and to the left of the SV and LV, and the SOV resided in the right rear SV blind spot. Shortly after operating at steady state with a longitudinal headway of 24.6 ft (7.5 m) to the front of the SV, the POV performed a single lane change into the SV and LV travel lane and was decelerated at either 0.3 or 0.5 g (2.9 m/s^2 or 4.9 m/s^2). Since neither SV used for the work described in this report was equipped with an ability to automatically steer around an object to avoid crashing into it, the only possible SV crash avoidance countermeasure was to automatically release the throttle and apply the brakes to avoid the POV.[4]

The POV lane change used during the LVLCB tests is shown in Figure 2-9, and was achieved by having the GST execute a pre-programmed path. The lane change consists of two constant-radius curves connected with a straight line. The POV lane change was performed 3 seconds after the POV had matched the SV speed and was at the desired longitudinal distance from the SV.

[4] In this driving situation potential SV crash avoidance options could conceivably include braking and/or steering into the travel lane previously occupied by the POV (i.e., before its lane change), and could therefore provide another potential way to assess SV crash avoidance decision-making.

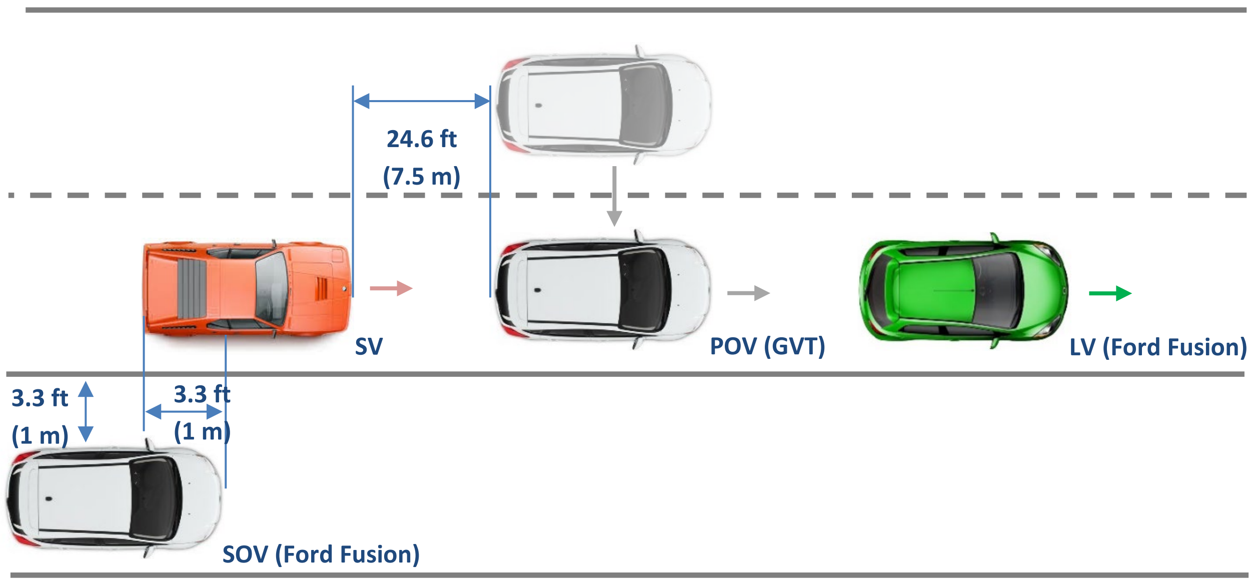

Figure 2-8. LVLCB path

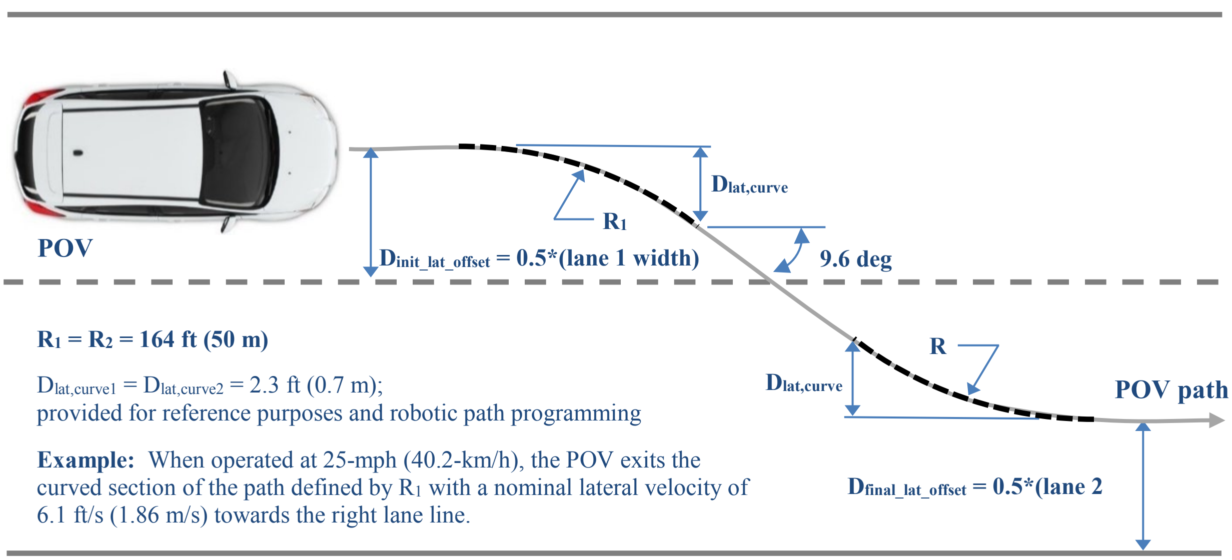

Figure 2-9. LVLCB POV path profile

The path defined in Figure 2-9 was successfully used during the 25-mph (40.2-km/h) tests, but was too severe when the test speed was increased to 35 mph (56.3 km/h) as the POV was unable to perform the lane change while satisfying the lateral path tolerances defined in Section 2.7.1.

At 25 mph (40.2 km/h), the POV would exit the curved section of the path with a nominal lateral velocity of 6.1 ft/s (1.86 m/s). At 35 mph (56.3 km/h), this nominal lateral velocity increases to 8.6 ft/s (2.61 m/s). For this reason, the POV path for the LVLCB tests for the 35-mph (56.3-km/h) tests was adjusted to that shown in Figure 2-10.

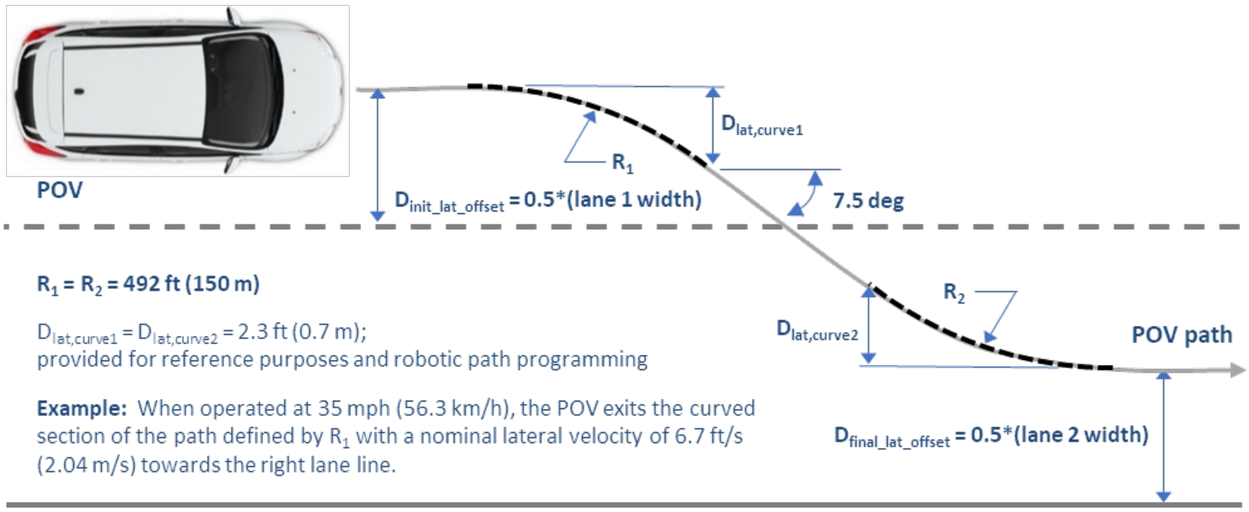

Figure 2-10. Revised LVLCB POV path profile

2.7 Validity Criteria

The test validity period, defined as the time during which certain test parameters were required to be within allowable specifications to ensure a test trial was properly and consistently performed, was generally taken to be 3 seconds before the onset of a lane change (LV lane change for SRSV or POV lane change for LVLCB) until either the SV contacted the POV or 1 second after the SV stopped in response to the test event. The following validity criteria were assessed for each test trial.

- LCC and ACC must be on and active.
- SV driver shall not provide manual inputs to the SV accelerator or brake pedals.
- The POV and LV speeds shall be within ± 1 mph (± 1.6 km/h) of the given test speed.
- Where applicable, deceleration magnitudes shall be reached within 0.5 s ± 0.1 s.
- Where applicable, average POV deceleration shall be maintained within ± 0.05 g (± 0.49 m/s^2) of the desired value over the applicable interval.
- The SRSV LV-to-POV reveal distance shall be 40 ft ± 1 ft (12.2 m ± 0.3 m).
- LV and POV lateral path tolerances shall be ± 0.8 ft (± 0.24 m).
- The forward most point of the SOVs shall be 3.3 ± 1.6 ft (1 ± 0.5 m) ahead of the rear most point of the SV.
- SOV lateral distance between the inside edge of the closest lane line to the edge of the vehicle shall be 3.3 ± 0.82 ft (1 ± 0.25 m).
- The forward most point of the SOV shall be 24.6 ± 3.3 ft (7.5 ± 1 m) from the rear most point of the POV until the lane change occurs.
- Lane change onset and completions are taken to be the instant when the vehicle lateral acceleration produced by the final steering input first becomes ± 0.03g (0.3 m/s^2).

- LVLCB decelerations must be applied within 250 ms of lane change completion.
- Three valid test trials must be completed on the same day per test condition.

Additionally, the SV driver was instructed to avoid touching the steering wheel to the greatest extent possible. Although it would have been preferred to avoid having any driver interaction with it within the validity period (to avoid potentially confounding the trial with their input), it was sometimes necessary for the driver to provide a small bump to the steering wheel to prevent the respective vehicle's driver monitoring system from "timing out" system operation due to perceived driver inattention. When used, these inputs were no more than a few degrees and were not enough to change the SV heading.

3 Test Results

SRSV and LVLCB with multi-actor results are outlined in Sections 3.1 and 3.2. For this report, the goal was to collect data from 3 valid trials per test condition to ensure repeatability, while managing the burden of the exploratory test effort to allow for testing of more conditions. To minimize the confounding effect of environmental changes on outcome, the goal was to collect these data on a single day. For each of the test conditions, 3 valid trials were performed, except SRSV 35-mph (56.3-km/h) tests performed with 2 SOVs, and the LVLCB 35-mph (56.3-km/h) tests performed with 0.5g (4.9 m/s^2) POV deceleration. For the SRSV 35-mph (56.3-km/h) test performed with two SOVs, only one valid trial was able to be performed during the testing, and no valid trials were able to be performed during the LVLCB 35-mph (56.3-km/h) testing performed with 0.5g (4.9 m/s^2) POV deceleration.

The tables shown in sections 3.1 and 3.2 provide the number of test days associated with data collection, the total number of valid test trials collected, and the number of tests that were performed to obtain three valid test trials within the same day. This is included to illustrate the overall test effort associated with performing these tests. None of the valid test trials performed with the Audi A6 impacted the POV. All but 3 of the test trials performed with the BMW 540i impacted the POV. In the context of this report, knowing whether SV-to-POV impacts occurred within a test condition is useful since their occurrence affects the testing time (due to the time needed to reconstruct the GVT, re-initialize the robotic platform, etc.).

3.1 SRSV Results

A summary of the minimum SV-to-POV ranges and SV-to-POV impact speeds (if applicable) observed during the SRSV trials performed with 1 or 2 SOVs is shown in Table 3-1. These tests were performed with the Audi A6 or the BMW 540i.

Table 3-1. SRSV With Multi-Actor Results

Vehicle Speed	# of SOVs	Total Impacts	Average SV-to-POV Impact Speed	Average SV-to-POV Min. Range	# of Test Days	# of Test Trials		# of Test Trials on the Day That 3 Valid Trials Were Collected (where applicable)
						All Valid	Total Overall	
25 mph (40.2 km/h)	1*	0/3*	-*	13.2 ft* (4.01 m)	3*	9*	30*	4*
	2**	0/3**	-**	1.5 ft** (0.46 m)	4**	6**	47**	3**
35 mph (56.3 km/h)	1**	3/3**	5.5 mph** (8.9 km/h)	-**	3**	8**	37**	3**
	2**	1/1**	4.1 mph** (6.6 km/h)	-**	6**	2**	55**	16**
Overall					16	25	169	26

* Denotes tests performed with the Audi A6
** Denotes tests performed with the BMW 540i

For the 25-mph (40.2-km/h) tests with one SOV, all valid tests ended without an impact. It took 4 trials to get 3 valid trials on the day the valid tests were obtained. Three testing days were required to obtain a set of 3 valid test trials in one workday. For the 25-mph (40.2-km/h) test with two SOVs, all valid test trials also ended without an impact. It took 3 test trials to get 3 valid tests on the day the valid tests were obtained. Four testing days were required to obtain a set of 3 valid tests in one workday.

For the 35-mph (56.3-km/h) tests performed with one SOV, all valid test trials ended with an impact. It took 3 test trials to get 3 valid tests on the day the valid tests were obtained. Three testing days were required to obtain a set of 3 valid trials in one workday. Only 1 valid trial was collected for the 35-mph (56.3-km/h) test with 2 SOVs. This is due to an issue with inconsistency of the reveal headway, which is discussed in more detail in Section 4.2. It ultimately took 16 test trials to get 1 valid test on the day the valid test was obtained, after which further tests were not performed due to time constraints. Tests were performed for this scenario over the course of 6 testing days.

3.2 LVLCB Results

A summary of the minimum SV-to-POV ranges observed during the LVLCB with multi-actor tests is shown in Table 3-2. All LVLCB with multi-actor testing was performed with the Audi A6.

Table 3-2. LVLCB With Multi-Actor Results

Vehicle Speed	Post Lane Change Deceleration	Total Impacts	Average SV-to-POV Min. Range	# of Test Days	# of Test Trials		# of Test Trials on the Day That 3 Valid Trials Were Collected (where applicable)
					All Valid	Total Overall	
25 mph (40.2 km/h)	0.3 g (2.9 m/s^2)	0/3	15.1 ft (4.59 m)	2	6	30	5
	0.5 g (4.9 m/s^2)	0/3	3.5 ft (1.06 m)	2	4	26	12
35 mph (56.3 km/h)	0.3 g (2.9 m/s^2)	0/3	18.8 ft (5.73 m)	4	4	76	7
	0.5 g (4.9 m/s^2)	--	--	3	--	41	--
Overall				11	14	173	25

For the 25-mph (40.2-km/h) tests performed with a 0.3 g (2.9 m/s^2) POV deceleration, all valid test trials ended without impacts. It took 5 trials to get 3 valid tests on the day the valid tests were obtained. Two testing days were required to obtain a set of 3 valid tests in one workday. For the 25-mph (40.2-km/h) test with a 0.5 g (4.9 m/s^2) POV deceleration, all valid test trials ended without impacts. It took 12 trials to get 3 valid tests on the day the valid tests were obtained. Two testing days were required to obtain a set of 3 valid tests in one workday.

For the 35-mph (56.3-km/h) tests performed with 0.3 g (2.9 m/s^2) POV deceleration, all valid test trials ended without impacts. It took 7 trials to get 3 valid tests on the day the valid tests were obtained. Four testing days were required to obtain a set of 3 valid tests in 1 workday. No valid 35-mph (56.3-km/h) trials performed with a POV deceleration of 0.5 g (4.9 m/s^2) were collected, despite 41 trials being performed over 3 days. Only 2 trials overall had the correct post lane change brake timing. This issue is discussed in further detail in Section 4.3

4 Assessment of Invalid Test Trials

The SRSV and LVLCB tests performed with an increased number of actors required multiple days of testing (including those dedicated to experimentation, iterative adjustment, and conduct refinement) to collect valid trials. In both scenarios, it was difficult to maintain the tolerance for longitudinal position choreography of the SOVs throughout the maneuver. For the SRSV tests, the LV was unable to consistently achieve the desired reveal headway for 35-mph (56.3-km/h) tests. For the LVLCB tests, the POV was unable to consistently achieve the post lane change braking timing for the 35-mph (56.3-km/h) tests. These difficulties, and solutions or potential future solutions, are presented in the following sections.

4.1 SOV Longitudinal Position

One difficulty common to both the SRSV and LVLCB scenarios performed with an increased number of actors was maintaining the longitudinal choreography of the SOVs throughout a given test trial. The goal was to position the SOVs in the blind spots of the SV and maintain it via vehicle-to-vehicle speed control. Closed-loop control of the SOVs speed relative to the SV through the full validity period was initially used in all tests. During the LVLCB with multi-actor tests, it became apparent that the SOV would not be able to maintain this positioning relative to the SV in the event of aggressive deceleration by the SV to avoid or mitigate an impending rear-end crash with the POV. At times, SV decelerations exceeded 1.0 g (9.8 m/s^2) during testing, a level of deceleration that a GST-based SOV could not achieve. Another concern was that attempting to have the SOV match the SV's deceleration would put the SOV close to the SV when it was responding to the threat of a rear-end collision, thus increasing the risk of a real collision if the SV were to laterally deviate from its travel lane.

To reduce the possibility of SV-to-SOV interference and to improve the ability to satisfy test trial validity criteria, it was decided that at approximately 2.5 seconds prior to reaching the stationary POV, the vehicle-to-vehicle speed control of the SOV would be switched to hold a constant speed by transitioning from closed- to open-loop control. This allowed the necessary relative longitudinal distance to be maintained during the steady-state period while resolving concerns of SOV speed and position at the time of SV deceleration or impact with the POV. Due to the constant speed of the SOV, the vehicle would likely not be near the potential impact location, supporting safer test conduct.

4.2 SRSV Lead Vehicle Reveal Headway

Regardless of how many SOVs were used during SRSV testing, the LV was to begin its lane change 40 ft (12.19 m) away from the POV. During the 25-mph (40.2-km/h) tests, once the lane change onset was properly configured (programmed), this was usually consistent. However, it was observed that as the number of actors and test speeds increased, there was a corresponding decrease in the consistency of the lane-change onset headway. This resulted in considerable difficulty in achieving the desired lane change position at 35 mph (56.3 km/h) with two SOVs.

To assess how the number of actors affected the proximity of the LV to the POV at the onset of its lane change, a series of 35-mph (56.3-km/h) tests were performed with an increasing number of actors. For these tests, all actors were connected to the same communication network used by the test equipment to transfer data and facilitate closed loop operation.

Overall, as the number of actors was increased, communication speed generally decreased, and this ultimately resulted in reduced lane change onset consistency. This can be seen in Table 4-1, where although the average LV-to-POV lane change onset headway was largely consistent, the associated standard deviations increased when more than three actors were used. From a test validity perspective, this is important since the test tolerance for the distance at the onset of the lane change is only ± 1 ft (± 0.3 m), and a standard deviation of nearly this magnitude make it very difficult to perform the maneuver precisely and to collect valid test trials.

At 35 mph (56.3 km/h) the window of validity for the onset of the lane change is approximately 8 data counts or 0.04 s. There were many trials that only missed this window by one data count. It is possible that either expanding the test tolerance as speed increases or additional path following tuning of the steering robot could resolve this issue.

Table 4-1. Distance at the Onset of the Lane Change

# of Vehicles Connected to the Network	Distance at the Onset of the Lane Change					
	Trial 1	Trial 2	Trial 3	Trial 4	Average	Standard Deviation
2	39.8 ft (12.14 m)	40.2 ft (12.26 m)	39.7 ft (12.10 m)	39.7 ft (12.09 m)	39.9 ft (12.15 m)	0.3 ft (0.08 m)
3	39.6 ft (12.07 m)	39.7 ft (12.10 m)	40.0 ft (12.20 m)	39.4 ft (12.00 m)	39.7 ft (12.09 m)	0.3 ft (0.08 m)
4	39.7 ft (12.10 m)	40.0 ft (12.19 m)	40.0 ft (12.21 m)	38.9 ft (11.90 m)	39.7 ft (12.10 m)	0.5 ft (0.16 m)
5	39.4 ft (12.02 m)	39.3 ft (11.99 m)	38.5 ft (11.73 m)	40.6 ft (12.37 m)	39.5 ft (12.03 m)	0.9 ft (0.26 m)

4.3 LVLCB POV Brake Onset

The LVLCB scenario is defined such that the onset of the POV braking shall occur within 250 ms of the lane change completion. In previously completed research, the POV braking parameters were tuned by first identifying the end of the POV lane change and then applying the POV's brakes to meet this criterion. However, this previous research focused on tuning the braking parameters during a 25-mph (40.2-km/h) test. Satisfying this test validity requirement for tests performed at 35 mph (56.3 km/h) was more problematic.

The values used to determine the end of the POV lane change, and therefore the onset of POV braking, were less consistent at 35 mph (56.3 km/h) than they were at 25 mph (40.2 km/h). Figure 4-1 shows a comparison of the steering angle of the POV and Figure 4-2 shows a comparison of the lateral acceleration during the lane change of the POV for the 25-mph and 35-mph (40.2-km/h and 56.3-km/h) tests. It was anticipated that the exact steering angle profile between the 25-mph and 35-mph (40.2-km/h and 56.3-km/h) tests would be different. However, it is evident in Figure 4-1 that the 35-mph (56.3-km/h) tests are significantly less consistent along the profile. Similarly, the lateral acceleration profile of 35-mph (56.3-km/h) tests is also less consistent than 25-mph (40.2-km/h) tests, shown in Figure 4.2.

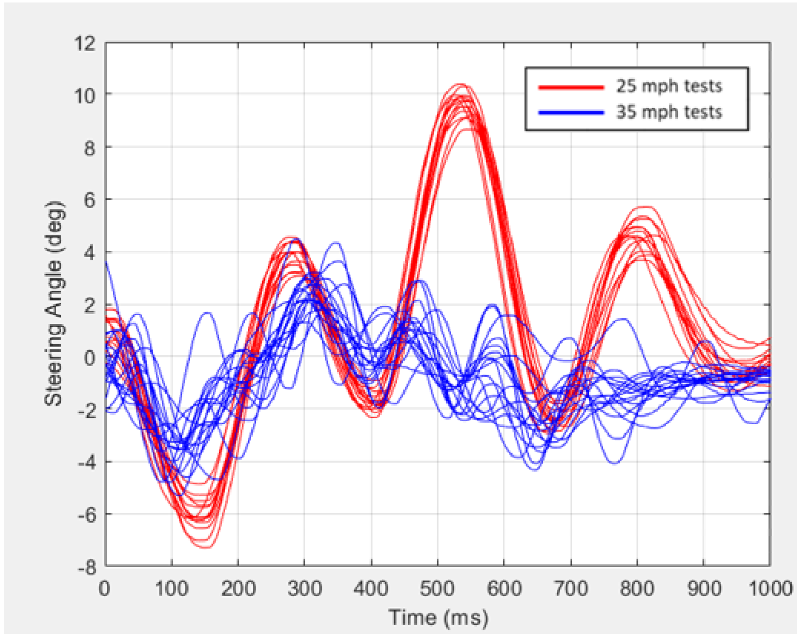

Figure 4-1. Steering angle comparison of 25-mph and 35-mph (40.2-km/h and 56.3-km/h) tests

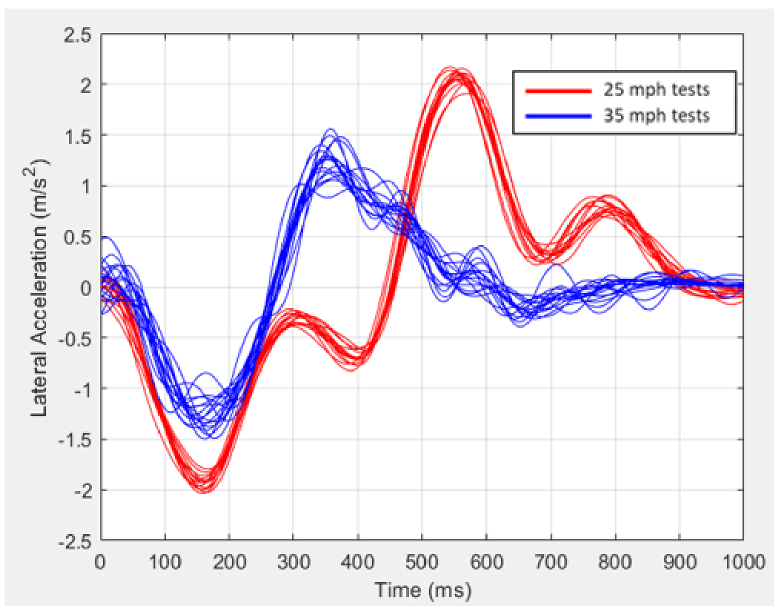

Figure 4-2. Lateral acceleration comparison of 25-mph and 35-mph (40.2-km/h and 56.3-km/h) tests

Due to these inconsistencies, identifying a suitable data channel and trigger point to meet the braking onset for 35-mph (56.3-km/h) tests was difficult and required several test iterations. After trying to use steering angle, yaw, heading, and lateral position as trigger channels, no reliable solution was found. As testing equipment continues to develop, it is anticipated that there will be the ability to apply a "live filter" directly to the lateral acceleration channel which could then be used as a more reliable brake activation trigger and provide a more consistent braking event.

4.4 Test Conduct Issue Summary

Several changes were made during testing to accommodate the increased speed and additional actors in these tests. These changes are recommended for any future work performed with these scenarios.

- The LVLCB lane change had to be lengthened, as the path error increased above the tolerance when performing the test at 35 mph (56.3 km/h).
- Initially during testing, the SOVs came to a stop beside the SV in the blind zones. After the critical point of the test was determined, the SOVs were programmed to maintain speed starting 2.5 seconds before the impact point and continue forward as the SV either comes to a stop or impacts the POV. This was modified to have fewer actors near a potential impact area, thereby increasing test safety.
- It is anticipated that additional path tuning, and live filtering may be able to resolve the variability issues associated with the SRSV reveal headway and the LVLCB braking onset timing.

5 Conclusions

The work described in this report demonstrates that increasing the number of actors for the SRSV and LVLCB test scenarios in (NHTSA, 2019) is possible; however, some additional adjustments are needed to satisfy all validity criteria, particularly if test speeds greater than 25 mph (40.2 km/h) are used. SRSV reveal headway and LVLCB post lane change braking onset timing proved to be the most exceeded validity criteria. Recommendations as how to address these issues have been provided.

- For the SRSV tests, the LV was unable to consistently achieve the desired reveal headway for 35-mph (56.3-km/h) tests. Performing additional path tuning with the steering robot or increasing the test tolerance as a function of speed is expected to improve the repeatability of the LV to perform at higher speeds.
- For the LVLCB tests, the POV was unable to consistently achieve the post lane change braking timing for the 35-mph (56.3-km/h) tests. Filtering the lateral acceleration data and using it to trigger POV braking may resolve the issues of increased variability, allowing for a more consistent braking event.

In addition to the adjustments needed to further improve test performability, an adjustment was made to increase test safety. This allowed the SOV to continue travelling instead of coming to a stop with the SV, reducing the chance of a collision.

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