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Assessing the Effect of Test Target Offset on Forward Collision Warning and Automatic Braking Onset Timing

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16. Abstract

This report compares the forward collision warning (FCW) and subject vehicle (SV) braking onset timing during tests where the SV was laterally aligned behind a principal other vehicle (POV) to that observed when the POV was offset to the left or right. Three light vehicles, a 2017 Mercedes E300, a 2018 Nissan Leaf, and a 2017 Volvo S90, were evaluated using the global vehicle target revision E (GVT) as the POV in three rear-end crash scenarios: lead vehicle stopped, lead vehicle moving, and lead vehicle decelerating. The SVs were evaluated in three levels of driving automation, levels 0, 1, and 2 (crash-imminent braking only, adaptive cruise control enabled, and adaptive cruise control plus lane centering control enabled). A majority of FCW alerts occurred while the vehicles were operating in driving automation level 0. The results show the FCW onset timing of the three vehicles evaluated was not affected by having the POV offset to the left or right of the SV. Regardless of whether the adaptive cruise control or crash-imminent braking system was responsible for initiating its deceleration, a 0.25g threshold was used to define the onset of SV braking. SV braking onset timing was affected by POV offset during tests performed in driving automation level 0 (no automation), but each SV response was unique. Based on available data from the three vehicles used in this study, SV braking onset timing does not appear to have been affected by POV offset during tests performed in driving automation levels 1 or 2 (i.e., tests performed with ACC enabled).

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Glossary

ACC	adaptive cruise control
AEB	automatic emergency braking
AV	automated vehicle
CIB	crash-imminent braking
Euro NCAP	European New Car Assessment Program
FCW	forward collision warning
GAWR	gross axle weight rating
GVWR	gross vehicle weight rating
GST	guided soft target
GVT	global vehicle target
LCC	lane centering control
LPRV	low-profile robotic vehicle
LRR	long-range radar
LVS	lead vehicle stopped
LVM	lead vehicle moving
LVD	lead vehicle decelerating
NCAP	New Car Assessment Program
POV	principal other vehicle
SRR	short-range radar
SV	subject vehicle
TTC	time-to-collision

Executive Summary

The work described in this report compares the forward collision warning and subject vehicle braking onset timing during tests where the SV was laterally aligned behind a principal other vehicle to that observed when the POV was offset to the left or right. Three light vehicles, a 2017 Mercedes E300, a 2018 Nissan Leaf, and a 2017 Volvo S90, were evaluated using the global vehicle target revision E as the POV in three rear-end crash scenarios: lead vehicle stopped, lead vehicle moving, and lead vehicle decelerating. Within each test scenario, trials were performed with the SV operating in one of three driving automation levels as defined by SAE J3016: level 0 (no automation; e.g., crash-imminent braking), level 1 (adaptive cruise control enabled), and level 2 (ACC plus lane centering enabled) (SAE International, 2018).

Most FCW alerts occurred while the vehicles were operating in driving automation level 0. The results show the FCW onset timing of the three vehicles evaluated was not affected by having the POV offset to the left or right of the SV.

The SV deceleration produced in response to the test scenarios were the result of either ACC- or CIB-based braking. Regardless of which system was responsible for automatically initiating the deceleration, a threshold of 0.25g was used to define the onset of the SV crash avoidance brake response. In summary, for the SVs used for the work described in this report,

- SV braking onset timing was affected by POV offset when the SV was operated in driving automation level 0, however the extent and manner in which it occurred was vehicle-dependent; and
- Based on available data from the three vehicles used in this study, SV braking onset timing does not appear to have been affected by POV offset during tests performed in driving automation levels 1 or 2 (i.e., tests performed with ACC enabled).

The Mercedes E300 braked sooner when operated directly behind the POV than when the POV was offset to the left during the LVS_20_0, LVS_25_0, LVM_35_10, LVM_45_20, LVD_25_25 and LVD_35_35 maneuvers. The center and right offset SV braking onsets were also different for the LVS_20_0 and LVS_25_0 maneuvers.

With two exceptions, the Volvo S90 braked sooner when it was directly behind the POV than when the POV was offset to the left or right. The center and right offset SV braking onsets were not different for the LVM_25_10 and LVM_35_20 maneuvers.

The Nissan Leaf SV braking onset TTCs were substantially similar among the three offset positions, therefore no significant differences were detected for any tests.

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Research Objective

This report compares the FCW and SV braking onset timing during tests where the SV was laterally aligned behind a POV to that observed when the POV was offset to the left or right in the travel lane by half its width. Three rear-end crash scenarios, three SVs, and three driving automation levels were used.

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Test Protocol

Principal Other Vehicle

The POV used for the work described in this report was the Dynamic Research, Inc.,[1] guided soft target system. The GST has two main parts, the low-profile robotic vehicle shown in Figure 1, and the global vehicle target, shown in Figure 2.

Figure 1. LPRV

Figure 2. GVT (revision E) atop the LPRV

Low-Profile Robotic Vehicle

The LPRV contains the batteries, drive motors, GPS receiver, and most of the control electronics for the GST system, which facilitates closed-loop control of the GVT position relative to that of the SV. It is approximately 110” L × 60” W × 4” H (2.8 m × 1.5 m × 0.1 m), weighs just over 700 lb (318 kg), and can be driven over by most passenger cars and heavy vehicles with axles loaded up to 20,000 lb (9,071.8 kg). The LPRV has a pneumatic suspension that compresses when 150 lb (68 kg) or more is applied to the top of the platform, a feature that allows the chassis (not the LPRV suspension) to take the full force of being run over by the SV. Nominal

[1] Dynamic Research, Inc., Torrance, CA.

performance parameters include a top speed of 50 mph (80 km/h); a maximum longitudinal acceleration and deceleration of 0.12g (1.18 m/s^2) and 0.8g (7.8 m/s^2), respectively; and a maximum lateral acceleration of 0.5g (4.9 m/s^2). In case of an emergency condition, the LPRV can be stopped at any time either by the GST operator (who typically resides in the SV) or by an external "remote safety officer" using a redundant handheld controller.

Global Vehicle Target

The GVT is secured to the top of the LPRV using hook and loop fasteners, which separate upon an SV-to-GVT collision. Internally, the GVT consists of 39 vinyl-covered foam pieces (also held together with hook and loop fasteners) that form the structure to which the skins are attached. When the GVT is hit at low speed, it is typically pushed off the LPRV but remains assembled. At higher impact speeds, the GVT breaks apart as the SV essentially drives through it. Reassembly of the GVT occurs on top of the LPRV.

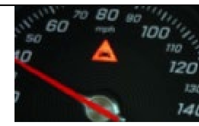
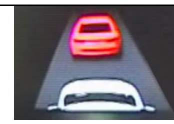
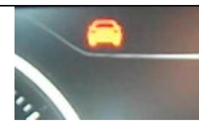
The GVT was designed to appear realistic from any approach direction to the sensors used by contemporary crash avoidance systems: radar (24 and 76-77 GHz), cameras, and lidar. To verify this, five public workshops and three radar tuning meetings were held from August 2015 to December 2016 to provide representatives from the automotive industry with an opportunity to inspect, measure, and assess the realism of the GVT. Feedback from the participants was an essential component of the GVT design process. Workshop and meeting participants used results from the measurements collected with their respective test equipment to provide specific recommendations about how the appearance of the GVT, from the perspective of any sensor, could be improved. When providing these recommendations, participants were asked to consider the balance between realism and practicality. While it is very important for a surrogate vehicle to look as realistic as possible, it must also remain strikeable from any approach angle, over a broad range of impact speeds, without affecting the safety of those using it or harming the vehicle being evaluated; important factors when the surrogate is used in the field.

After feedback from the automotive vehicle manufacturers and suppliers had been incorporated into the design of the GVT (known at the time as revision E), a series of high-resolution radar scans were performed by MTRI using the same equipment previously used to measure the radar characteristics of NHTSA's Strikeable Surrogate Vehicle under NHTSA contract. These measurements provided an independent assessment of how the radar characteristics of the GVT compared to those from four real passenger cars. Using two figures of merit to evaluate the radar measurements (empirical cumulative density functions (CDF) to evaluate target detectability, and high-resolution range profile scans to assess specular scattering), MTRI concluded that a sensor intended for the purpose of detecting vehicles should perform well with the GVT, and that the spatial distribution of the GVT scattering sources was reasonable. Variation of the GVT radar return characteristics present after reconstruction was found to be small (Buller et al., 2017).

Subject Vehicles

Three SVs were used in this study, a 2017 Mercedes E300 4MATIC, a 2018 Nissan Leaf SL, and a 2017 Volvo S90 T6 AWD. Each vehicle was equipped with a branded suite of crash avoidance technologies that use a combination of radar- and camera-based sensors to detect other vehicles in the SV forward path, and an ability to avoid or mitigate rear-end collisions by automatically applying the brakes. All three vehicles were equipped with driver-selectable ACC settings that can be used to adjust the SV-to-POV headway. For the LVM and LVS tests performed in this study, the farthest ACC headway was selected (i.e., the most conservative setting). Sensor details and FCW alert iconography are provided in Table 1. Additional vehicle details are provided in the following sections, and in Tables 13 and 14 of Appendix A.

Table 1. Subject Vehicles, Sensing Technologies, and Display Iconography

Subject Vehicle	**Sensing Technology**		**FCW Visual Alert**
	Radar	**Vision**	
2017 Mercedes E300 4MATIC	Two SRR (24 GHz) One LRR (77 GHz)	Stereo-cameras	
2018 Nissan Leaf SL	One LRR (77 GHz)	Mono-camera	
2017 Volvo S90 T6 AWD	One LRR (77 GHz)	Mono-camera	

2017 Mercedes E300 4MATIC

The 2017 Mercedes E300 4MATIC is an all-wheel drive, 4-door passenger car equipped with the Premium 3 Package option, which includes active brake assist (FCW and an automatic emergency brake[2] system), Distance Pilot DISTRONIC (an ACC system), and active lane keeping assist (ALKA, an LCC system). When both Distance Pilot DISTRONIC and ALKA are activated together, the vehicle is capable of being operated in driving automation level 2.

The Mercedes E300 brakes had been fully conditioned using the burnishing process defined in the FMVSS No. 135 test procedure (NHTSA, 2005) shortly before the tests described in this study were performed. Therefore, the abbreviated brake burnish defined in the FMVSS No. 126 test procedure (NHTSA, 2011) was used to establish a baseline for the Mercedes E300 brakes prior to testing. This ensured that the condition of the vehicle's foundation brakes was stable and maximized the consistency by which the Mercedes E300 CIB braking performance could be assessed.

2018 Nissan Leaf SL

The 2018 Nissan Leaf SL is a compact, all-electric 5-door hatchback equipped with the SL Technology Package option, which includes AEB with pedestrian detection and Nissan's ProPILOT Assist that includes intelligent cruise control (an ACC system) and steering assist (an LCC system). When these features are activated together, the vehicle is capable of being operated with level 2 automated driving.

The Nissan Leaf had two stages of FCW, an initial yellow icon and audible alert without vehicle braking, followed a half second later by a red icon and audible alert with vehicle braking. During

[2] AEB is typically comprised of CIB and dynamic brake support. Both systems address the rear-end crash problem; however DBS activation requires the driver apply the brakes whereas CIB does not.

testing, the SV driver released the throttle at the first audible alert to be consistent with the specifications found in NHTSA's New Car Assessment Program FCW and CIB test procedures (NHTSA 2010; 2015).

The Leaf also had two levels of regenerative braking, which could be selected using the electric shift control (gear selector) located in the center console. The gear selector indicator light is shown the yellow circle in Figure 3. Testing was conducted in the default "D" setting, which has a less aggressive level of regenerative braking than the "B" setting. In addition, the deceleration level associated with regenerative braking was automatically reduced when the battery was fully charged to prevent overcharging (see page 5-134 in the Leaf's owner's manual [Nissan North America, 2018]).

Since the Nissan Leaf's brakes were new prior to this study, a full FMVSS No. 135 brake burnish was performed.

Figure 3. Nissan Leaf shift control and regenerative braking selector

2017 Volvo S90 T6

The 2017 Volvo S90 T6 is an all-wheel drive, 4-door passenger car equipped with City Safety (an AEB system), Volvo Intellisafe (i.e., ACC), and Pilot Assist, a feature that provides lane-keeping steering assistance). When Intellisafe and Pilot Assist are activated together, the vehicle is capable of being operated in driving automation level 2.

The Volvo S90 was the only test vehicle with driver-configurable FCW alert settings. For this study the most conservative FCW setting (i.e., the earliest possible) was used.

Like that used for the Mercedes E300, an FMVSS No. 126 mini-burnish was used to establish a baseline for the Volvo S90 brakes prior to testing since they had also been previously conditioned with a full FMVSS No. 135 brake burnish shortly before the tests described in this study were performed.

Test Scenarios, Speeds, and Level of Driving Automation

The 10 maneuvers used in this study were three rear-end pre-crash scenarios and various SV-to-POV test-speed combinations (see Table 2). Each maneuver was repeated three times for each POV offset position (left, center, right). These 30 test conditions were then evaluated at driving automation levels 0 (no automation; e.g., CIB only), 1 (ACC enabled), and 2 (ACC plus LCC enabled) as the technology allowed (e.g., certain ACC systems did not operate at 15 mph (24.1 km/h)).

*Table 2. Test Scenarios and Speeds Used to Elicit AEB Responses (*n*=3 per test condition)*

Pre-Crash Test Scenario	Nominal Test Speeds in mph (km/h)	
	SV	POV
Lead Vehicle Stopped (LVS)	15 (24.1)	0
	20 (32.2)	0
	25 (40.2)	0
Lead Vehicle Moving (LVM)	25 (40.2)	10 (16.1)
	35 (56.3)	10 (16.1)
	35 (56.3)	20 (32.2)
	45 (72.4)	20 (32.2)
Lead Vehicle Decelerates (LVD)	15 (24.1)	15 (24.1)
	25 (40.2)	25 (40.2)
	35 (56.3)	35 (56.3)

The test maneuvers used for this study were based on those specified in the 2015 NHTSA NCAP CIB test procedure (NHTSA, 2015) but were adjusted to include a greater number of SV and POV speed combinations and fewer repeated trials per test condition (three rather than seven). In this report, the convention used to describe a particular test condition is scenario abbreviation (i.e., LVS, LVM, LVD), followed by SV speed, POV speed, and driving automation level. For example, a test performed using the LVD test scenario with the SV and POV both traveling at an initial speed of 25 mph (40.2 km/h), and the SV operating in driving automation level 0, is referred to as an "LVD_25_25 L0" test in this report.

NHTSA's 2015 NCAP CIB test procedure also provided guidance on test conduct, particularly with normalizing the input conditions so as not to unduly influence test outcome. For the research described in this report, the validity period (an interval during which test tolerances must be respected) was taken to begin at least 3 seconds before an FCW alert and/or SV braking occurred (while the SV was being operated at steady state), and concluded at the time of SV-to-POV impact or 2 seconds after the SV came to a stop.

To ensure the tests were accurately performed, the following tolerances were observed during the validity period for test performed in driving automation level 0 with the POV centered in the lane.

- SV and POV speed: ±1.0 mph (±1.6 km/h) using smooth accelerator pedal inputs
- SV yaw rate: ±1.0 deg/s
- Lateral distance between the centerlines of the SV and POV: ±1 ft (±0.3 m)

Additionally, the average POV deceleration during the LVD scenarios was 0.3g ± 0.03g (2.9 m/s^2 ± 0.29 m/s^2) during an interval from 1.25 ± 0.25s after the POV brakes were applied to 250 ms before the POV stopped. SV to POV headway distance was 45.3 ft (13.8 m) ±8 ft (±2.4 m) for all LVD test speeds.

Certain test tolerances were removed when the SV was operating in driving automation levels 1 or 2 if the SV controlled those aspects of vehicle performance. For driving automation level 1, speed and accelerator pedal inputs were controlled by the SV for all scenarios, while the SV to POV headway distance was controlled during the LVD scenario. For driving automation level 2, lane position and yaw rate, which were controlled by LCC for all scenarios, were added to the list of 1 test tolerances to be removed.

For the left and right POV offset tests, the lateral distance between the SV and POV centerlines was displaced half the width of the POV (2.5 feet) in the direction of the offset. The tolerance remained at ±1 ft (±0.3 m) about the respective offset.

POV Offset

A determination of whether POV offset affects FCW and/or CIB performance has been part of the Euro NCAP Test Protocol for AEB systems (Euro NCAP, 2017) since January 2018 (see Figure 4 for the varying amounts of POV to SV overlap used). In this protocol, Page 5, Section 3.3.1 states:

> The lateral overlap is defined as a percentage of the width of the VUT[3] overlapping the GVT, where the reference line for the overlap definition is the centerline of the VUT. In case of 100 [percent] overlap, the centerlines of the VUT and GVT are aligned.

[3] vehicle under test

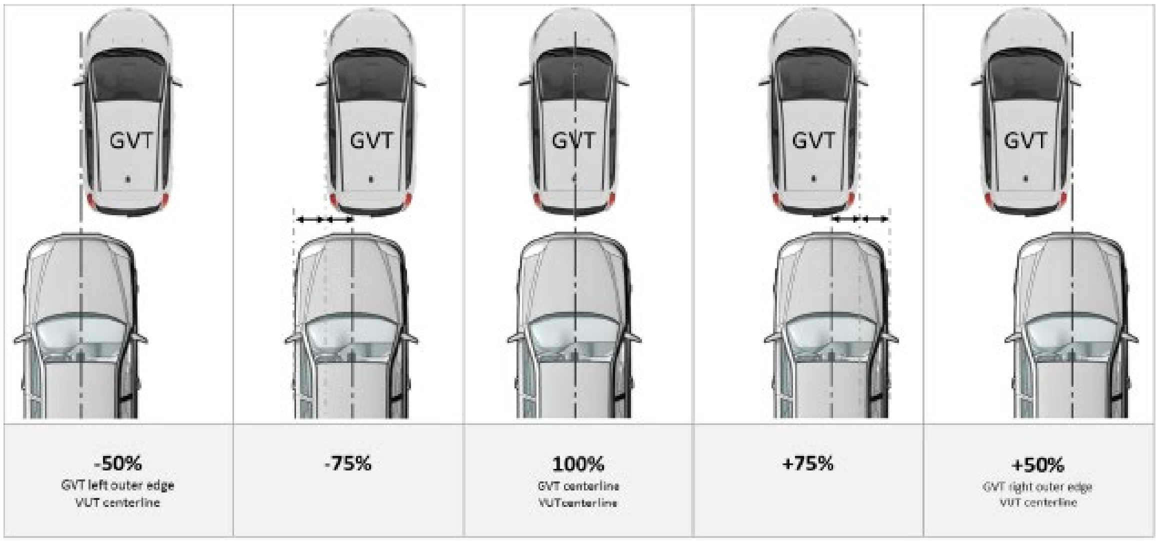


Figure 4. Lateral overlap of the VUT and GVT from the Euro NCAP AEB test procedure

Although the position of the test vehicle relative to the lane was not explicitly defined, it can be inferred from topographical views (shown in Figure 5) that the GVT remained in the center of the lane and the VUT was repositioned to achieve the desire overlap.

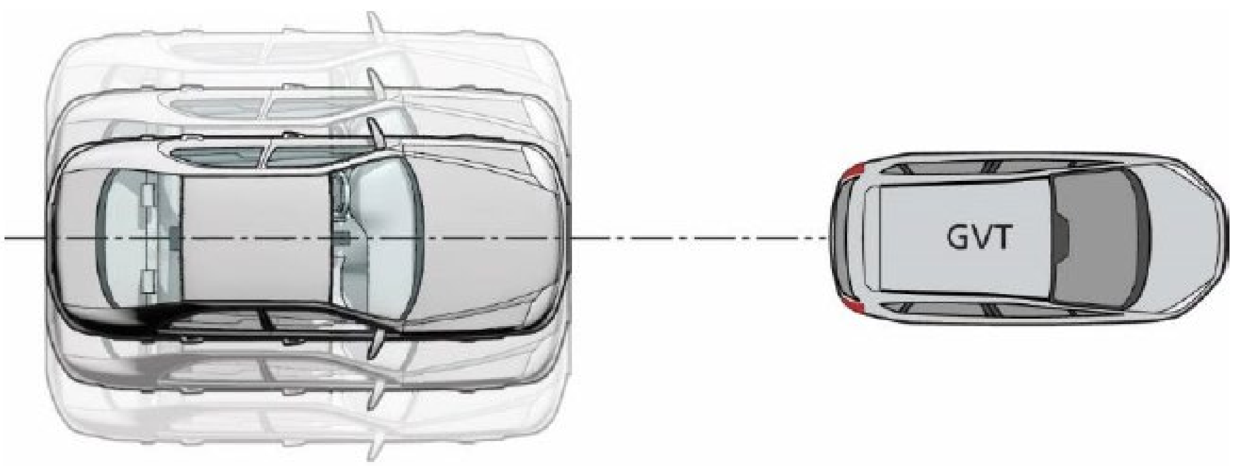


Figure 5. Relative lane position of VUT and GVT from the Euro NCAP AEB test procedure

Unlike those specified within the Euro NCAP protocol, the tests performed in this study included tests with the SV operating in driving automation levels 0, 1, and 2. This is an important distinction since the SV can be expected to operate at or near the center of the SV travel lane during the tests performed using driving automation level 2. This attribute required the POV (not the SV) be laterally displaced during the offset POV tests.

Therefore, to retain consistency among the tests performed with each level of driving automation, the POV offset condition used for the tests described in this report required one side of the POV to be aligned with the travel lane centerline and the SV remain centered in the lane, as shown in Figure 6 (comparable offset magnitude to the 50 percent overlap condition used by Euro NCAP). Tests directly comparable to the Euro NCAP 75 percent overlap tests were not run.

For the remainder of this report, POV offset position has been added to the end of the maneuver naming convention used to describe the test results: scenario, SV speed, POV speed, driving automation level, and POV offset position. Using the example from the previous section, if that example test was performed with the POV centered in the lane, the results for that test condition would be described as an "LVD_25_25 L0 center" test in this report.

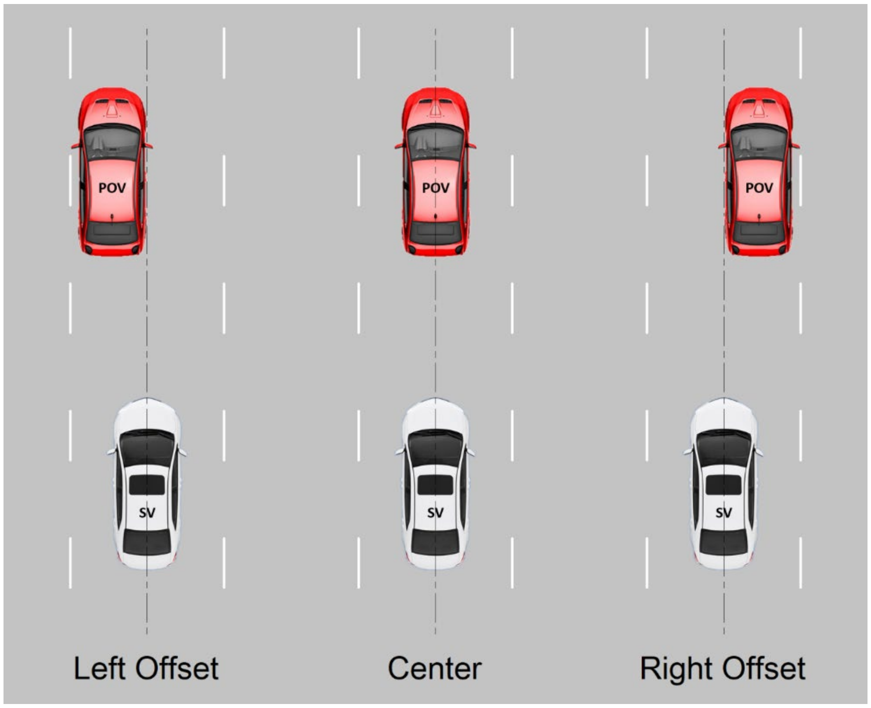


Figure 6. POV offset as used in this research (with black centerlines)

Comparison Metrics

Two metrics were used to compare the SV response to the POV: FCW alert onset (FCW onset) and when the SV deceleration first became equal to or greater than 0.25g (SV braking onset). These metrics are practical because they are easily obtained, and objective because the SV response to a crash-imminent rear-end scenario, when operating in driving automation level 0, is typically comprised of an FCW alert followed by SV braking (i.e., measurable attributes). When operating in driving automation levels 1 or 2, ACC had sufficient braking authority to satisfy the 0.25g threshold. ACC braking lower than that threshold was not examined in the research described in this report.

Both onset metrics have two parts, a measured attribute and a calculated time to collision (TTC) value. There are three scenario-specific equations used to calculate FCW onset TTC and one for SV braking onset TTC. The three FCW equations can be found in the 2010 FCW NCAP Test Procedure (NHTSA, 2010). Note that the equation used to calculate FCW onset TTC in the LVD scenario has a term that accounts for SV deceleration (a_{SV}). Since SV braking onset occurs, by definition, after the SV has already initiated braking, it is the appropriate equation for calculating SV braking onset TTC for all three scenarios.

For FCW onset, the measured attribute was taken from the auditory portion of the FCW alert. Using data associated with the beginning of the alert (Figure 7 provides three examples), the instantaneous position, speed, and acceleration of the SV and POV were identified and used to derive the respective TTC.

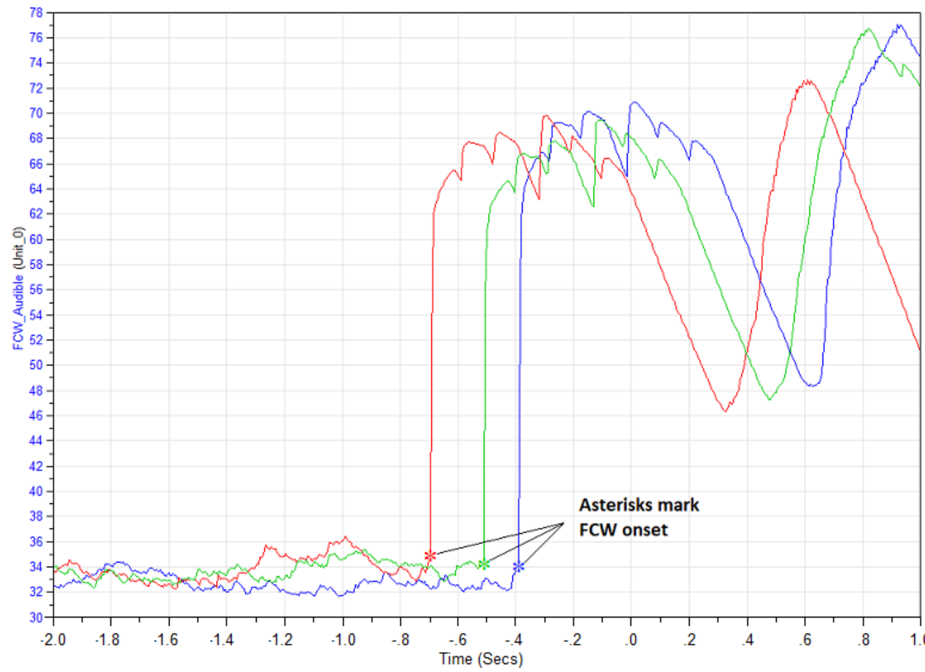


Figure 7. FCW audible alerts plotted over time (onset data count marked with an asterisk)

For SV braking onset, the measured attribute was taken from the SV deceleration channel. The first data count where deceleration was equal to or greater than 0.25g was taken to be the beginning of the SV brake application (Figure 8 provides three examples). The position, speed, and acceleration of the SV and POV were found at that identical point in time and then used to derive the TTC for SV braking onset.

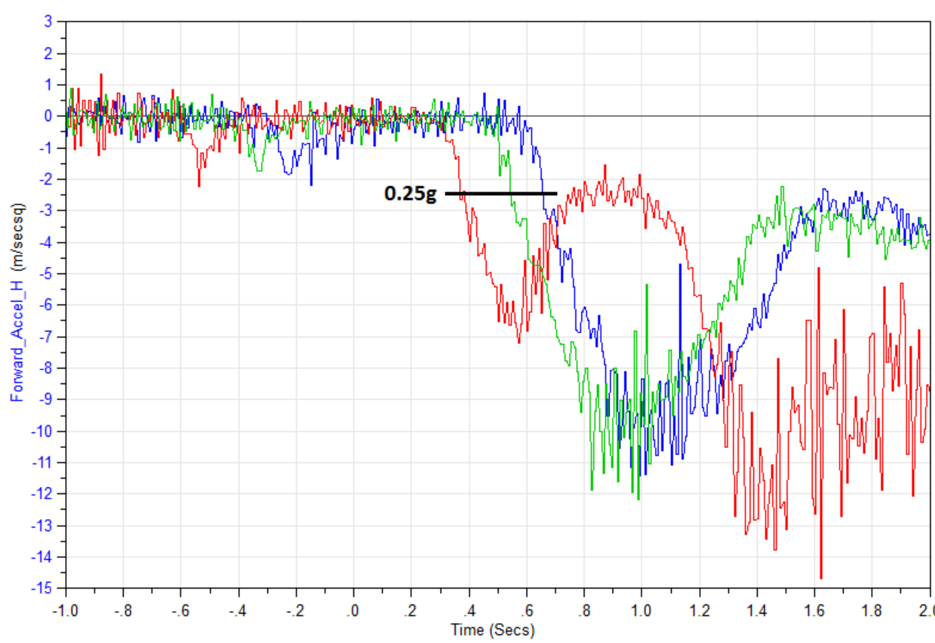


Figure 8. Forward acceleration plotted over time (SV braking onset threshold marked with a line)

Using SV Braking Onset Instead of CIB Onset

In the analyses of SV braking onset TTCs, it is important to distinguish between the two ways by which an SV could potentially reach or exceed 0.25g (2.45 m/s^2) while braking. In the 2015 NHTSA NCAP CIB procedure upon which the research described in this report was based, the threshold for CIB onset is defined as equal to or greater than 0.25g. For the work described in this report, this is problematic since it is not appropriate to classify ACC-based braking that exceeds 0.25g as a CIB intervention, nor is it acceptable to simply raise the SV braking onset threshold to a level ACC would never exceed since this would misrepresent the true onset of the SV brake application in time. This is why "SV braking onset" was adopted for this research.

Generally speaking, when the SV was being operated in driving automation levels 1 or 2, its ACC would initiate gradual braking early in the pre-crash timeline.[4] It was often the case that the SV deceleration never exceeded 0.25g while braking this way. In contrast, when the SV was evaluated in driving automation level 0 and CIB braking occurred, it was typically initiated late in the pre-crash timeline, abruptly, and of much higher magnitude than that generally associated with ACC. The differences associated with CIB-based braking and ACC-based braking can be seen in Figure 9.

Clockwise from the upper left are four SV parameters (SV speed, SV longitudinal acceleration, FCW alert, and SV to POV longitudinal range) recorded during six LVD tests; three performed with driving automation level 0, and three with level 1. Note that although the deceleration profile of the tests performed in driving automation level 1 (early and gradual, shown in green) is markedly different than that of the tests performed in level 0 (later and abrupt, shown in blue), all tests produced deceleration magnitudes high enough to breach the 0.25g threshold used to define the onset of SV braking.

[4] Exceptions to this generalization are more fully explained in SV Braking Onset Activity in Driving Automation Levels 1 and 2, below.

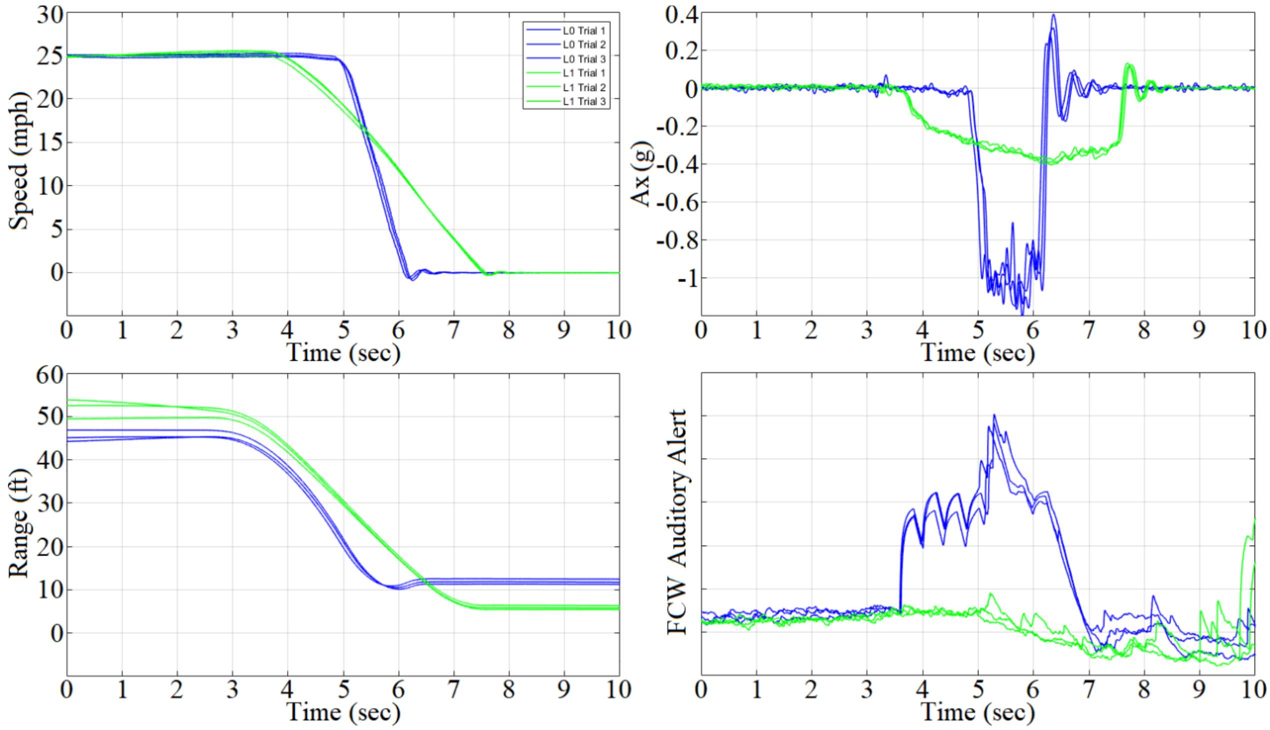


Figure 9. Mercedes E300 LVD_25_25 centered POV test data – driving automation level 0 (blue) and 1 (green)

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Test Results

The results provided in this chapter are presented in four sections. The first explains adjustments made to the testing process to integrate the use of different SV driving automation levels and an offset POV into NHTSA's existing FCW and CIB test protocols. The second describes the analysis approach, while the third and fourth sections examine the FCW and SV braking onset results, respectively. The third, titled Summary of Non-Activations and Impacts is a summary of SV-to-POV impacts.

Test Adjustments Due to SV Driving Automation and POV Offset

For tests performed with driving automation level 0, careful and deliberate throttle and steering inputs were maintained during the validity period that preceded the FCW alert or SV brake application, so as to avoid any confounding effects unintentionally introduced by the manner in which the SV was being operated before responding to the POV. The length of the validity period was at least 3 seconds. A similar approach was used when ACC or ACC plus LCC was enabled, but with the vehicle maintaining some or all of the steady state inputs depending on the level of SV driving automation.

For the LVS and LVM tests performed in driving automation level 1 or 2, the SV driver would accelerate to the test speed, center the vehicle in the lane, and enable either ACC or ACC/LCC. This marked the earliest possible start for the validity period, with the goal of having at least 3 seconds of steady state behavior before ACC began slowing the vehicle in response to the POV.

As previously stated, the LVD test procedures for driving automation level 0 specify that an SV-to-POV headway of 45.3 ft (13.8 m) ±8 ft (±2.4 m) be maintained during the validity period. When the SV was operating in driving automation levels 1 or 2, the ACC headway setting was adjusted to accomplish this. The nearest ACC setting (i.e., that which provided the closest SV-to-POV following distance) was used for the 25 and 35 mph tests (40.2 km/h and 56.3 km/h, respectively), while the setting for the 15 mph tests (24.1 km/h) was usually increased one increment. The actual headway while testing at 35 mph (using the nearest setting) would typically be at or just over the +8 ft (2.4 m) tolerance when ACC was enabled.

LVD testing performed in driving automation level 1 or 2 began with the SV driver maintaining the desired headway while the POV was accelerated to test speed. Once at the desired test speed and headway, the driver would center the vehicle in the lane before enabling ACC or ACC/LLC. For the 35 mph tests, if the nearest ACC setting produced a final headway of 55 ft (for example), the driver would maintain that headway while accelerating up to 35 mph. Once the SV reached 35 mph at 55 ft (in this example), the driver would enable the SV's ACC. For tests when LCC was enabled, it sometimes took the SV a few seconds before the system began to actively manage lane position.[5] Once a stable speed and headway were achieved, and LCC was actively controlling lane position (when enabled), this would mark the earliest possible start for the validity period. Again, the goal was to have at least 3 seconds of steady state behavior before ACC began slowing the vehicle.

[5] In the case of the Nissan Leaf, LCC had to be engaged at 37 mph (59.5 km/h) to initialize (NHTSA, 2015, page 5-31). After it began actively managing lane position, the driver would lower the ACC by 2 mph (3.2 km/h).

Analysis Approach

A "box-and-whisker" plot (box plot) format was selected to compare the various groups of onset TTCs to provide a good visual overview of how the distribution of data from the three POV offsets relate to one another. The box plots were generated in SAS using the generalized linear model (GLM) procedure. Additional details regarding box plots can be found in the Appendix section titled Interpreting Box Plots.

Data analysis began by reviewing sets of box plots made for each scenario by speed combination, for each SV and SV driving automation level. The purpose of examining smaller data sets first was primarily to look for patterns in the SV's onset TTC response and, to a lesser extent, how different the responses were. Knowing this provided an indication which test speeds within a scenario could be combined for additional analysis.

For example, recall that the LVD scenario was performed with 15_15, 25_25, and 35_35 mph test speed combinations. Figures 10, 11, and 12 present SV braking onset box plots for the three Volvo S90 LVD speed combinations for tests performed with driving automation level 0. The pattern that emerged in the three plots was similar regardless of speed, showing that the Volvo S90 began braking sooner[6] when it was directly behind the POV than for when the POV was offset to the left or right.

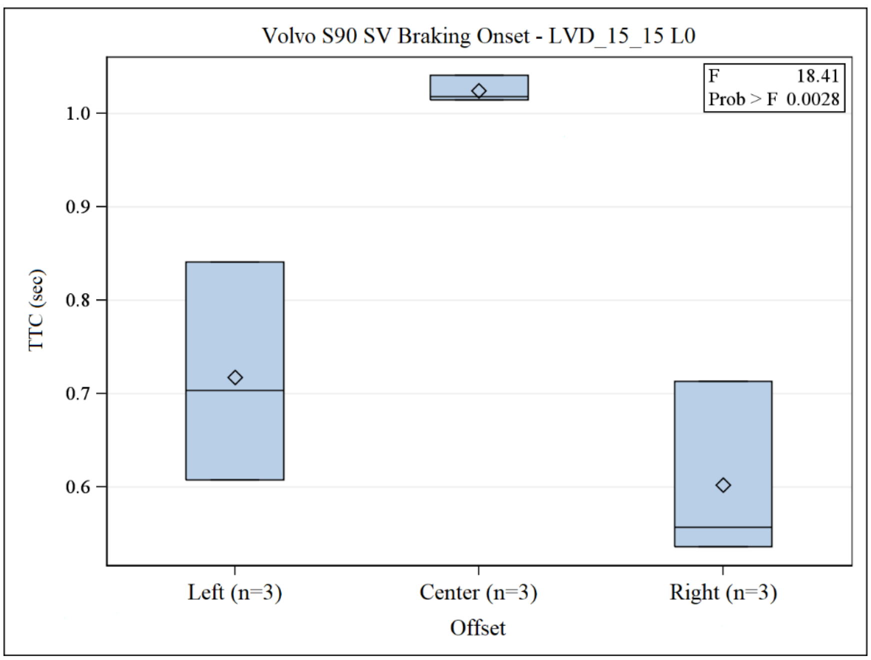

Figure 10. Volvo S90 LVD_15_15 driving automation level 0 SV braking onset TTCs

[6] As a rule, the higher the TTC, the earlier in time the event occurred.

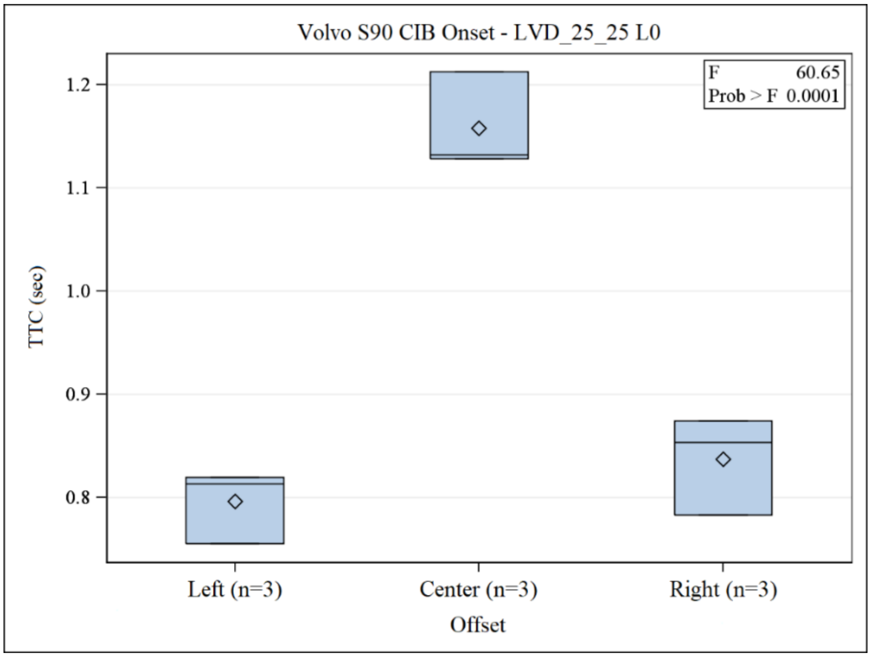

Figure 11. Volvo S90 LVD_25_25 driving automation level 0 SV braking onset TTCs, with center responses highlighted

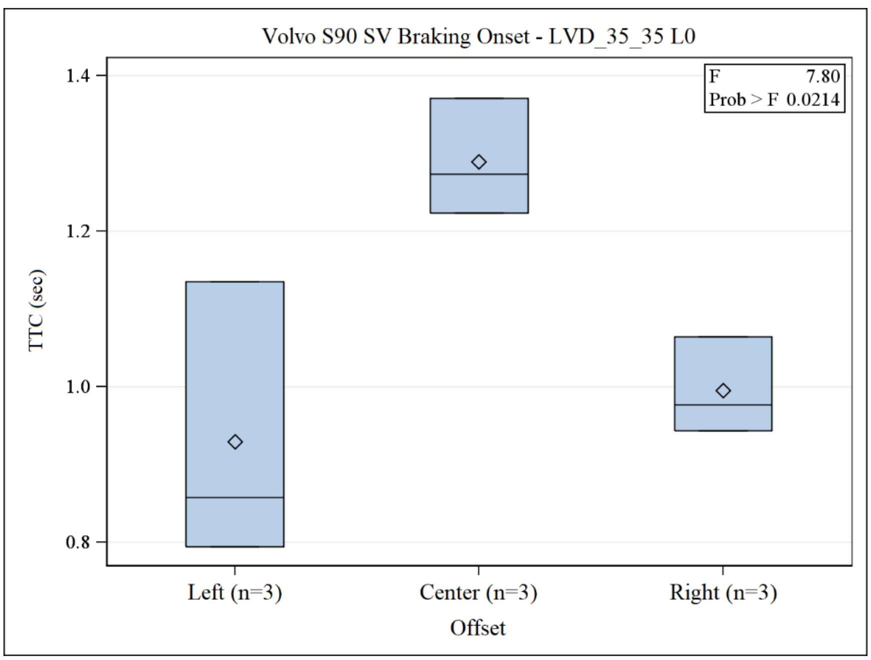

Figure 12. Volvo S90 LVD_35_35 driving automation level 0 SV braking onset TTCs

The similarity of the SV braking onset TTCs show that, in this case, the data sets produced by each test speed combination could be combined into a larger data set without losing any potentially significant effect. The process of combining smaller data sets into a larger one is also called “collapsing,” where the dependent variable (SV braking onset TTC) is being measured at different levels of one independent variable (SV-POV speed in this case). Pooling similar data from several speeds (i.e., collapsing across speed within scenario) is statistically advantageous.

Larger sample sizes make for stronger and more convincing analyses because it increases the probability of detecting a difference between groups when one exists, which is the objective of this research.

Going forward, SV braking onset data within a scenario was always combined if they had a similar pattern. This includes data that were not significantly different, since combining several non-significant results will not alter that conclusion. However, data with dissimilar patterns were not combined. In other words, significantly different onset TTCs were not combined with data that were not significantly different to avoid obscuring the significance of the first data set.

Figure 13 contains box plots of the combined data from the three Volvo S90 LVD driving automation level 0 speed combinations previously plotted in Figures 10, 11, and 12. It is an example of how combining similar data within a scenario is beneficial; sample size increased threefold while a significant difference between the left, center, and right offset positions ($p<.0001$) was shown to exist in the SV braking onset TTCs for the combined LVD driving automation level 0 data set. It is apparent from the box plots that the Volvo S90 began braking sooner when it was directly behind the POV than when the POV was offset to the left or right.

To prove which offset TTCs were different using statistics required a post hoc examination of the least-square means (LSMeans), which estimated the individual means of the onset TTCs for each offset position and assigned a unique significance level between the three pairwise comparisons (left to center, left to right, and center to right). In this example, LSMeans verified that the left and right SV braking onset TTCs were significantly different from the center SV braking onset TTCs, but not different from each other. Going forward, if the combined data was significantly different, LSMeans was used to determine which of the three offset positions were significantly different from each other.

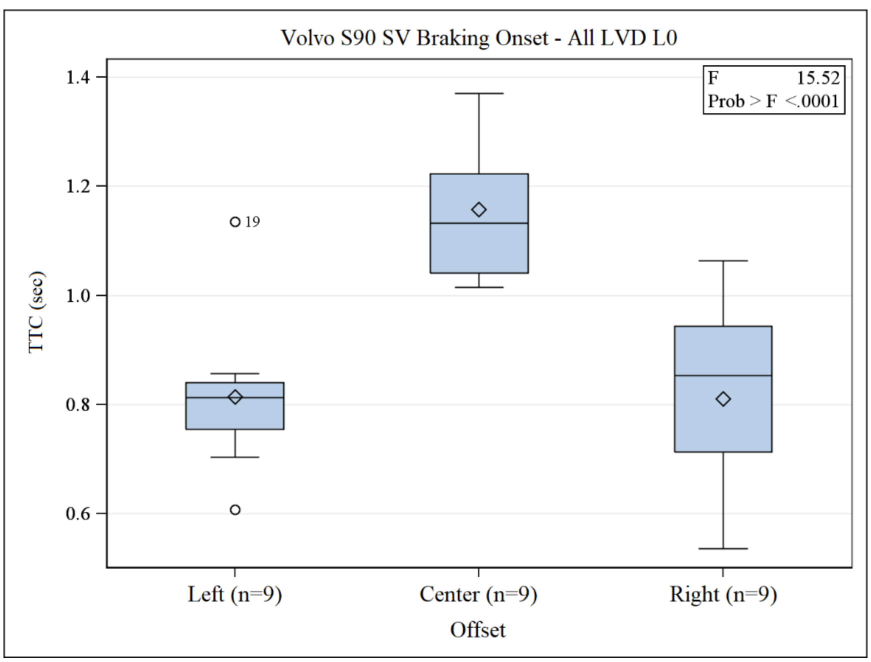

Figure 13. Volvo S90 LVD driving automation level 0 SV braking onset TTCs, collapsed across speed

Analyzing and Reporting FCW Onset Activity

FCW onset data occurred primarily when the SV was operated in driving automation level 0, since ACC usually slowed the SV well in advance of a potential SV-to-POV impact. For this reason, the absence of an FCW alert during an driving automation level 0 test is described as an FCW non-activation, whereas the presence of an FCW alert during a test performed in level 1 or 2 is described as an FCW activation. FCW onset activity in the driving automation level 1 or 2 test conditions were vehicle and/or scenario dependent.

SV Braking Onset Activity in Driving Automation Levels 1 and 2

The Comparison Metrics section above drew distinctions between the deceleration profiles of tests performed in driving automation level 0 with those performed in levels 1 or 2. However, exceptions to these generalized deceleration profiles were observed when a CIB intervention occurred during a test performed with ACC enabled. In these cases (eight from the Volvo S90 and one from the Nissan Leaf), the SV came to rest late in the pre-crash timeline by way of CIB activation. The similarity of the CIB-based deceleration profiles can be seen in one of the tests plotted in Figure 14.

Clockwise from upper left are SV speed, SV longitudinal acceleration, FCW alert, and SV to POV longitudinal range recorded during six LVS tests. In the red zoomed-in area, note that the deceleration profile of one test performed in driving automation level 1 (shown in green) diverges from the two ACC-based decelerations (also in green) and followed the deceleration profiles of the tests performed in driving automation level 0 (shown in blue).

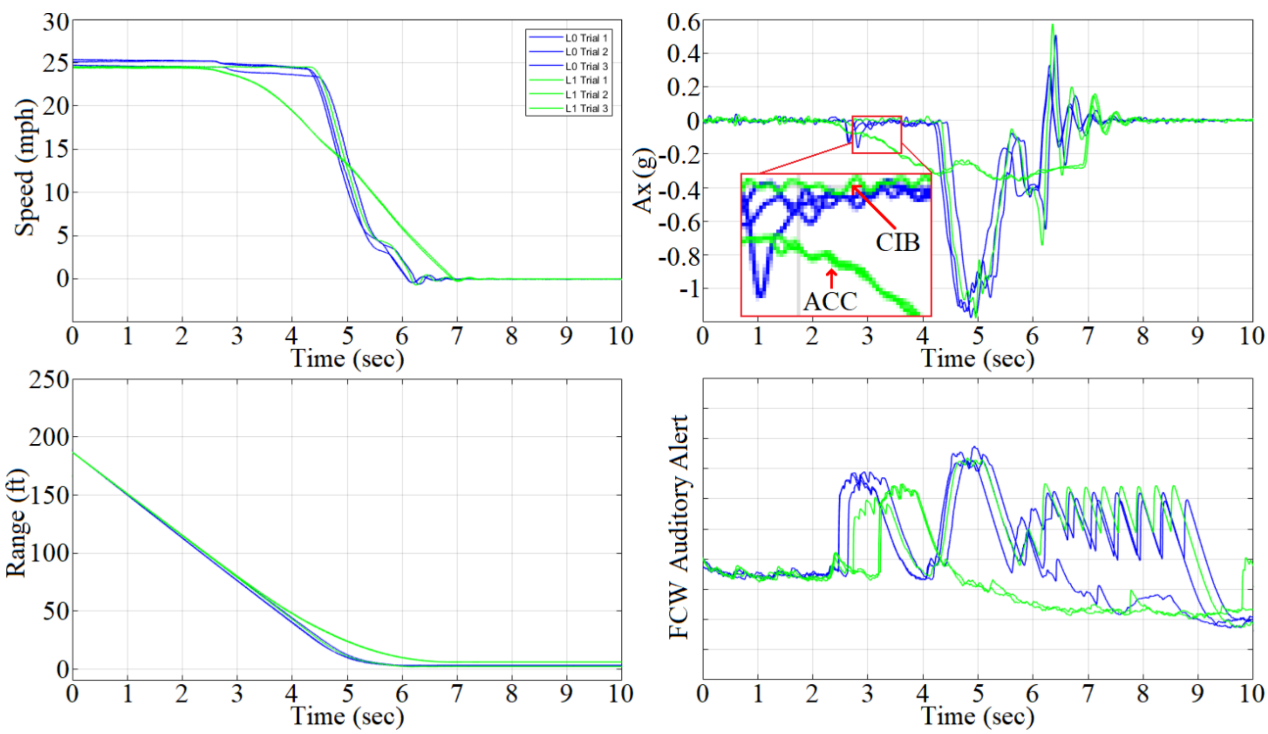

Figure 14. Braking observed during six Volvo S90 LVS_25_0 left offset trials

Going forward, the presence of a CIB-based deceleration (i.e., late and abrupt) when ACC was enabled will be described as an ACC non-activation.[7] Those late SV braking onset TTCs (i.e., numerically lower) appear in the SV braking onset TTC Tables (marked by footnotes) but were not used in the box plot analyses. Additional details regarding ACC non-activations can be found in the Analyzing SV Braking Onset Activity section in Appendix A.

FCW Onset Responses

This section examines the FCW onset TTC results. The range of FCW onset TTCs are first presented in a table, then followed with box plots of each vehicles' FCW onset TTCs by scenario, collapsed across speed within that scenario. The Mercedes E300, Nissan Leaf, and Volvo S90 results are presented in the Test Results sections above. The Test Results chapter above summarizes them.

Mercedes E300

The range of FCW onset TTCs for the Mercedes E300, for each combination of scenario, test speed, and POV offset position, are presented in Table 3. The FCW alerts only occurred when the SV was operated in driving automation level 0. The Mercedes E300 issued an FCW alert for all tests performed in driving automation level 0; i.e., there were no FCW non-activations regardless of scenario, speed, driving automation level, and POV offset combination.

For all driving automation level 0 scenarios and test speeds, the range of FCW onset TTCs were substantially similar across the three POV offset positions, which can be seen in the three box plots presented in this section. Incidentally, the LVS and LVM data do show that as SV to POV closing velocity increased, so did the FCW onset TTCs. For the LVD scenario, the FCW onset TTCs increased with increasing test speed combinations. While this is outside the scope of the research, it is noted here to demonstrate the sensitivity of the data collection process.

The Mercedes E300 FCW onset data from the LVS scenario was collapsed across speed, creating a sample size of n=9 for each offset position. The box plots in Figure 15 show that there were no significant differences in FCW onset between the left, center, and right offset positions ($p=0.9905$) for the LVS scenario.

[7] Referring only to the braking aspect of an ACC test; ACC correctly managed SV test speeds throughout testing.

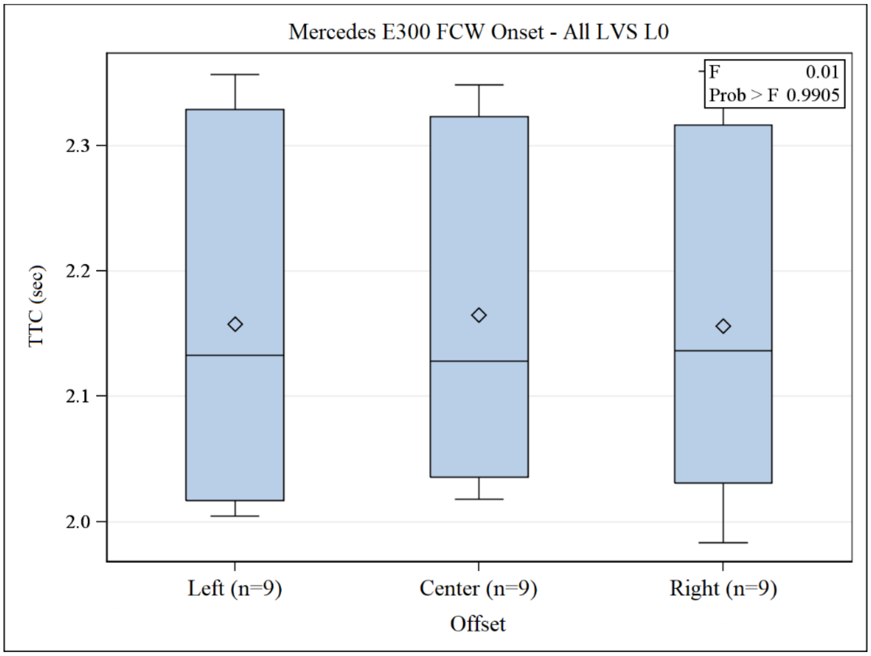

Figure 15. Mercedes E300 LVS driving automation level 0 FCW onset TTCs, collapsed across speed

The Mercedes E300 FCW onset data from the LVM scenario was also collapsed across speed, which created a sample size of n=12 for each offset position. The box plots in Figure 16 show that there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.9464) for the LVM scenario.

Table 3. Range of Mercedes E300 FCW Onset TTCs

Crash-imminent Test Conditions			Range of Mercedes E300 FCW Onset TTCs								
Pre-Crash Scenario	**Test Speeds (mph)**		**Driving Automation Level 0**			**Driving Automation Level 1**			**Driving Automation Level 2**		
	SV	**POV**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**
Lead Vehicle Stopped (LVS)	15	0	2.00 – 2.02	2.02 – 2.04	1.98 – 2.03	–	–	–	–	–	–
	20	0	2.09 – 2.15	2.09 – 2.15	2.11 – 2.14	–	–	–	–	–	–
	25	0	2.33 – 2.36	2.32 – 2.35	2.32 – 2.36	–	–	–	–	–	–
Lead Vehicle Moving (LVM)	25	10	2.11 – 2.14	2.10 – 2.12	2.13 – 2.14	–	–	–	–	–	–
	35	10	2.71 – 2.76	2.72 – 2.76	2.75 – 2.84	–	–	–	–	–	–
	35	20	2.50 – 2.57	2.51 – 2.52	2.51 – 2.58	–	–	–	–	–	–
	45	20	2.79 – 2.92	2.89 – 2.93	2.92 – 2.96	–	–	–	–	–	–
Lead Vehicle Decelerates (LVD)	15	15	1.94 – 1.98	1.95 – 2.02	1.94 – 1.95	–	–	–	–	–	–
	25	25	2.16 – 2.29	2.16 – 2.21	2.16 – 2.30	–	–	–	–	–	–
	35	35	2.22 – 2.28	2.20 – 2.34	2.28 – 2.29	–	–	–	–	–	–

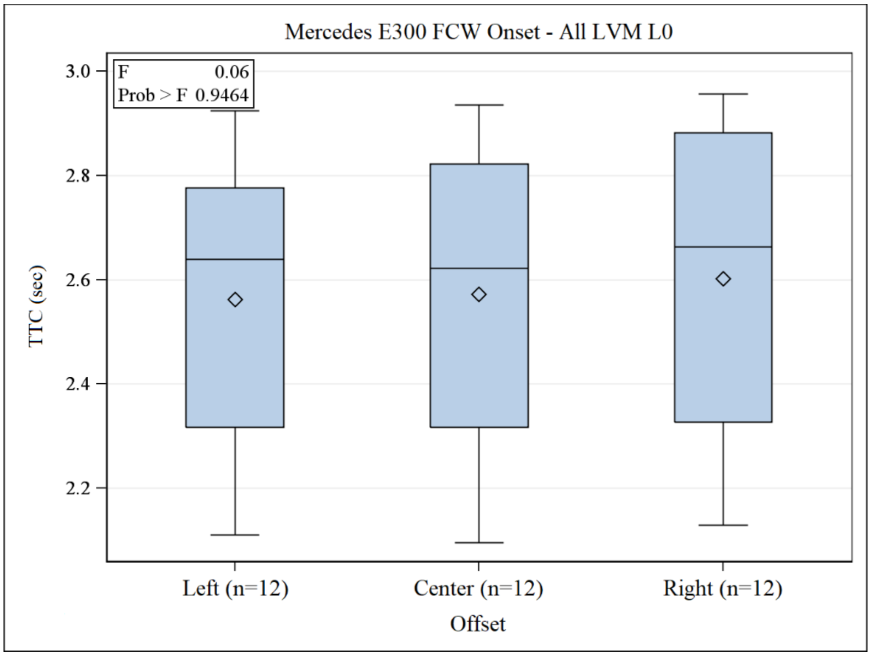

Figure 16. Mercedes E300 LVM driving automation level 0 FCW onset TTCs, collapsed across speed

The substantial similarity of the FCW onset TTCs continued for Mercedes E300 data collected in the LVD scenario. After collapsing across the three LVD test speeds for a total sample size of n=9 for each offset position, there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.9951) for the LVD scenario. The results are shown in Figure 17.

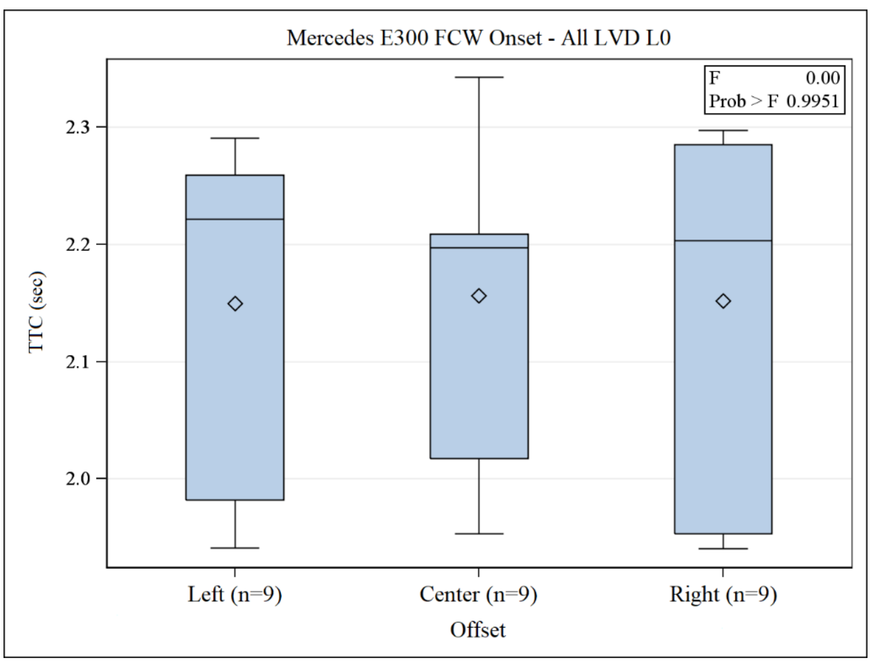

Figure 17. Mercedes E300 LVD driving automation level 0 FCW onset TTCs, collapsed across speed

Nissan Leaf

The range of FCW onset TTCs for the Nissan Leaf, for each combination of scenario, test speed, and POV offset position, are presented in Table 4. The FCW alerts occurred primarily when the SV was operated in driving automation level 0. Due to a testing oversight, the LVM_35_10 L0 left trials were not performed. The LVS_15_0 tests for driving automation levels 1 and 2 were not conducted since they were below the 20 mph (32.2 km/h) ACC activation speed. Testing in driving automation level 2 was limited to maneuvers where the SV was traveling 35 mph (56.3 km/h) or faster.

With two exceptions, the Nissan Leaf issued an FCW alert during all tests performed in driving automation level 0. One LVS_15_0 L0 centered POV test had an FCW non-activation, as did one of the LVM_35_10 L0 centered POV tests. Both tests ended with a CIB non-activation and an SV-to-POV impact. The range of FCW onset TTCs from the Nissan Leaf had substantial similarity across the three POV offset positions for all driving automation level 0 scenarios and test speeds, which can be seen in the three box plots presented in this section.

FCW alerts were observed during two driving automation level 1 tests performed with the Nissan Leaf. One of the LVS_25_0 left offset tests had an ACC non-activation, which lead to an FCW alert and CIB braking. The other occurred during one of the LVS_25_0 centered POV tests.

The Nissan Leaf FCW onset data from the LVS scenario was collapsed across speed, creating a sample size of n=9 for the left and right offset positions. The one FCW non-activation in the LVS_15_0 L0 center condition led to a sample size of n=8. The box plots in Figure 18 show that there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.9425) for the LVS scenario.

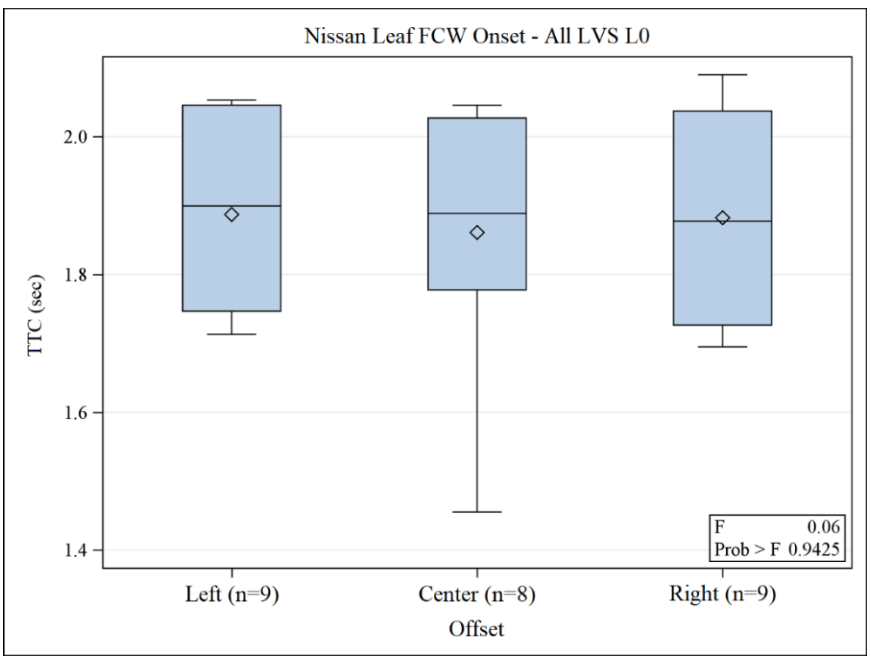

Figure 18. Nissan Leaf LVS driving automation level 0 FCW onset TTCs, collapsed across speed

Table 4. Range of Nissan Leaf FCW Onset TTCs

Crash-imminent Test Conditions			**Range of Nissan Leaf FCW-Onset TTCs**								
Pre-Crash Scenario	**Test Speeds (mph)**		**Driving Automation Level 0**			**Driving Automation Level 1**			**Driving Automation Level 2**		
	SV	**POV**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**
Lead Vehicle Stopped (LVS)	15	0	1.71 – 1.75	1.46 – 1.72[1]	1.69 – 1.73	Below ACC activation level.[3]			Below ACC and LCC activation levels.[6]		
	20	0	1.86 – 1.90	1.84 – 1.90	1.86 – 1.90	–	–	–	Below LCC activation level.		
	25	0	2.05 – 2.05	2.02 – 2.05	2.04 – 2.09	1.41[4]	2.72[5]	–	Below LCC activation level.		
Lead Vehicle Moving (LVM)	25	10	1.92 – 1.97	1.86 – 1.92	1.93 – 1.99	–	–	–	Below LCC activation level.		
	35	10	Not tested.	0.76[2] – 2.47	2.22 – 2.46	–	–	–	–	–	–
	35	20	2.06 – 2.13	2.13 – 2.20	2.13 – 2.17	–	–	–	–	–	–
	45	20	2.57 – 2.69	2.62 – 2.69	2.64 – 2.66	–	–	–	–	–	–
Lead Vehicle Decelerates (LVD)	15	15	1.52 – 1.56	1.55 – 1.61	1.49 – 1.58	–	–	–	Below LCC activation level.		
	25	25	1.83 – 1.90	1.68 – 1.76	1.68 – 1.82	–	–	–	Below LCC activation level.		
	35	35	1.86 – 2.00	1.76 – 1.91	1.91 – 1.97	–	–	–	–	–	–

[1] One impact was observed during the tests performed in this series because the SV did not alert or brake.
[2] This late FCW onset was followed by a late SV braking onset and impact. A second impact was observed in this series because the SV did not alert or brake.
[3] The Nissan Leaf's ACC does not operate below 20 mph (32.2 km/h).
[4] An ACC non-activation lead to an FCW alert and CIB stop.
[5] This was an anomalous event. It is the highest FCW onset TTC observed, and it occurred approximately 1.6 seconds after SV braking onset.
[6] The Nissan Leaf's LCC could not be engaged below 37 mph (59.5 km/h). Once it was engaged however, LCC would continue to operate down to 35 mph (56.3 km/h).

The Nissan Leaf FCW onset data from the LVM scenario was also collapsed across speed, which created sample sizes of 9, 11, and 12 for the left, center, and right offset positions, respectively. The box plots in Figure 19 show that there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.6265) for the LVM scenario.

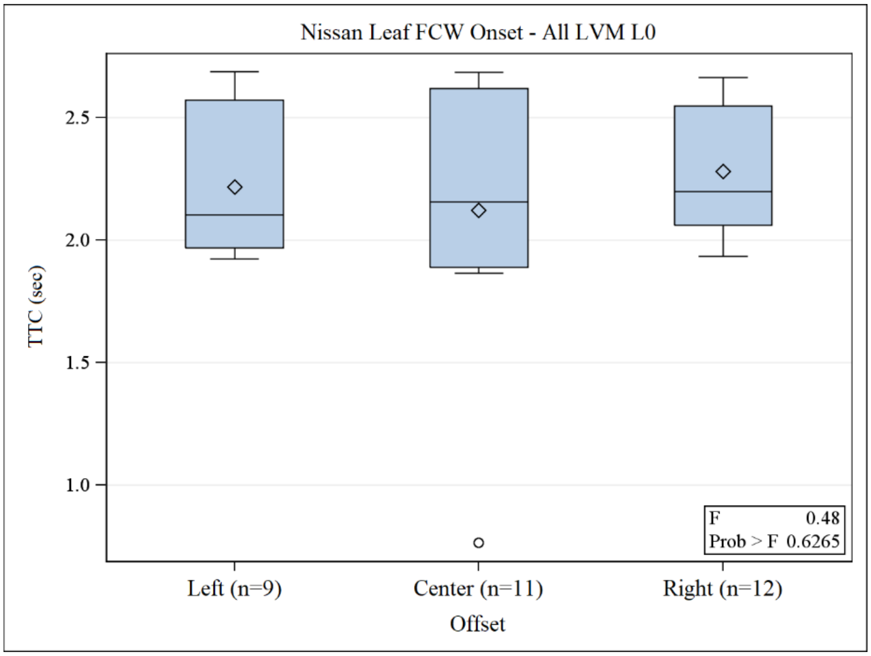

Figure 19. Nissan Leaf LVM driving automation level 0 FCW onset TTCs, collapsed across speed

The FCW onset TTCs for the LVD scenario are plotted in Figure 20. Collapsing across the three LVD test speeds created a sample size of n=9 for each offset position. The results show there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.7440) for the LVD scenario.

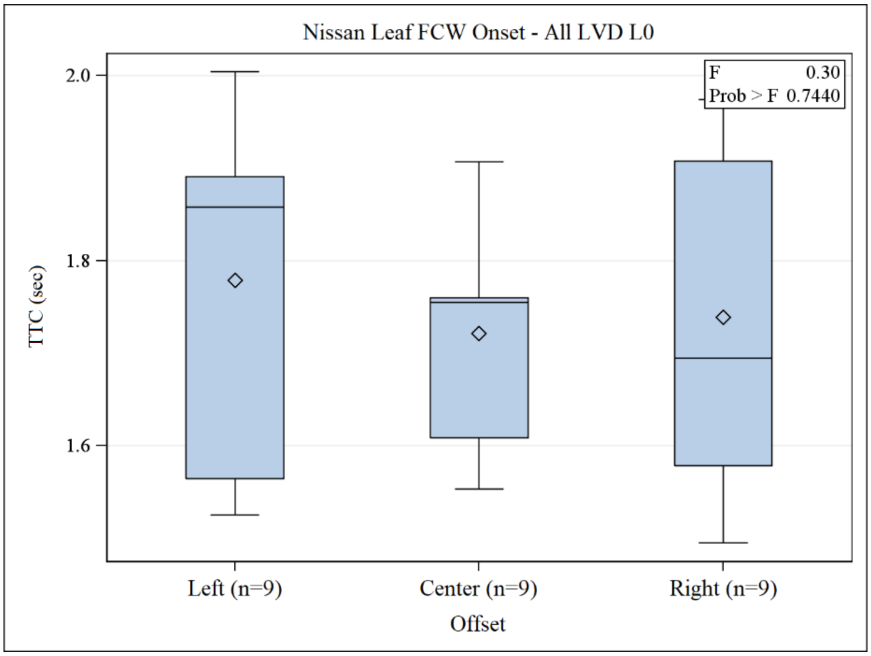

Figure 20. Nissan Leaf LVD driving automation level 0 FCW onset TTCs, collapsed across speed

Volvo S90

The range of FCW onset TTCs for the Volvo S90, for each combination of scenario, test speed, and POV offset position, are presented in Table 5. The Volvo S90 issued an FCW alert for all tests performed in driving automation level 0 (i.e., there were no FCW non-activations). FCW activations were also observed during most of the LVS_25_0 and LVD_25_25 tests performed in driving automation levels 1 and 2. The footnotes that accompany Table 5 detail where those FCW activations occurred.

The range of FCW onset TTCs from the Volvo S90 had substantial similarity across the three POV offset positions for all driving automation level 0 scenarios and test speeds, which can be seen in the four box plots presented in this section.

Driving Automation Level 0 FCW Onset Results

The Volvo S90 FCW onset data from the LVS scenario was collapsed across speed, creating a sample size of n=9 for each offset position. The box plots in Figure 21 show that there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.9984) for the LVS scenario.

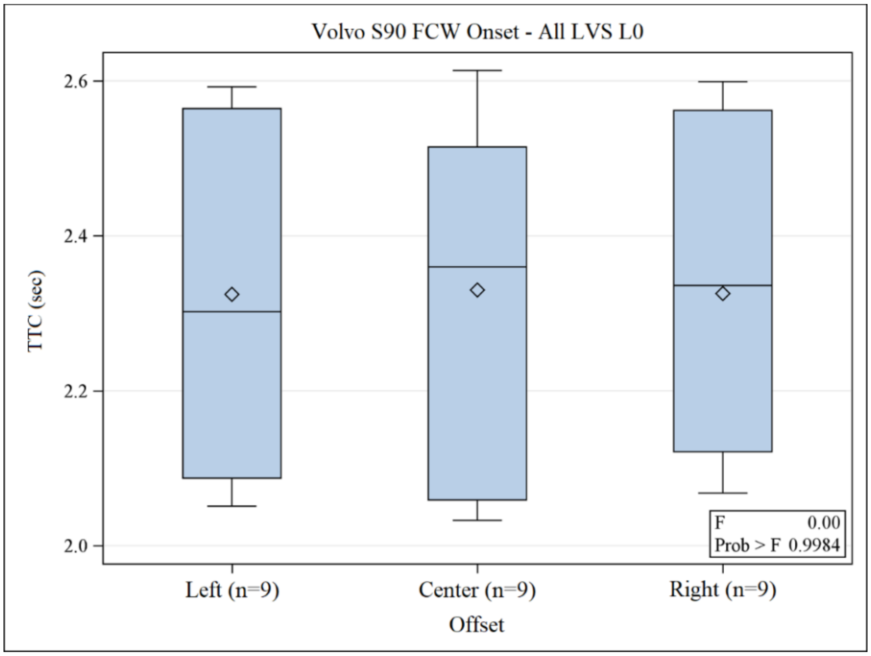

Figure 21. Volvo S90 LVS driving automation level 0 FCW onset TTCs, collapsed across speed

The Volvo S90 FCW onset data from the LVM scenario was also collapsed across speed, creating sample sizes of n=12 for each offset position. The box plots in Figure 22 show that there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.9749) for the LVM scenario.

Table 5. Range of Volvo S90 FCW Onset TTCs

Crash-imminent Test Conditions			Range of Volvo S90 FCW-Onset TTCs								
Pre-Crash Scenario	**Test Speeds (mph)**		**Driving Automation Level 0**			**Driving Automation Level 1**			**Driving Automation Level 2**		
	SV	**POV**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**
Lead Vehicle Stopped (LVS)	15	0	2.06 – 2.09	2.03 – 2.06	2.07 – 2.12	Below ACC activation level.[1]			Below ACC activation level.		
	20	0	2.30 – 2.36	2.35 – 2.38	2.24 – 2.34	–	–	–	–	–	–
	25	0	2.56 – 2.59	2.51 – 2.61	2.56 – 2.60	2.17 – 2.46	2.43 – 2.44[2]	2.19 – 2.45	2.44 – 2.47	2.23 – 2.46	2.17 – 2.47
Lead Vehicle Moving (LVM)	25	10	2.00 – 2.01	1.99 – 2.06	1.98 – 2.06	–	–	–	–	–	–
	35	10	2.66 – 2.77	2.74 – 2.81	2.67 – 2.79	–	–	–	–	–	–
	35	20	2.15 – 2.21	2.21 – 2.28	2.17 – 2.30	–	–	–	–	–	–
	45	20	2.65 – 2.76	2.63 – 2.72	2.65 – 2.74	–	Not tested	–	–	–	–
Lead Vehicle Decelerates (LVD)	15	15	0.83 – 1.08	1.87 – 1.91	1.11 – 1.85	–	–	–	–	–	–
	25	25	1.96 – 2.05	1.93 – 2.03	1.98 – 2.08	2.25 – 2.32	2.21[3]	2.33 – 2.55	2.28 – 2.51[2]	2.23 – 2.34[2]	2.21 – 2.41[2]
	35	35	2.15 – 2.32	2.11 – 2.17	2.23 – 2.28	–	–	–	–	–	–

[1] The Volvo S90's ACC does not operate below 20 mph (32.2 km/h).
[2] Two FCW activations were observed during the tests performed in this series.
[3] One FCW activation was observed during the tests performed in this series.

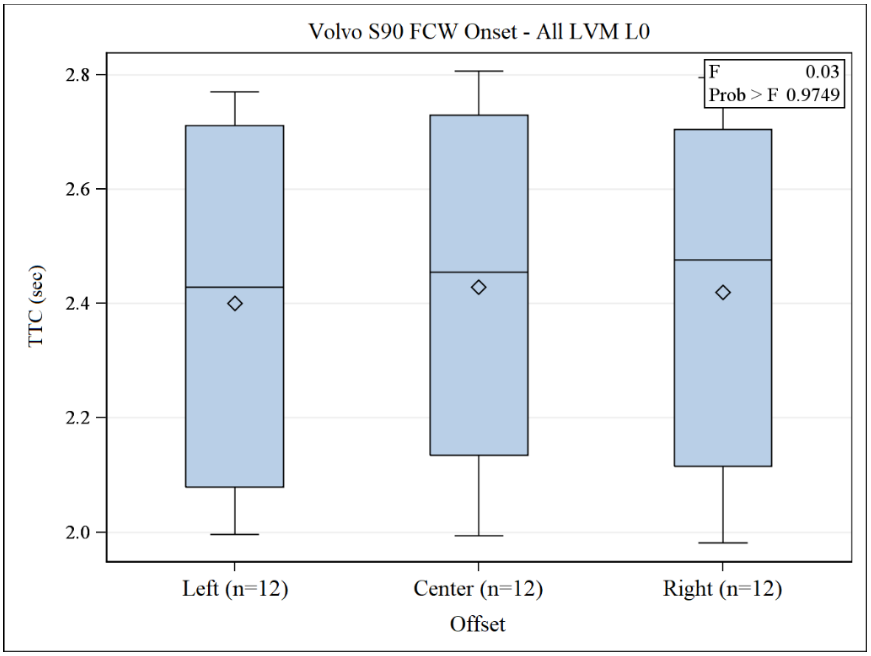

Figure 22. Volvo S90 LVM driving automation level 0 FCW onset TTCs, collapsed across speed

The Volvo S90 FCW onset data from the LVD scenario was collapsed across speed, creating sample sizes of n=9 for each offset position. The box plots in Figure 23 show there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.3946) for the LVD scenario.

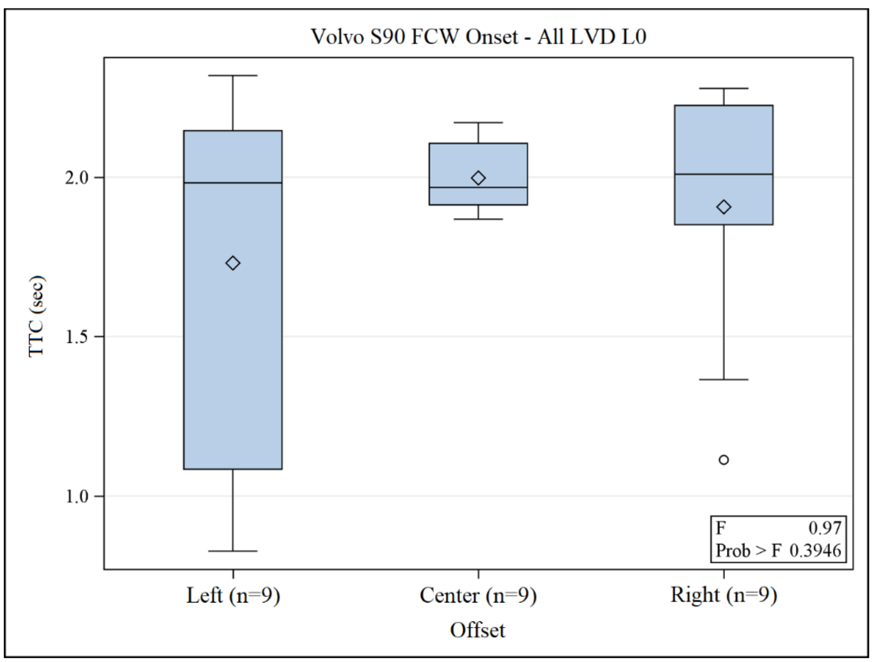

Figure 23. Volvo S90 LVD driving automation level 0 FCW onset TTCs, collapsed across speed

Driving Automation Level 1 and 2 FCW Onset Results

The FCW activations observed during the LVS_25_0 and LVD_25_25 maneuvers are shown in Table 6. From the perspective of test conduct, the primary difference between driving automation levels 1 and 2 was whether the driver or LCC kept the SV centered in the lane. As such, it is appropriate to combine the FCW onset TTCs across level of driving automation for analysis purposes.

Table 6. Location of FCW Activations in the LVS_25_0 and LVD_25_25 Driving Automation Level 1 and 2 Maneuvers

Maneuver	Driving Automation Level	Left	Center	Right
LVS_25_0	1	3/3	2/3	3/3
LVS_25_0	2	3/3	3/3	3/3
LVD_25_25	1	3/3	1/3	3/3
LVD_25_25	2	2/3	2/3	2/3

The Volvo S90 FCW onset data from the driving automation level 1 and 2 LVS maneuvers was collapsed across level of automation, creating a sample size of n=6 for the left and right offset positions and n=5 for the centered POV tests. The box plots in Figure 24 show that there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.3200) for the LVS maneuvers performed with driving automation levels 1 and 2.

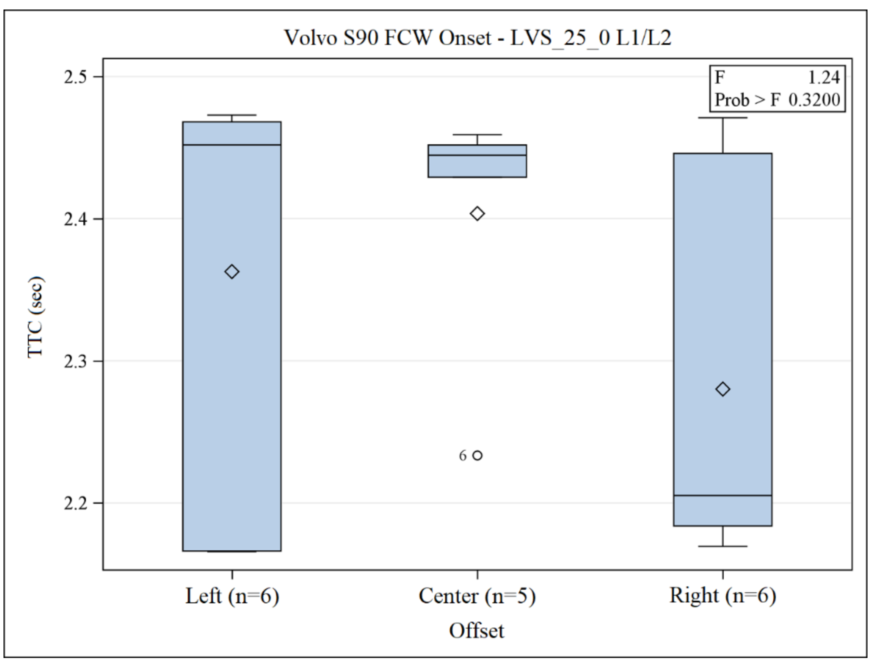

Figure 24. Volvo S90 LVS_25_0 driving automation level 1 and 2 FCW onset TTCs, collapsed across level of automation

The Volvo S90 FCW onset data from the LVD scenarios performed in driving automation level 1 and 2 was also collapsed across level of automation, creating a sample size of n=5 for the left and right offset positions and n=3 for the centered POV tests. The box plots in Figure 25 show that there were no significant differences in FCW onset between the left, center, and right offset positions (p=0.3826) for the LVD scenarios performed in driving automation level 1 and 2.

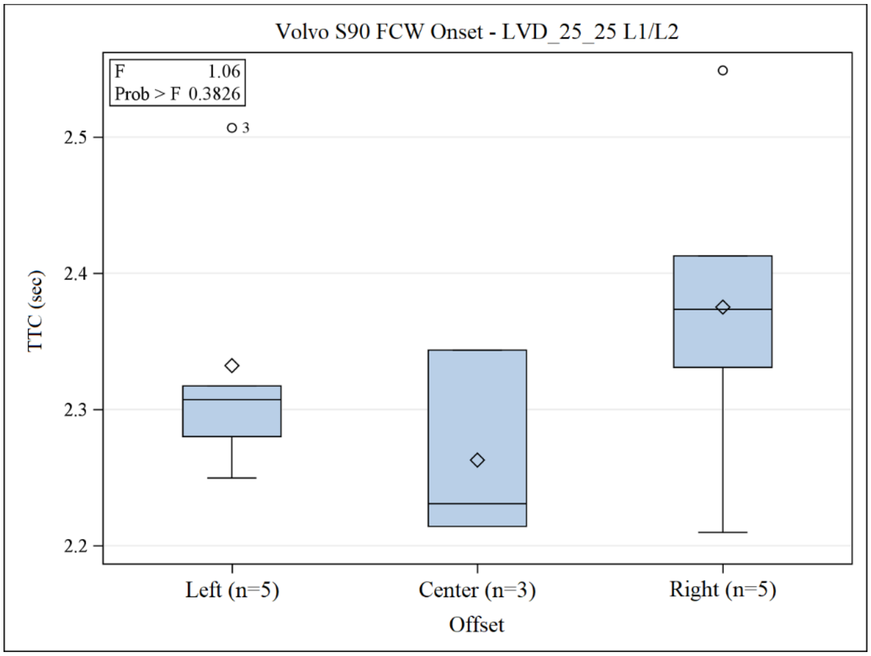

Figure 25. Volvo S90 LVD_25_25 driving automation level 1 and 2 FCW onset TTCs, collapsed across level of automation

FCW Onset Summary

In summary, POV offset did not significantly affect the FCW onset of the Mercedes E300, Nissan Leaf, or Volvo S90 while they were operated in driving automation level 0. Additionally, POV offset did not significantly affect the FCW onset of the combined Volvo S90 tests while it was operated in driving automation levels 1 and 2.

SV Braking Onset Responses

This section examines the SV braking onset TTC results. The range of SV braking onset TTCs are first presented in a table, then followed with box plots of each vehicles' SV braking onset TTCs by scenario, collapsed across speed within that scenario. The Mercedes E300, Nissan Leaf, and Volvo S90 results are presented in the Test Results chapter above, and an overall summary is in it. Going forward, any test operating in driving automation level 0 that did not reach the 0.25g SV braking onset threshold AND ended with an impact will be described as having had a CIB non-activation.

Mercedes E300

The range of SV braking onset TTCs for the Mercedes E300, for each combination of scenario, test speed, and POV offset position, are presented in Table 7. The SV braking onset threshold of 0.25g was not reached for any of the LVS or LVM scenarios when ACC was enabled.

An inspection of the Table 7 data shows that when the Mercedes E300 was operated in driving automation level 0, the range of SV braking onset TTCs for the LVS_15_0, LVM_25_10, LVM_35_20, and LVD_15_15 tests were numerically similar across the three POV offset positions. For the other six maneuvers (LVS_20_0, LVS_25_0, LVM_35_10, LVM_45_20, LVD_25_25 and LVD_35_35), the data show the Mercedes E300 began braking sooner when it was directly behind the POV than when the POV was offset to the left or right (i.e., the SV braking onset TTCs were numerically higher when the POV was centered in the lane).

These trends were confirmed during the initial review of the box plots, where a similar pattern emerged in the data. To avoid obscuring any significant findings, the data was collapsed across speed within scenario, but only for the data where the SV began braking sooner when it was directly behind the POV (i.e., LVS_20_0 and LVS_25_0 were the first group, the LVM_35_10 and LVM_45_20 the second, and LVD_25_25 and LVD_35_35 the third). For the sake of brevity, only the significant results are examined next.

Driving Automation Level 0 SV Braking Onset Results

The Mercedes E300 SV braking onset data produced from the LVS scenario performed in automaton level 0 was collapsed across the LVS_20_0 and LVS_25_0 test conditions, creating a sample size of n=6 for each offset position. The box plots in Figure 26 show that there was a significant difference in the SV braking onset TTCs between the left, center, and right offset positions ($p<0.0001$). Examination of the LSMeans verified that the left and right offset SV braking onsets were significantly different from the center SV braking onset TTCs, and different from each other.

The Mercedes E300 SV braking onset data produced from the LVM scenario performed in driving automation level 0 was collapsed across the LVM_35_10 and LVM_45_20 maneuvers, creating a sample size of n=6 for each offset position. The box plots in Figure 27 show that there was a significant difference in the SV braking onset TTCs between the left, center, and right offset positions ($p=0.0119$). Examination of the LSMeans verified that the left offset and center SV braking onsets were significantly different, but neither were significantly different from the right offset.

Table 7. Range of Mercedes E300 SV Braking Onset TTCs

Crash-imminent Test Conditions			Range of Mercedes E300 SV Braking Onset TTCs								
Pre-Crash Scenario	Test Speeds (mph)		Driving Automation Level 0			Driving Automation Level 1			Driving Automation Level 2		
	SV	POV	Left	Center	Right	Left	Center	Right	Left	Center	Right
Lead Vehicle Stopped (LVS)	15	0	0.87 – 0.88	0.86 – 0.90	0.86 – 0.88	–	–	–	–	–	–
	20	0	0.92 – 0.98	1.06 – 1.12	0.98 – 1.02	–	–	–	–	–	–
	25	0	0.92 – 0.93	1.04 – 1.08	0.96 – 0.99	–	–	–	–	–	–
Lead Vehicle Moving (LVM)	25	10	0.86 – 0.91	0.85 – 0.90	0.85 – 0.93	–	–	–	–	–	–
	35	10	1.02 – 1.04	1.09 – 1.26	1.05 – 1.12	–	–	–	–	–	–
	35	20	0.83 – 0.93	0.87 – 0.96	0.90 – 0.99	–	–	–	–	–	–
	45	20	1.10 – 1.16	1.27 – 1.32	1.22 – 1.28	–	–	–	–	–	–
Lead Vehicle Decelerates (LVD)	15	15	0.75 – 0.88	0.74 – 0.79	0.77 – 0.91	1.83 – 1.98	1.86 – 1.96	1.90 – 1.97	1.87 – 1.93	1.84 – 1.98	1.87 – 2.01
	25	25	0.88 – 0.94	1.03 – 1.04	0.96 – 1.03	2.39 – 2.56	2.39 – 2.53	2.46 – 2.76	2.54 – 2.62	2.50 – 2.71	2.75 – 2.76
	35	35	1.01 – 1.03	1.18 – 1.26	1.12 – 1.16	2.69 – 2.81	2.95 – 3.22	2.63 – 3.09	2.71 – 2.87	2.78 – 2.82	2.80 – 2.85

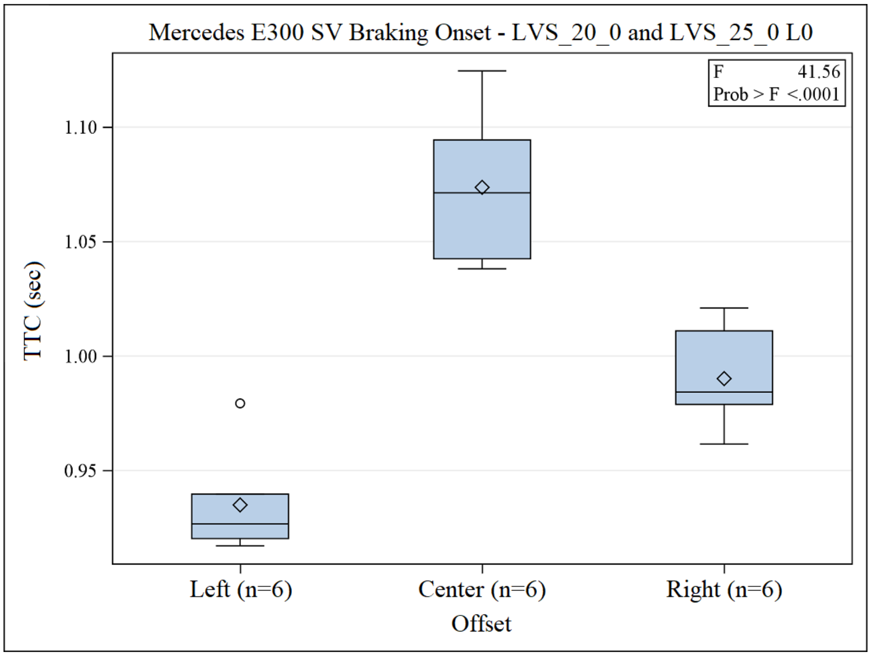

Figure 26. Mercedes E300 driving automation level 0 SV braking onset TTCs, collapsed across LVS_20_0 and LVS_25_0

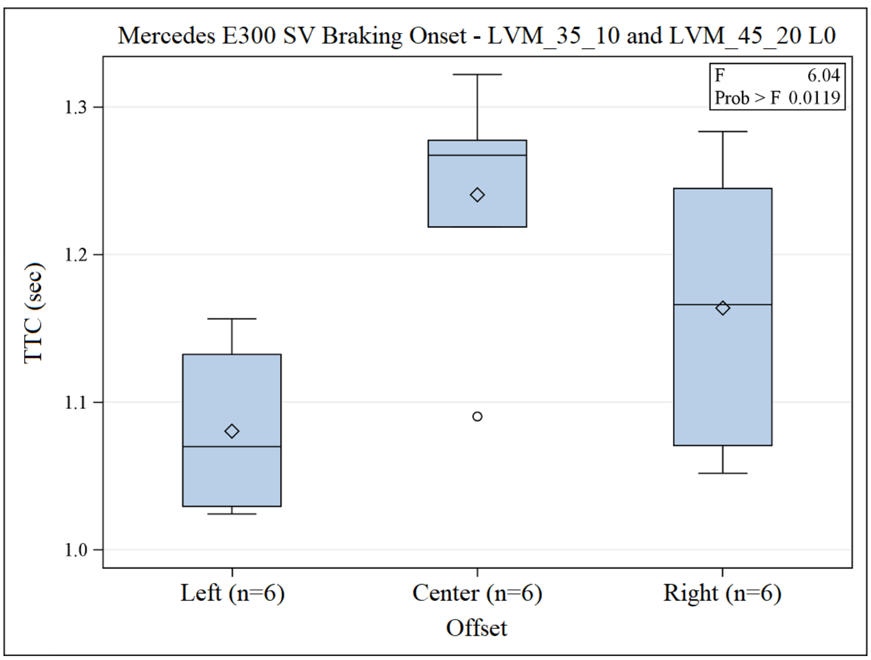

Figure 27. Mercedes E300 driving automation level 0 SV braking onset TTCs, collapsed across LVM_35_10 and LVM_45_20

The Mercedes E300 SV braking onset data produced from the LVD scenario performed in driving automation level 0 was collapsed across the LVD_25_25 and LVD_35_35 maneuvers, creating a sample size of n=6 for each offset position. The box plots in Figure 28 show that for the combined SV braking onset data, there was a significant difference in the SV braking onset TTCs between the left, center, and right offset positions (p=0.0154). Examination of the

LSMeans verified that only the left offset and center SV braking onsets were significantly different, but neither were significantly different from the right offset SV braking onsets.

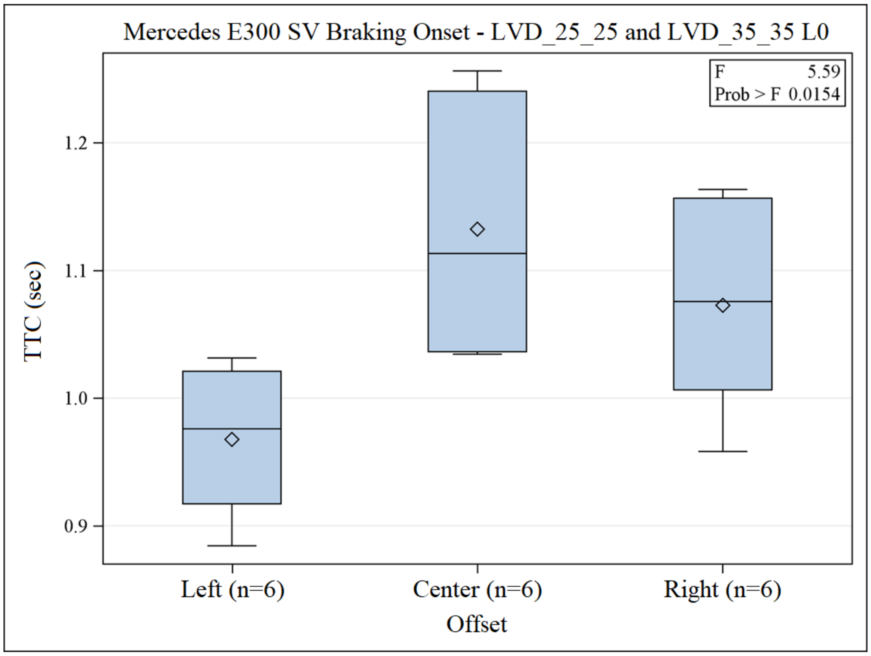

Figure 28. Mercedes E300 driving automation level 0 SV braking onset TTCs, collapsed across LVD_25_25 and LVD_35_35

Since the differences found between offsets in the LVM and LVD maneuvers were not particularly strong (due to the right offset data overlapping the center and left offset data), there was no benefit to combining the data into a larger data set.

Driving Automation Level 1 and 2 SV Braking Onset Results

When operating in driving automation levels 1 and 2, SV braking onsets were only observed during LVD tests for the Mercedes E300, as shown in Table 7. Since the primary difference between driving automation levels 1 and 2 was whether the driver or LCC kept the SV centered in the lane, it was deemed appropriate to combine the SV braking onset TTCs across level of automation for analysis purposes. This created a sample size of n=18 for the three offset positions.

Although the SV braking onset TTCs increased with increasing maneuver speed for the Mercedes E300 (similar to the trend observed for FCW onset TTCs in driving automation level 0), each row was numerically similar across the three POV offset positions. This can also be seen in Figure 29, where the results show that there were no significant differences in SV braking onset between the left, center, and right offset positions (p=0.8272) for all LVD tests, collapsed across driving automation levels 1 and 2.

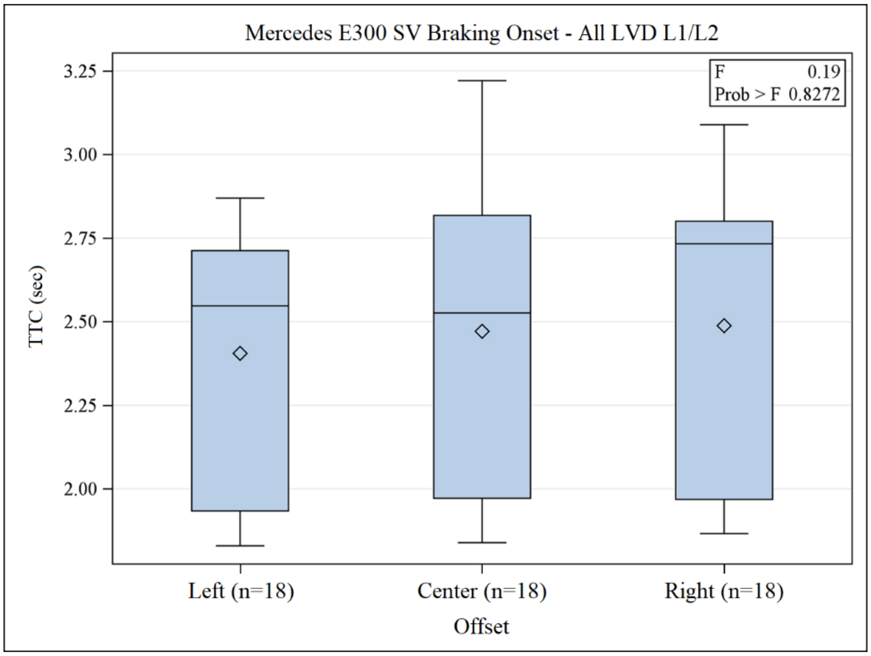

Figure 29. Mercedes E300 LVD driving automation levels 1 and 2 SV braking onset TTCs, collapsed across speed and level of automation

Nissan Leaf

The range of SV braking onset TTCs for the Nissan Leaf, for each combination of scenario, test speed, and POV offset position, are presented in Table 8. The SV braking onset threshold of 0.25g was not reached for any of the LVM scenarios when ACC was enabled. However, SV braking onsets were observed during all the LVD tests performed in driving automation levels 1 and 2, and several of the LVS tests performed in level 1.

The LVS_15_0 tests for driving automation levels 1 and 2 were not performed because they were below the 20 mph (32.2 km/h) ACC activation speed. Testing in driving automation level 2 was limited to maneuvers where the SV was traveling 35 mph (56.3 km/h) or faster. The LVM_35_10 L0 left tests were not performed.

Table 8. Range of Nissan Leaf SV Braking Onset TTCs

Crash-imminent Test Conditions			**Range of Nissan Leaf SV Braking Onset TTCs**								
Pre-Crash Scenario	**Test Speeds (mph)**		**Driving Automation Level 0**			**Driving Automation Level 1**			**Driving Automation Level 2**		
	SV	**POV**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**
Lead Vehicle Stopped (LVS)	15	0	1.18 – 1.26	1.13 – 1.23[6]	1.09 – 1.19	Below ACC activation level.			Below ACC and LCC activation levels.		
	20	0	1.49 – 1.59	1.44 – 1.59	1.47 – 1.56	–	–	–	Below LCC activation level.		
	25	0	1.43 – 1.55[1]	1.78 – 1.93	1.78 – 1.88	1.65[8]	4.34 – 4.35	4.19 – 4.24	Below LCC activation level.		
Lead Vehicle Moving (LVM)	25	10	1.63 – 1.72[2]	1.53 – 2.13	0.46[3] – 1.76	–	–	–	Below LCC activation level.		
	35	10	Not tested.	0.53[7] – 1.78	1.53 – 1.91[5]	–	–	–	–	–	–
	35	20	0.87[3,2] – 1.95	2.03 – 2.25	0.12[3] – 2.04	–	–	–	–	–	–
	45	20	0.65[3] – 1.57	0.66 – 1.83	1.58 – 1.76	–	–	–	–	–	–
Lead Vehicle Decelerates (LVD)	15	15	0.98 – 1.13	0.80 – 1.28	0.84 – 1.05	2.31 – 2.41	2.32 – 2.54	2.24 – 2.36	Below LCC activation level.		
	25	25	0.81 – 0.87[4]	0.85 – 0.87[5]	0.75 – 0.85[4]	3.10 – 3.35	3.08 – 3.18	3.27 – 3.31	Below LCC activation level.		
	35	35	0.74 – 0.81[5]	0.81 – 0.82[5]	0.72 – 0.77[4]	3.39 – 3.49	3.14 – 3.35	3.16 – 3.39	3.14 – 3.24	3.19 – 3.39	3.25 – 3.77

[1] One impact was observed during the tests performed in this series because the SV did not alert or brake.
[2] Three impacts were observed during the tests performed in this series; one because the SV did not brake.
[3] This late SV braking onset resulted in an impact.
[4] Three impacts were observed during the tests performed in this series.
[5] Two impacts were observed during the tests performed in this series.
[6] One impact was observed during the tests performed in this series because the SV did not alert or brake.
[7] This late SV braking onset was preceded by a late FCW onset and resulted in an impact. A second impact was observed in this series because the SV did not alert or brake.
[8] An ACC non-activation lead to an FCW alert and CIB braking to a stop.

Driving Automation Level 0 SV Braking Onset Results

SV braking onsets were observed during all LVS tests performed with the Nissan Leaf in driving automation level 0. The LVS_15_0 and LVS_20_0 data in Table 8 show that each row was numerically similar across the three POV offset positions and were therefore not significantly different. The LVS_25_0 data did not follow that trend and were analyzed separately. Since only three tests were performed per offset condition, no attempt was made to interpret the ostensible differences between the three offset positions, despite the box plot analysis providing a p-value. The LVS_25_0 data are plotted in Figure 30.

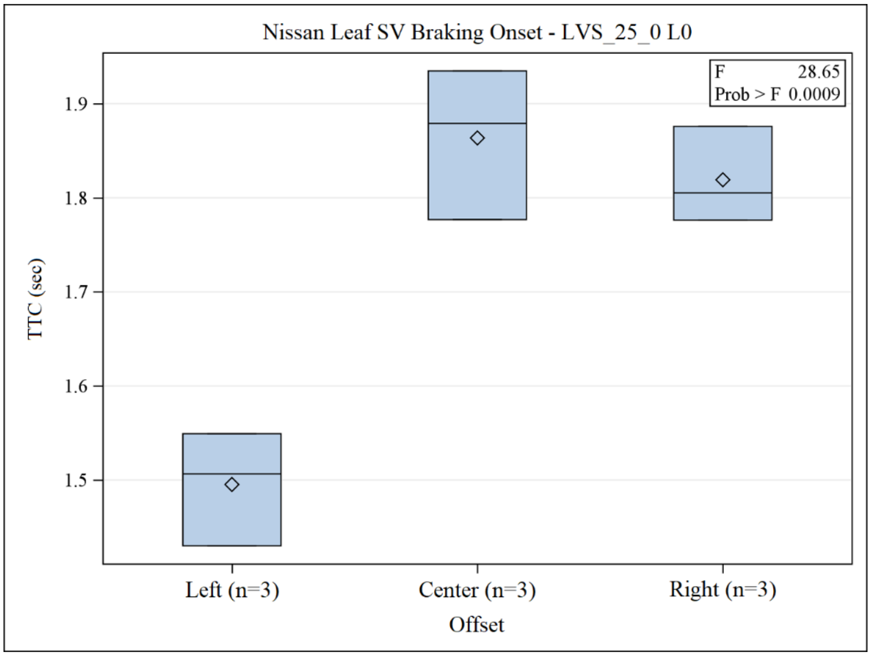

Figure 30. Nissan Leaf LVS_25_0 driving automation level 0 SV braking onset TTCs

Collapsing across the four LVM test speeds created SV braking onset TTC sample sizes of 7, 11, and 12 for the left, center, and right offset positions, respectively. There were three CIB non-activations in the LVM scenario for the tests performed in driving automation level 0: one LVM_25_10 left offset test, one LVM_35_10 center test, and one LVM_35_20 left offset test. The box plots in Figure 31 show that there were no significant differences in SV braking onset between the left, center, and right offset positions (p=0.6633) for the LVM scenario.

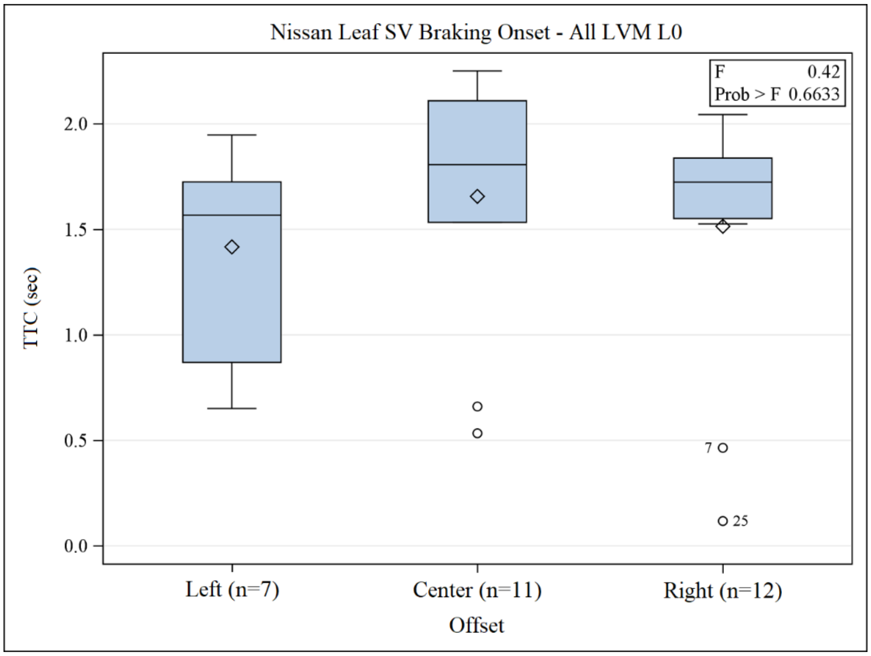

Figure 31. Nissan Leaf LVM driving automation level 0 SV braking onset TTCs, collapsed across speed

Collapsing across the three LVD test speeds created an SV braking onset sample size of n=9 for each POV offset position. The box plots shown in Figure 32 show that there were no significant differences in SV braking onset between the left, center, and right offset positions (p=0.3099) for the LVD tests performed in driving automation level 0.

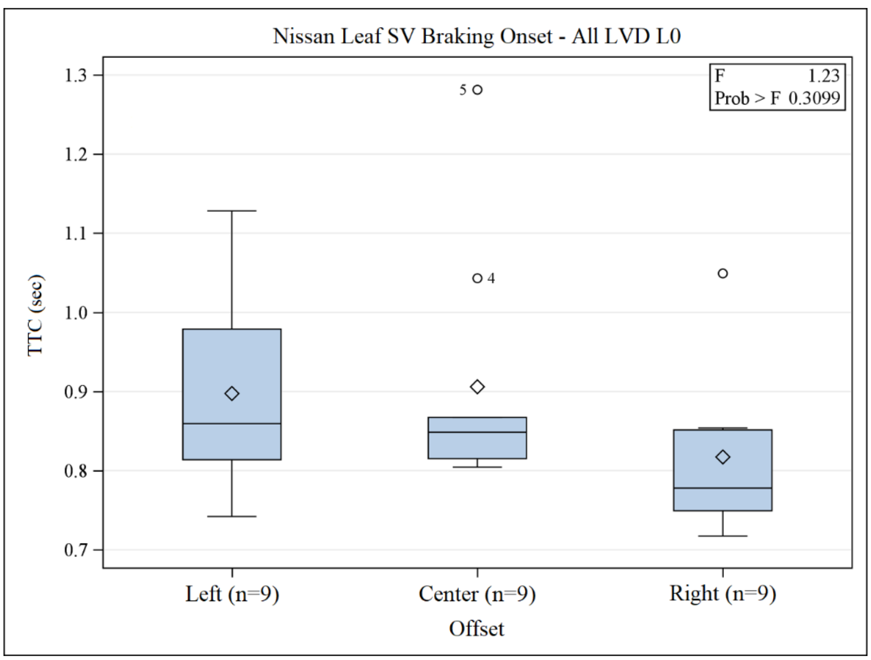

Figure 32. Nissan Leaf LVD driving automation level 0 SV braking onset TTCs, collapsed across speed

Driving Automation Level 1 and 2 SV Braking Onset Results

For the Nissan Leaf, SV braking onsets were observed during all LVD tests performed in driving automation levels 1 and 2, and during isolated incidents within the LVS_25_0 tests performed in level 1, as previously shown in Table 8. However, there were too few data points produced in the LVS_25_0 driving automation level 1 test series to determine if a statistically significant difference existed, as explained next.

Two of the LVS_25_0 tests performed in driving automation level 1 with a left POV offset had no SV braking onset because ACC deceleration never exceeded the 0.25g SV braking onset threshold. The third test in that left offset series had an ACC non-activation but stopped prior to impact with a CIB-based braking event [8]. Therefore, the LVS_25_0 tests performed with driving automation level 1 and a left offset POV had no ACC-based SV braking onset data to compare. Three of the centered POV tests and two of the right offset tests stopped with ACC-based braking that exceeded the 0.25g SV braking onset threshold. The third test in the right offset series stopped without exceeding 0.25g. The plotted data are shown in Figure 33.

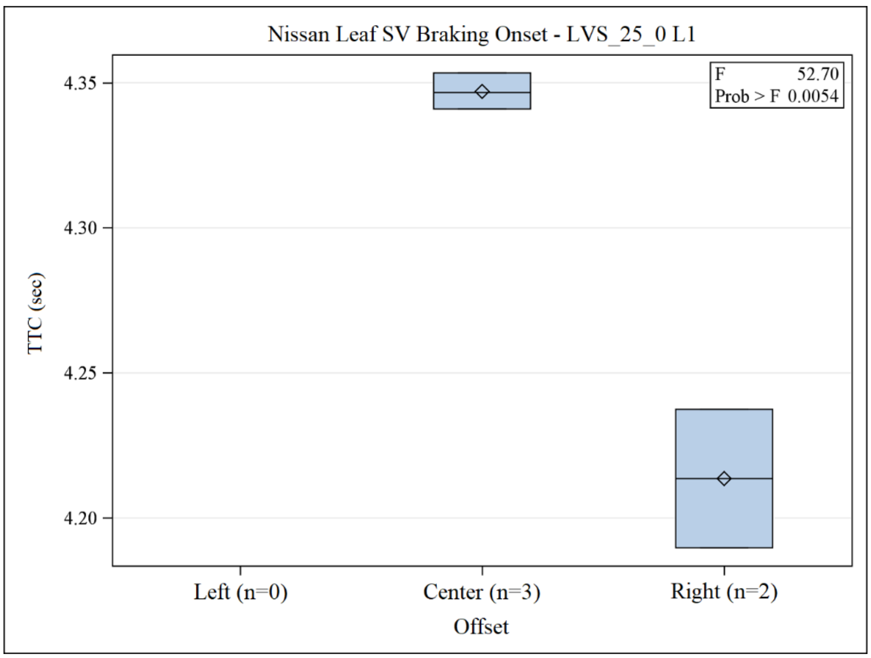

Figure 33. Nissan Leaf LVS_25_0 driving automation level 1 SV braking onset TTCs (ACC non-activation not included)

The SV braking onset data from the LVD_35_35 test series performed in driving automation level 2 was combined with data from the three LVD test series performed in level 1, which created a sample size of n=12 for the three offset POV positions. The box plots in Figure 34 show that there were no significant differences in SV braking onset between the POV offsets (p=0.9086) for this LVD-based data set.

[8] As noted in Section. 3.2.2, SV braking onset data that had an ACC non-activation were not used in the ACC evaluations. Appendix Section 6.3 notes the complications that arise from mixing the two types of SV braking onsets.

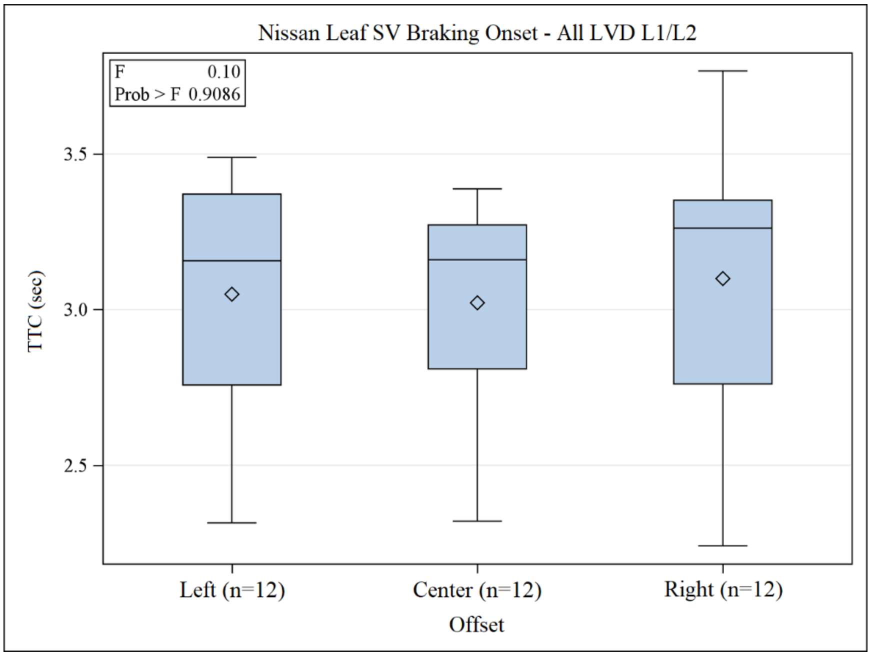

Figure 34. Nissan Leaf LVD driving automation levels 1 and 2 SV braking onset TTCs, collapsed across speed and level of automation

Volvo S90

The range of SV braking onset TTCs for the Volvo S90, for each combination of scenario, test speed, and POV offset position, are presented in Table 9. SV braking onsets occurred during all Volvo S90 tests performed in driving automation level 0. The SV braking onset threshold of 0.25g was not reached for any of the LVM scenarios when ACC was enabled. No LVS_15_0 tests were performed in driving automation level 1 and 2 since the ACC activation speed was 20 mph (32.2 km/h). During the LVS_25_0 tests performed in driving automation levels 1 and 2, the Volvo S90 had eight ACC non-activations interspersed among the three POV offset positions. The footnotes below Table 9 detail where these non-activations occurred.

Close inspection of the Table 9 data shows that when the Volvo S90 was operated in driving automation level 0, it began braking sooner when it was directly behind the POV than when the POV was offset to the left or right (i.e., the SV braking onset TTCs were numerically higher for the centered POV tests than for the left and right offset tests). This can also be seen in the box plot analyses presented in this section.

Automation Level 0 SV Braking Onset Results

The Volvo S90 SV braking onset data from the LVS tests performed in driving automation level 0 were collapsed across speed, creating a sample size of n=9 for each POV offset position. The box plots in Figure 35 show that there was a significant difference in the SV braking onset TTCs between the left, center, and right offset positions ($p<0.0001$). Examination of the LSMeans verified that the left and right offset SV braking onsets were significantly different from the center SV braking onsets, but not different from each other.

Table 9. Range of Volvo S90 SV Braking Onset TTCs

Crash-imminent Test Conditions			Range of Volvo S90 SV Braking Onset TTCs								
Pre-Crash Scenario	**Test Speeds (mph)**		**Driving Automation Level 0**			**Driving Automation Level 1**			**Driving Automation Level 2**		
	SV	**POV**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**	**Left**	**Center**	**Right**
Lead Vehicle Stopped (LVS)	15	0	0.42 – 0.59	0.89 – 0.92	0.61 – 0.63	Below ACC activation level.			Below ACC activation level.		
	20	0	0.63 – 0.66	0.98 – 1.01	0.64 – 0.72	2.23 – 2.39	2.34 – 2.55	2.14 – 2.42	2.30 – 2.41	2.33 – 2.41	2.27 – 2.37
	25	0	0.86 – 0.92	1.09 – 1.17	0.87 – 0.96	0.89[1] – 3.05	1.10[1] – 2.81	2.19 – 2.43	0.87 – 0.90[2]	1.16[3] – 2.72	0.92[1] – 2.68
Lead Vehicle Moving (LVM)	25	10	0.71 – 0.80	1.05 – 1.15	1.08 – 1.15	–	–	–	–	–	–
	35	10	1.02 – 1.05	1.34 – 1.41	1.12 – 1.18	–	–	–	–	–	–
	35	20	0.78 – 0.90	1.05 – 1.24	1.04 – 1.11	–	Not tested	–	–	–	–
	45	20	0.87 – 1.14	1.41 – 1.43	1.11 – 1.27	–	–	–	–	–	–
Lead Vehicle Decelerates (LVD)	15	15	0.61 – 0.84	1.01 – 1.04	0.54 – 0.71	2.33 – 2.38	2.35 – 2.45	2.33 – 2.38	2.36 – 2.49	2.38 – 2.51	2.39 – 2.60
	25	25	0.75 – 0.82	1.13 – 1.21	0.78 – 0.87	2.41 – 2.53	2.60 – 2.66	2.71 – 2.96	2.55 – 2.79	2.62 – 2.73	2.61 – 2.81
	35	35	0.79 – 1.13	1.22 – 1.37	0.94 – 1.06	2.85 – 3.21	3.21 – 3.61	2.85 – 3.02	3.88 – 4.34	3.62 – 4.06	3.21 – 3.22

[1] One ACC non-activation was observed during the tests performed in this series.
[2] Three ACC non-activations was observed during the tests performed in this series.
[3] Two ACC non-activations were observed during the tests performed in this series.

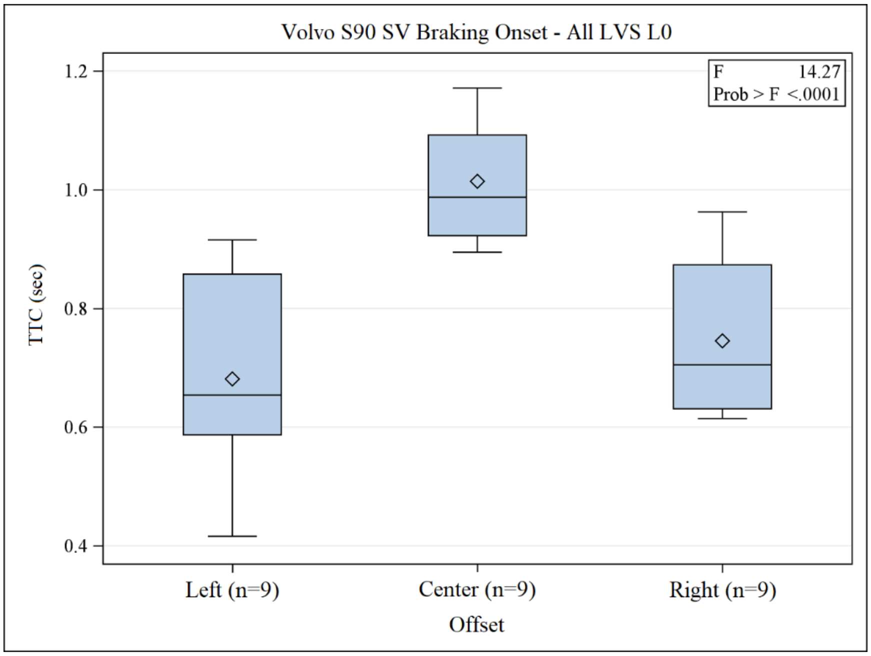

Figure 35. Volvo S90 LVS driving automation level 0 SV braking onset TTCs, collapsed across speed

The Volvo S90 SV braking onset data from the LVM scenario performed in driving automation level 0 were collapsed across speed, creating a sample size of n=12 for each offset position. The box plots in Figure 36 show that there was a significant difference in the SV braking onset TTCs between the left, center, and right offset positions ($p<0.0001$). Examination of the LSMeans verified that the left and right offset SV braking onsets were significantly different from the center SV braking onsets, and different from each other.

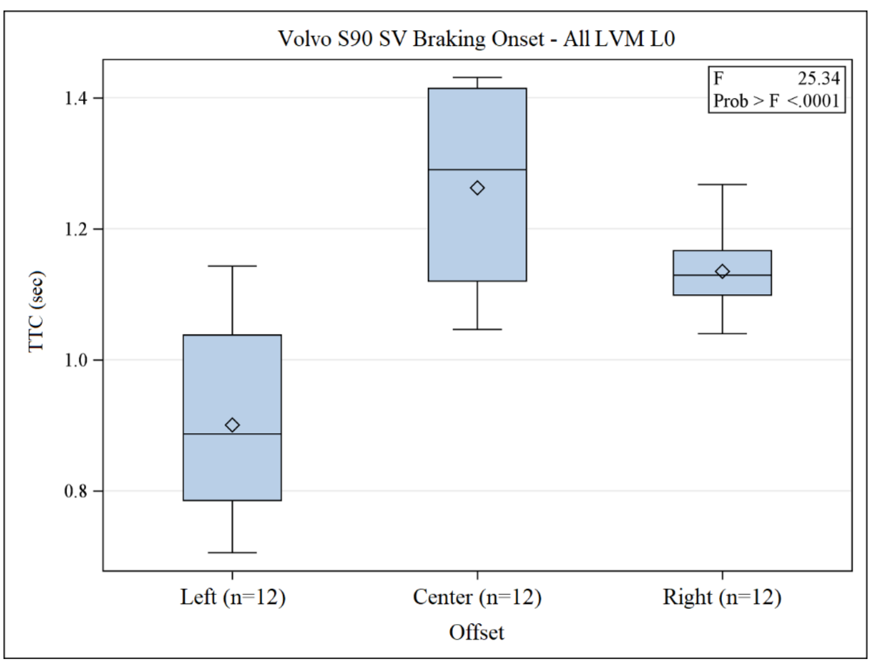

Figure 36. Volvo S90 LVM driving automation level 0 SV braking onset TTCs, collapsed across speed

The Volvo S90 SV braking onset data from the LVD tests performed in driving automation level 0 were collapsed across speed, creating a sample size of n=9 for each offset position. The box plots in Figure 37 show that there was a significant difference in the SV braking onset TTCs between the left, center, and right offset positions (p<0.0001). Examination of the LSMeans verified that the left and right offset SV braking onsets were significantly different from the center SV braking onset TTCs, but not different from each other.

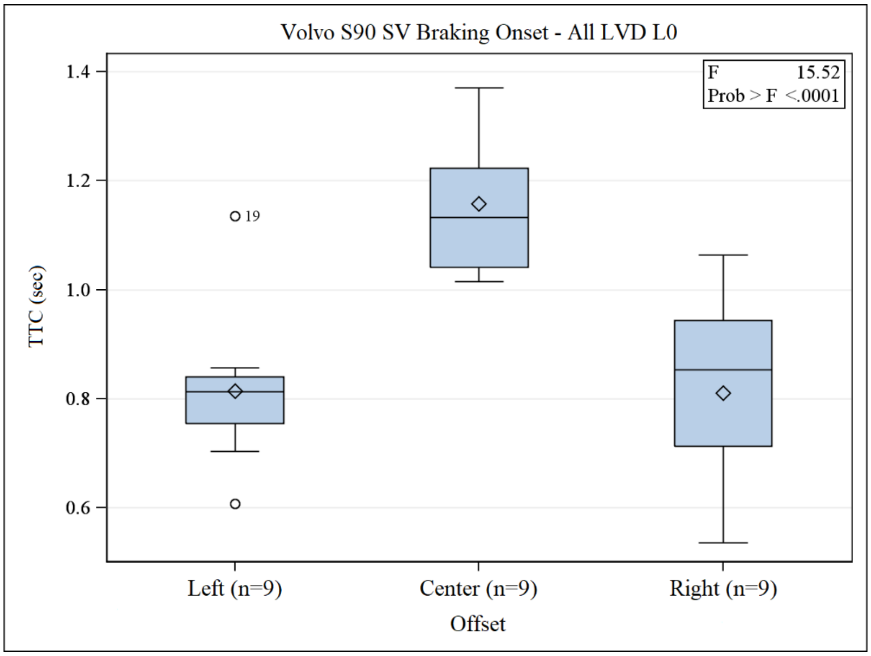

Figure 37. Volvo S90 LVD driving automation level 0 SV braking onset TTCs, collapsed across speed

Since the SV braking onset TTC results from each scenario were significantly different and the box plots had a similar pattern, one additional analysis was made by collapsing the data across scenario within vehicle. In other words, all data from the Volvo S90 tests performed in driving automation level 0 were combined and used to perform a single analysis. This created a sample size of n=30 for each of the three offset positions, thus providing for a stronger and even more convincing statistical argument toward the overall goal of this analysis.

The combined results show that there was a significant difference in the SV braking onset TTCs between the left, center, and right offset positions (p<0.0001) for the Volvo S90 when operated in driving automation level 0. The box plots are shown in Figure 38. Examination of the LSMeans verified that the left and right offset SV braking onsets were significantly different from the center SV braking onset TTCs, but not different from each other.

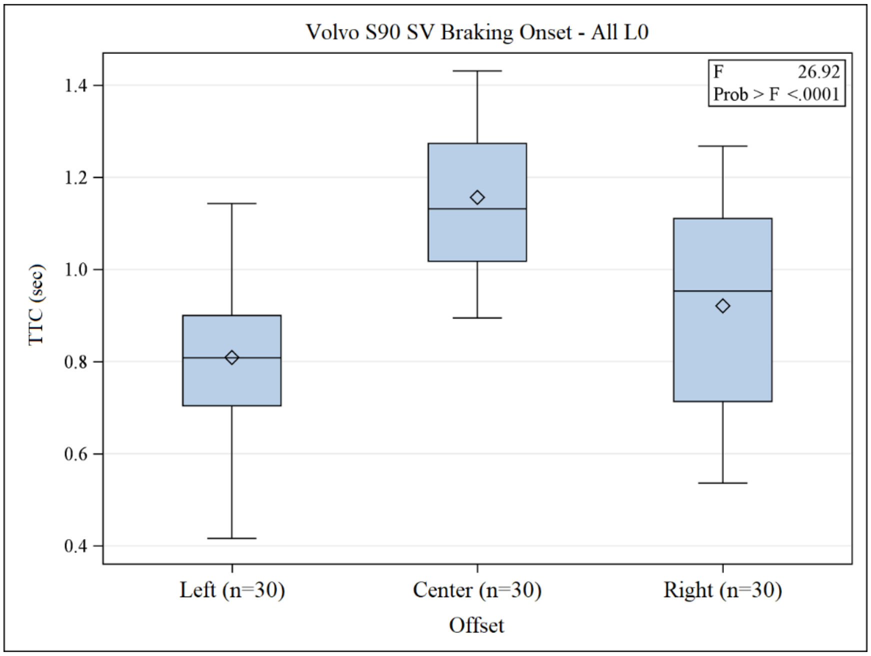

Figure 38. Volvo S90 driving automation level 0 SV braking onset TTCs, collapsed across all data

Driving Automation Level 1 and 2 SV Braking Onset Results

When the Volvo S90 was operating in driving automation levels 1 and 2, SV braking onsets were observed during all LVD tests, and all of the LVS_20_0 and LVS_25_0 tests, as previously shown in Table 9. However, 8 of the 18 LVS_25_0 SV braking onsets (3 offset positions × 2 levels of automation × 3 tests per condition) were due to ACC non-activations (i.e., CIB-based braking).[9] The data in Table 10 shows which SV braking onset TTCs were attributable to ACC-based braking for these maneuvers.

Table 10. Location of ACC-Based SV Braking Onset Activity Within the Volvo S90 LVS_25_0 Test Series Performed in Driving Automation Levels 1 and 2

Maneuver	Driving Automation Level	Left	Center	Right
LVS_25_0	1	2/3	2/3	3/3
LVS_25_0	2	0/3	1/3	2/3

The Volvo S90 SV braking onset data from the LVS tests performed in driving automation levels 1 and 2 was collapsed across the LVS_20_0 and LVS_25_0 test conditions and level of automation, creating sample sizes of 8, 9 and 11 for the left, center, and right offset positions, respectively. The box plots in Figure 39 show that there were no significant differences in SV braking onset between the left, center, and right offset positions (p=0.4635) for the LVS scenario.

[9] As noted in Section. 3.2.2, SV braking onset data that had an ACC non-activation were not used in the ACC evaluations. Appendix Section 6.3 notes the complications that arise from mixing the two types of SV braking onsets.

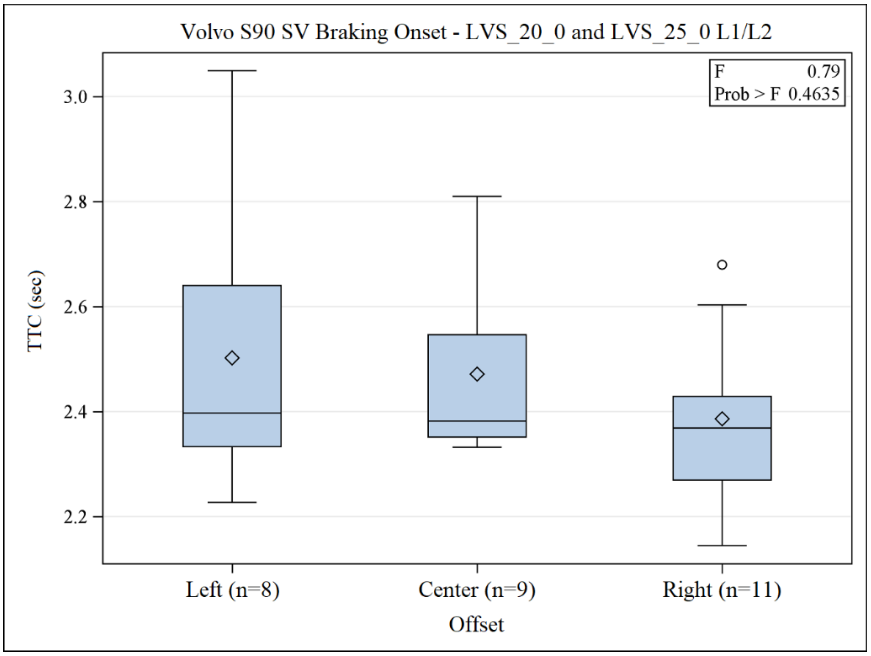

Figure 39. Volvo S90 LVS driving automation levels 1 and 2 SV braking onset TTCs, collapsed across speed and level of automation (ACC non-activations not included)

The Volvo S90 SV braking onset data from the LVD tests performed in driving automation levels 1 and 2 was collapsed across speed and level of automation, creating a sample size of n=18 for the three offset positions. The box plots in Figure 40 show that there were no significant differences in SV braking onset between the left, center, and right offset positions (p=0.6803) for these tests.

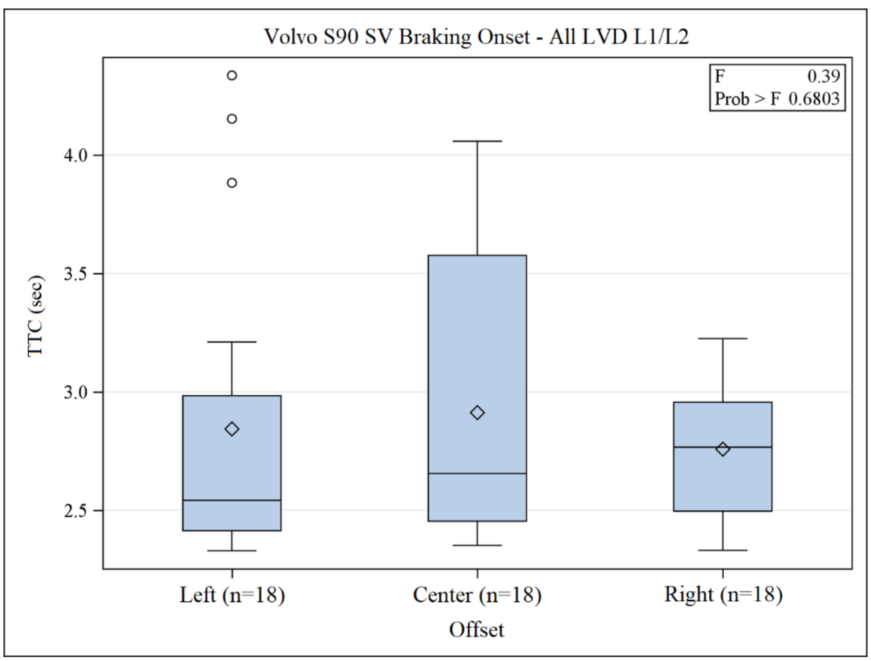

Figure 40. Volvo S90 LVD driving automation levels 1 and 2 SV braking onset TTCs, collapsed across speed and level of automation

SV Braking Onset Summary

When the Mercedes E300 was operating in driving automation level 0, offsetting the POV to the left had a significant difference on the SV braking onsets TTCs for the LVS_20_0, LVS_25_0, LVM_35_10, LVM_45_20, LVD_25_25 and LVD_35_35 maneuvers. The results also showed that there were significant differences between the SV braking onset TTCs when the POV was offset to the right for the LVS_20_0 and LVS_25_0 maneuvers. When the Mercedes E300 was operating in driving automation level 1 or 2, POV offset did not significantly affect the SV braking onset performance.

For the Nissan Leaf, POV offset did not significantly affect the SV braking onset performance while it was operating in driving automation levels 0, 1, or 2.

When the Volvo S90 was operating in driving automation level 0, the SV braking onset TTCs from the left and right offset positions were significantly different than those observed when the POV was centered in the lane. POV offset did not significantly affect the SV braking onset performance of the Volvo S90 operating in driving automation level 1 or 2.

Summary of Non-Activations and Impacts

This section provides a summary of the non-activations and SV-to-POV impacts observed during testing. The next section discusses an adjustment that arose from testing with an offset POV. The Mercedes E300, Nissan Leaf, and Volvo S90 results are presented right after.

Explicitly Defining What Constitutes as a Stop

As testing progressed, the end of the validity period needed to be refined with regards to what constituted a stop. As written in NHTSA's 2015 NCAP CIB test procedure, the end of the validity period for the LVS scenario occurred at SV to POV impact or the SV stopping before making contact, while the end of the validity period for the LVD scenario occurred at SV-to-POV impact or one second after minimum longitudinal range occurs. During some tests performed in this study, the SV, while operating in driving automation level 0, would briefly come to a stop, release its brakes, and then lightly hit the decelerating or stationary POV. This happened 4 times with the Nissan Leaf (out of 204 tests) in the LVD scenario and once with the Volvo S90 (out of 249 tests) in an LVS scenario. Four of the five times occurred when the POV was offset to the left or right.

To clarify whether a "stop-and-release" test result should be classified as a stop or an impact, it was decided that the SV had to remain stopped for 2 seconds to be classified as a stop. This was consistent with the Nissan Leaf owner's manual (Nissan North America, 2018), which stated on page 5-112, "If the AEB system has stopped the vehicle, the vehicle will remain at a standstill for approximately 2 seconds before the brakes are released." During testing, if the SV started to move after being stationary for 2 seconds, the driver would manually stop the SV before impact occurred. All impacts reported in the following tables occurred before the SV had been stopped for 2 seconds or longer.

Mercedes E300

No SV-to-POV impacts were observed during tests performed with the Mercedes E300, regardless of driving automation level. There were no FCW non-activations while operating in driving automation level 0. There were no ACC non-activations while operating in driving automation levels 1 and 2.

Nissan Leaf

The Nissan Leaf had 30 impacts, all while operating in driving automation level 0 (see Table 11). There were two tests where neither FCW or CIB activated. There were two additional tests with CIB non-activations that did have an FCW alert. During four tests, the vehicle came to a brief stop in the LVD scenario (ranging from 0.37 – 1.40 sec), released its brakes, and then hit the POV at relative impact speeds from 0.9 – 2.3 mph (1.4 – 3.7 km/h). Based on available data, POV offset does not appear to have influenced the SV-to-POV impact frequency or speed. There was one ACC non-activation in the LVS_25_0 maneuver performed in driving automation level 1 with a left POV offset.

Table 11. Nissan Leaf SV-to-POV Impact Summary

Maneuver	Offset	Number of Impacts	Number of Tests	Relative Impact Speeds (mph)	Relative Impact Speeds (km/h)
LVS_15_0	center	1	3	15.4	24.8
LVS_25_0	left	1	3	9.7	15.6
LVM_25_10	left	3	3	1.6, 1.8, 11.7	2.6, 2.9, 18.8
LVM_25_10	right	1	3	10.6	17.1
LVM_35_10	center	2	3	19.2, 24.9	30.9, 40.1
LVM_35_10	right	2	3	2.5, 9.6	4.0, 15.4
LVM_35_20	left	3	3	2.6, 2.9, 10.0	4.2, 4.7, 16.1
LVM_35_20	right	1	3	11.4	18.3
LVM_45_20	left	1	3	6.0	9.7
LVD_25_25	left	3	3	1.6, 3.4, 13.2	2.6, 5.5, 21.2
LVD_25_25	center	2	3	2.1, 3.5	3.4, 5.6
LVD_25_25	right	3	3	0.9, 1.4, 11.9	1.4, 2.3, 19.2
LVD_35_35	left	2	3	2.3, 3.1	3.7, 5.0
LVD_35_35	center	2	3	3.2, 3.3	5.1, 5.3
LVD_35_35	right	3	3	2.8, 3.0, 10.1	4.5, 4.8, 16.3

Volvo S90

The Volvo S90 had four SV-to-POV impacts, all while operating in driving automation level 0 (see Table 12). During one of the LVS_15_0 tests, the vehicle briefly came to a stop (for 0.19 sec), released its brakes, and then hit the POV. In the three LVD maneuvers with SV-to-POV impacts, the Volvo S90 matched POV speed in an initial deceleration phase, released its brakes, and then hit the still-decelerating POV. There were no FCW or CIB non-activations. The Volvo S90 had eight ACC non-activations during LVS_25_0 tests performed with driving automation levels 1 and 2. Based on available data, POV offset does not appear to have influenced the frequency or speed of impacts, nor the frequency of ACC non-activations.

Table 12. Volvo S90 SV-to-POV Impact Summary

Maneuver	Offset	Number of Impacts	Number of Tests	Relative Impact Speeds (mph)	Relative Impact Speeds (km/h)
LVS_15_0	left	1	3	0.7	1.1
LVD_35_35	left	1	3	5.3	8.5
LVD_35_35	right	2	3	2.7, 2.9	4.3, 4.7

Concluding Remarks

Effect of POV Offset on SV FCW and Braking Onset Timing

A majority of FCW alerts occurred while the vehicles were operating in driving automation level 0. The results show the FCW onset timing of the three vehicles evaluated was not affected by having the POV offset to the left or right of the SV.

SV braking onset timing was affected by POV offset when the SV was operated in driving automation level 0, however the extent and manner in which it occurred was vehicle-dependent.

- The Mercedes E300 braked earlier when it was directly behind the POV than when the POV was offset to the left, but only during the LVS_20_0, LVS_25_0, LVM_35_10, LVM_45_20, LVD_25_25 and LVD_35_35 maneuvers. In addition, the center and right offset SV braking onsets were different for the LVS_20_0 and LVS_25_0 maneuvers.
- The Volvo S90 braked earlier when it was directly behind the POV than when the POV was offset to the left or right, with two exceptions. The center and right offset SV braking onsets were not different for the LVM_25_10 and LVM_35_20 maneuvers.
- The Nissan Leaf's SV braking onset TTCs were substantially similar among the three POV offset positions, meaning that no significant differences were detected for any tests.

Based on available data from the three vehicles used in this study, SV braking onset timing does not appear to have been affected by POV offset during tests performed in driving automation levels 1 or 2 (i.e., tests performed with ACC enabled).

During some LVS_25_0 trials performed in driving automation levels 1 and/or 2, the Nissan Leaf and Volvo S90 ACC systems did not brake the vehicles in response to the stationary POV. However, in these instances, CIB was activated and an SV-to-POV impact was avoided. The frequency of CIB brake activations observed during the LVS_25_0 trials performed in driving automation levels 1 and 2 is presented in Table 13.

Table 13. CIB-Based SV Braking Frequency During Tests Performed in Driving Automation Levels 1 and 2

Maneuver	Driving Automation Level	Vehicle	POV Offset		
			Left	Center	Right
LVS_25_0	1	Nissan Leaf	1/3	--	--
		Volvo S90	1/3	1/3	--
LVS_25_0	2	Volvo S90	3/3	2/3	1/3

Effect of POV Offset on SV-to-POV Impacts

No SV-to-POV impacts were observed during tests performed with the Mercedes E300, regardless of automation level.

The Nissan Leaf had 30 impacts, all while operating in driving automation level 0. There were two tests where neither FCW or CIB activated. There were two additional tests with CIB non-activations that did have an FCW alert. During four tests, the vehicle came to a brief stop in the

LVD scenario, released its brakes, and then hit the POV at a low relative impact speed. Based on available data, POV offset does not appear to have influenced the SV-to-POV impact frequency or speed.

The Volvo S90 had four SV-to-POV impacts, all while operating in driving automation level 0. During one of the LVS_15_0 tests, the vehicle briefly came to a stop, released its brakes, and then hit the POV. In the three LVD maneuvers with SV-to-POV impacts, the Volvo S90 matched POV speed in an initial deceleration phase, released its brakes, and then hit the still-decelerating POV. Based on available data, POV offset does not appear to have influenced the frequency or speed of impacts.

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Appendix A

Test Vehicle Weight Information

Table A-1. Subject Vehicle Weight Information (Standard Units)

Subject Vehicle	Vehicle Weight Information (lb)			
	Baseline[1]	Overall[2] (GVWR)	Front Axle[2] (GAWR)	Rear Axle[2] (GAWR)
2017 Mercedes E300 4MATIC (WDDZF4KB0HA0xxxxx)	3,924[3]	4,556 (5,258)	2,297 (2,502)	2,259 (2,756)
2017 Volvo S90 T6 AWD (YV1A22MK6H10xxxxx)	4,124	4,756 (5,200)	2,437 (2,620)	2,319 (2,690)
2018 Nissan Leaf SL (1N4AZ1CP1JC3xxxxx)	3,290[3]	3,922 (4,497)	2,183 (2,344)	1,739 (2,209)

[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

Table A-2. Subject Vehicle Weight Information (SI Units)

Subject Vehicle	Vehicle Weight Information (kg)			
	Baseline[1]	Overall[2] (GVWR)	Front Axle[2] (GAWR)	Rear Axle[2] (GAWR)
2017 Mercedes E300 4MATIC (WDDZF4KB0HA0xxxxx)	1,780.0[3]	2,066.6 (2,385)	1041.9 (1,135)	1024.7 (1,250)
2017 Volvo S90 T6 AWD (YV1A22MK6H10xxxxx)	1,870.6	2,157.3 (2,358.7)	1,105.4 (1,188.4)	1,051.8 (1,220.2)
2018 Nissan Leaf SL (1N4AZ1CP1JC3xxxxx)	1,492.3	1779.0 (2,040)	990.2 (1,063)	788.8 (1,002)

[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

Interpreting Box Plots

Box plots are a standardized way of displaying how the values in a dataset are spread out (e.g., concentrated or dispersed). Each box plot is divided into four quarters (quartiles) using five features shown in Figure A-1 (a generic box plot example). These quartiles each contain approximately 25 percent of the data.

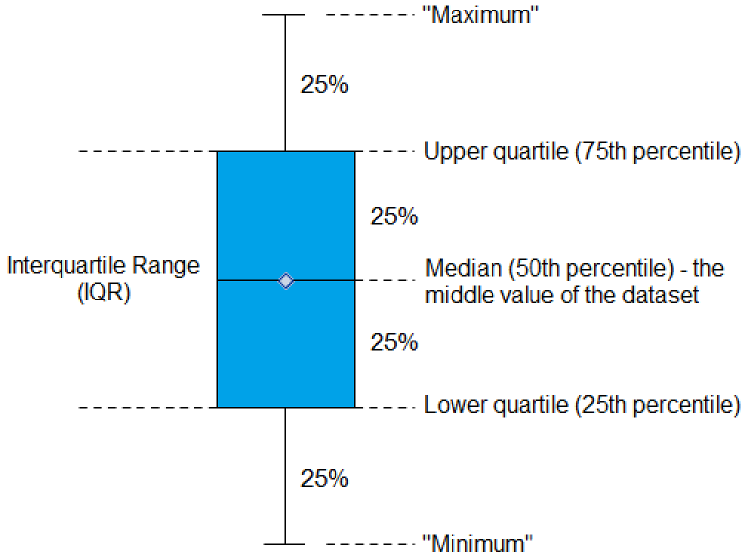

Figure A-1. Generic box and whiskers plot (whiskers not to scale)

The terminologies provided in Figure A-1 are defined as follows:

- **Median (50th Percentile)**: The mid-point of the data and is shown by a line that divides the box into two halves.
- **“Maximum”**: Upper quartile + 1.5*Interquartile Range
- **“Minimum”**: Lower quartile -1.5*Interquartile Range
- **Lower quartile (25th Percentile)**: The middle number between the smallest number (not the “minimum”) and the median of the dataset.
- **Upper quartile (75th Percentile)**: The middle number between the median and the highest value (not the “maximum”) of the dataset.
- **Interquartile Range**: The box in “box plot” that represents the middle 50 percent of values from the dataset (from the 25th to the 75th percentile). A diamond (centered on the median line above) is the mean value and will always appear inside the box.

The lines extending from the boxes are known as the “whiskers,” which are used to show variability outside the upper and lower quartiles. Datasets with low variability have shorter whiskers, while datasets with high variability often have whiskers that stretch over a wider range of scores than the middle quartile groups. Whiskers are absent when there are three or few data points.

When there are outliers within a dataset, they are plotted as separate points beyond the ends of the whiskers, appearing as an “o” in the plot. Not all datasets have outliers. Occasionally outliers are numbered, which shows where that exact point can be found in the dataset.

Comparing Box Plots

The p-value, or probability value, is the probability of obtaining the observed test results, assuming that the null hypothesis is correct. For example, if three box plots are compared and a value of P=0.002 is returned, it would be interpreted as “if these data sets are equal, you would expect to see these results only twice in one thousand attempts.” The null hypothesis (that the datasets are equal) is then rejected in favor of the alternative hypothesis (they are not equal).

When P-values are unavailable, a more subjective approach is needed. Box plots provide a quick overview of how to visualize differences between two or more batches of data. Box plots were used in this report to compare select vehicle responses to a target located at three different positions in the subject vehicle’s forward path. SAS 9.4 was used to analyze the data. This software package generated the box plots, compared the three sets of data to each other, and evaluated the certainty of the differences using a P-value.

The key information to glean from interpreting box plots is a determination of which of the datasets are different. To understand how these differences are determined, the following guidelines are used to provide a methodical way for comparing individual features, assuming that there is a sufficient number of samples within each dataset.

To begin, the boxes represent the interquartile range, or the middle half of the values in each dataset. If two boxes do not overlap with one another, say, one box is completely above or below the other, then it is highly likely there is a difference between those two datasets.

If there is any amount of overlap, the respective medians inside the boxes are compared. If the median of one or both datasets lies outside of the other box entirely, then there is likely to be a difference between the two datasets.

If both median lines lie within the overlap between two boxes, then it is likely the two datasets are not different. When datasets are dispersed, have different box and/or whisker lengths, are skewed or have outliers, then uncertainty about the underlying shape of the distribution increases, making it is harder to clearly interpret the relationship between the datasets. As with any determination of equality or inequality, certainty in the conclusion is positively correlated with the amount of data collected.

Analyzing SV Braking Onset Activity in Driving Automation Levels 1 and 2

The vast majority of SV braking onsets observed while the vehicle was operated in driving automation levels 1 and 2 were due to the SV’s ACC braking the vehicle gradually and early in the pre-crash timeline. Many stops were so gradual that they did not exceed the 0.25 SV braking onset threshold. The Test Results chapter discussed those instances where an ACC-enabled SV braking onset was due to a CIB intervention, not ACC braking (once out of 204 Nissan Leaf tests and 8 times out of 249 Volvo S90 tests). These tests were categorized as ACC non-activations.

The objective of this research was to assess whether SV braking onset timing was affected by the lateral offset of the POV using an SV operated in three different levels of automation. Testing and analysis of the driving automation level 0 data was straightforward because it was consistent enough to be considered normally distributed. Conversely, driving automation levels 1 and 2 data were occasionally inconsistent because of the aforementioned ACC non-activations (i.e., driving automation level 0 SV braking onsets). The ACC non-activation SV braking onset TTCs were not included in the subsequent ACC analyses because those results were so different from the ACC-based SV braking onset results that it was clear they were not from the same population. Only normally distributed data could be used to address the research objective of determining if SV braking onset timing was affected by POV offset while operating in driving automation levels 1 and 2. This section examines in greater detail why it was appropriate to exclude this data.

First, the vehicle performance data for the tests where ACC non-activations occurred were plotted. The Volvo S90 had a total of eight ACC non-activations in the LVS_25_0 maneuver; four when the POV was offset to the left (one in driving automation level 1 and three in level 2), three when the POV was centered in the lane (one in driving automation level 1 and two in level 2), and one when the POV was offset to the right (driving automation level 1). The Nissan Leaf had an ACC non-activation in the LVS_25_0 maneuver with the POV offset to the left (driving automation level 1).

The differences between ACC non-activation braking (CIB-based) and ACC-based braking are examined using the format used previously in Figure 9 and 3Figure 14. This approach plotted the following four SV parameters in a clockwise direction, starting from the upper left: SV Speed, SV longitudinal acceleration, FCW alert, and SV-to-POV longitudinal range. Driving automation levels 0, 1, and 2 are plotted with blue, green, and red lines, respectively. The Volvo S90 LVS_25_0 tests plotted in Figure A-2 are used as an example for interpreting these plots. This data was collected when the POV offset to the left.

The speed pane in Figure A-2 shows that two ACC-based tests (driving automation level 1 tests are green) begin slowing earlier in time, while one ACC non-activation diverged to follow the level 0 data profiles (shown in blue). All three tests performed in driving automation level 2 (shown in red) were ACC non-activations. As such, they too followed the driving automation level 0 data profiles and are easier to distinguish in the various plots because there are three of them (as opposed to the one L1 ACC non-activation). Similar ACC non-activations are shown in the figures that follow.

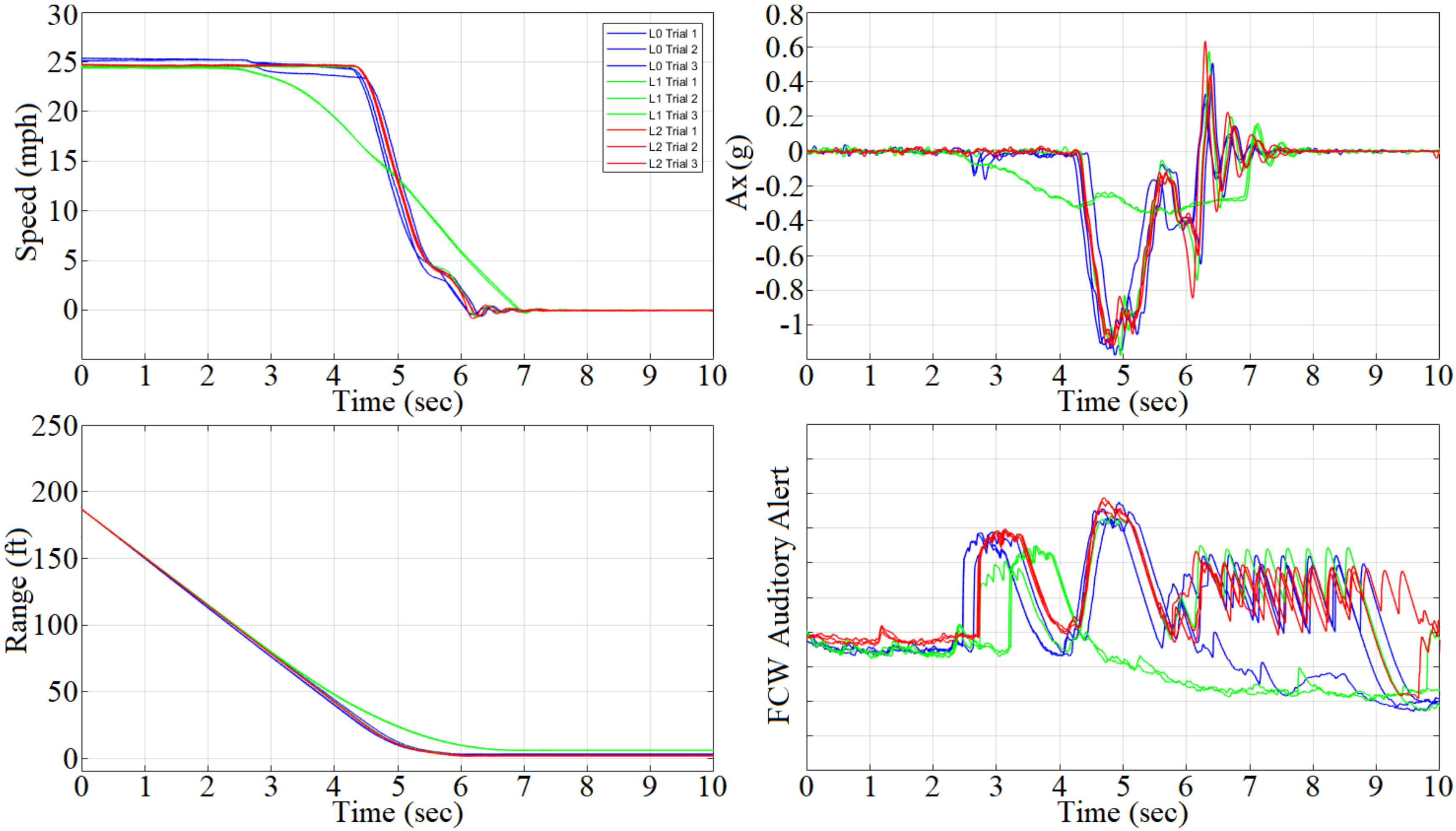

Figure A-2. Volvo LVS_25_0 left POV test data – driving automation level 0 (blue), 1 (green), and 2 (red)

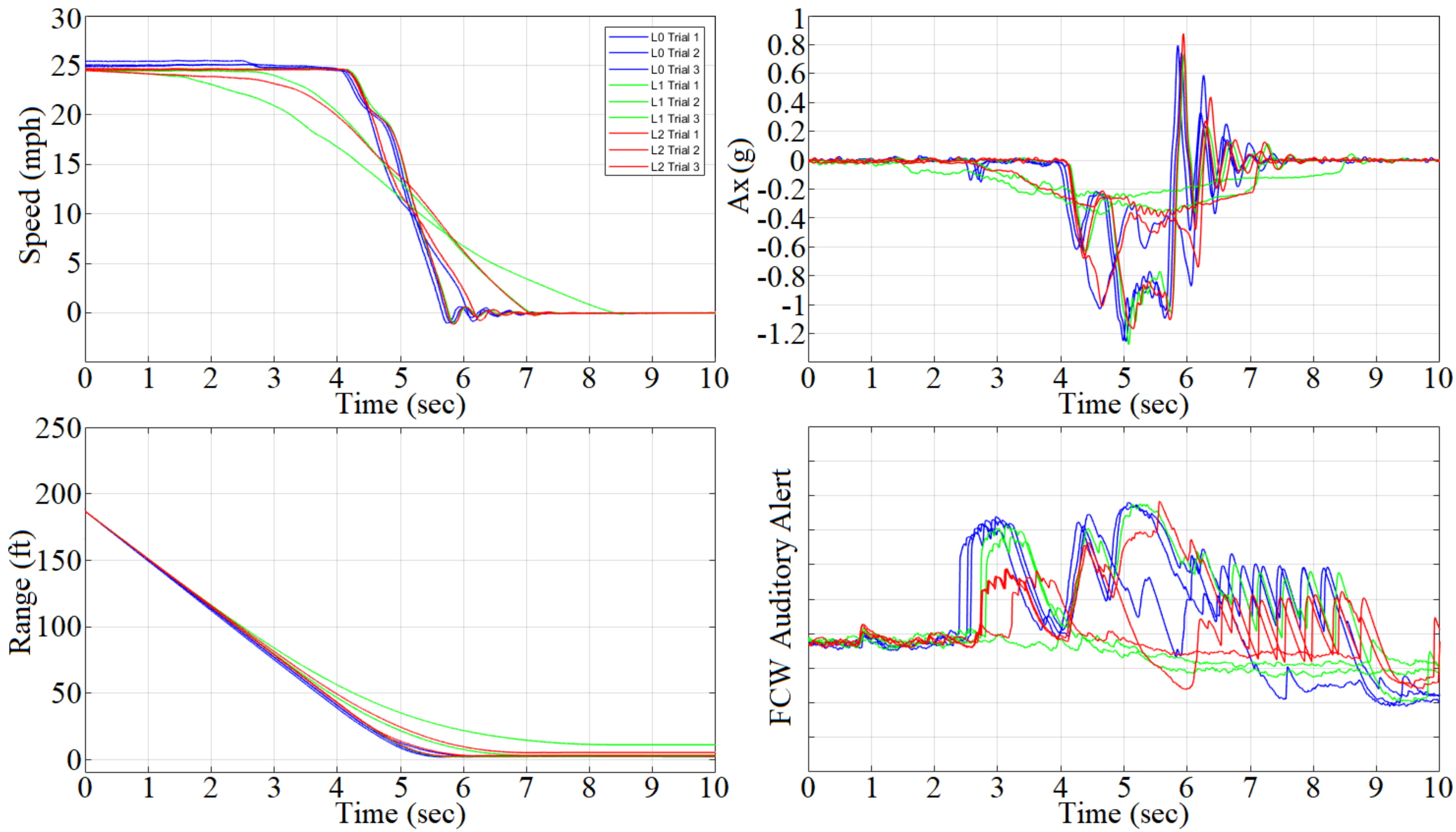

Figure A-3. Volvo LVS_25_0 centered POV test data – driving automation level 0 (blue), 1 (green), and 2 (red)

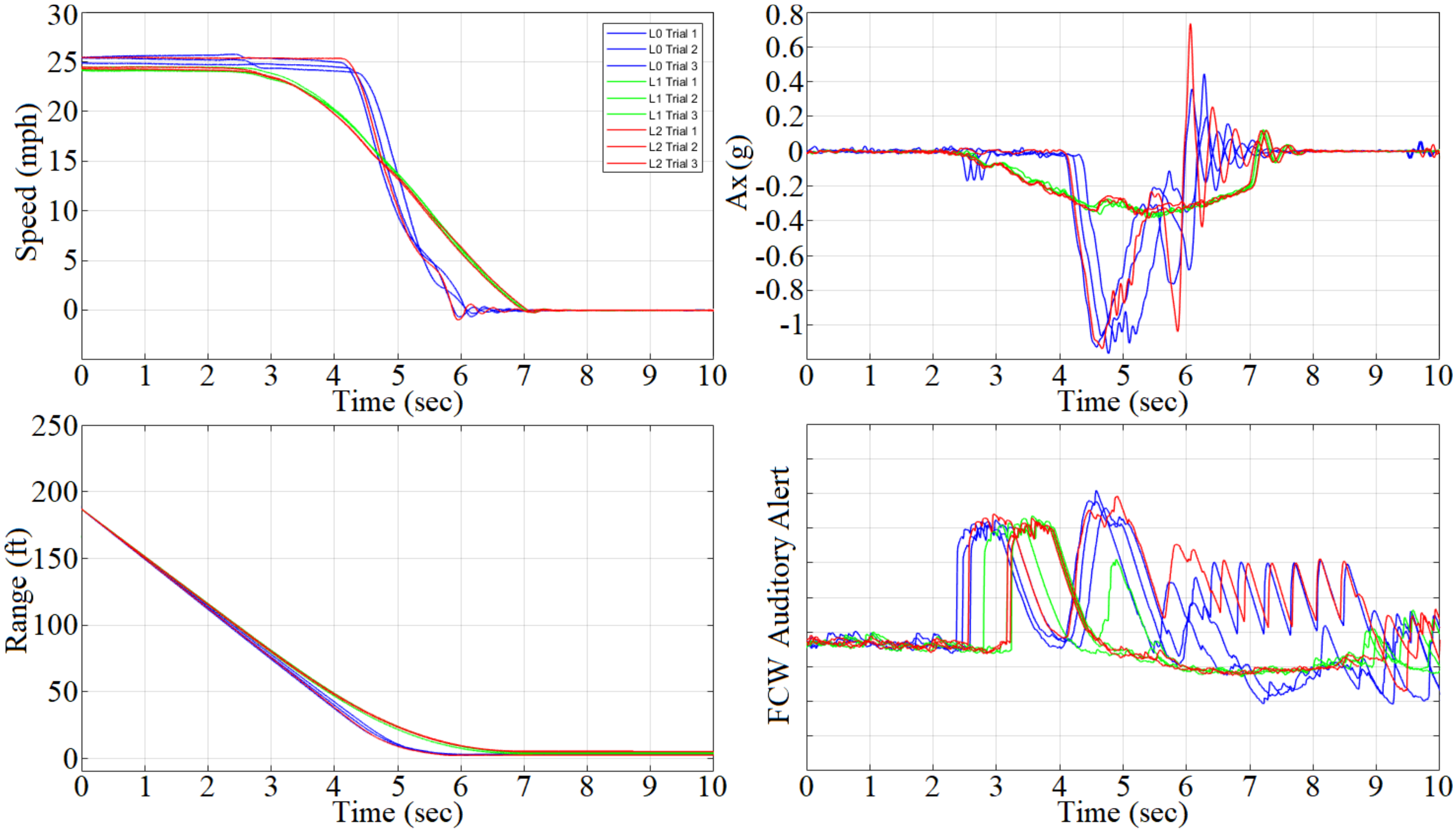

Figure A-4. Volvo LVS_25_0 right POV test data – driving automation level 0 (blue), 1 (green), and 2 (red)

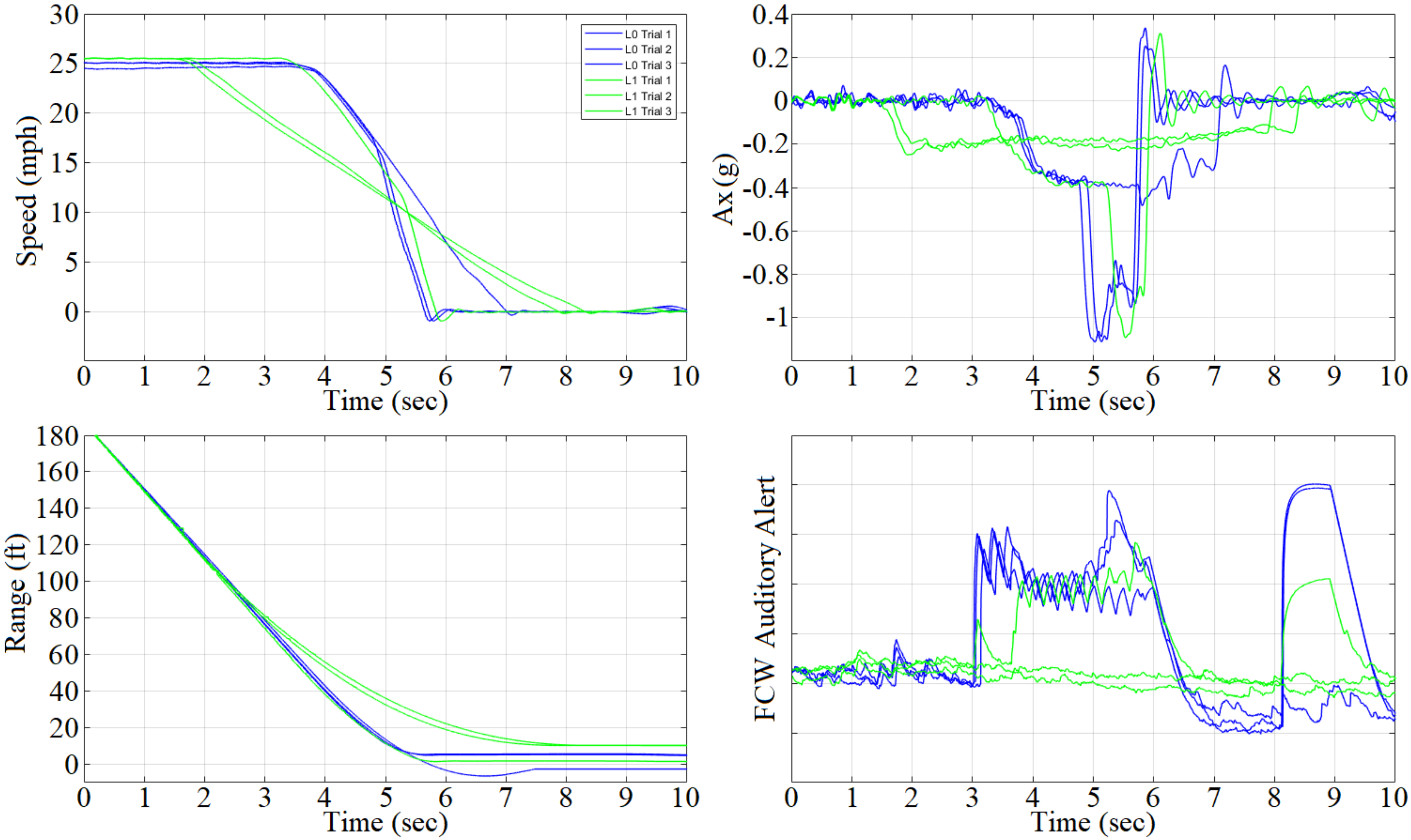

Figure A-5. Nissan Leaf LVS_25_0 left POV test data – driving automation level 0 (blue) and 1 (green)

How Differences in Data Sets Influence Analyses

The box plots in Figure A-6 show the Volvo S90 SV braking onset data from all LVS tests performed in the LVS_25_0 test conditions collapsed across driving automation levels 1 and 2. They are also split into two groups: the ACC-based SV braking onset values (upper) previously discussed in the Test Results section (Figure 39), and the ACC non-activation values (lower), labeled as "CIB" in the plot's legend.

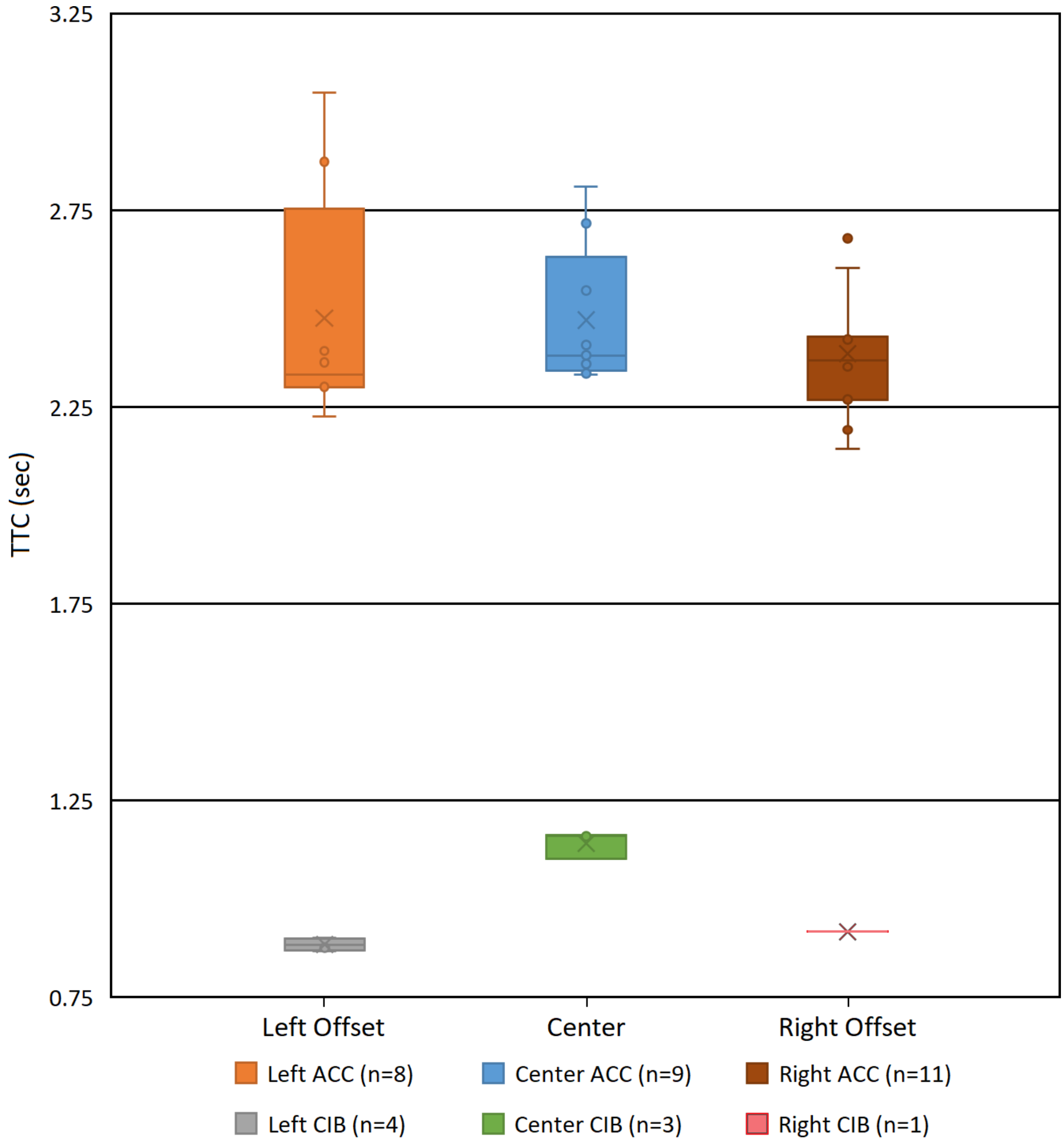

Figure A-6. Volvo S90 LVS driving automation levels 1 and 2 SV braking onset TTCs, collapsed across speed and level of automation (ACC non-activations at the bottom are labeled "CIB" in the legend)

The reader will observe that the upper group is the same data previously analyzed in Figure 39, which is shown again in Figure A-7. Those previous results showd that there were no significant differences in SV braking onset between the left, center, and right offset positions (p=0.4635) for the LVS scenario while operating in driving automation levels 1 and 2. This approach succinctly answered the research objective of "Does POV offset affect when SV braking onset occurs in driving automation levels 1 and 2?" with the implicit understanding that ACC was operating as it was intended (i.e., gradual braking early in the pre-crash timeline).

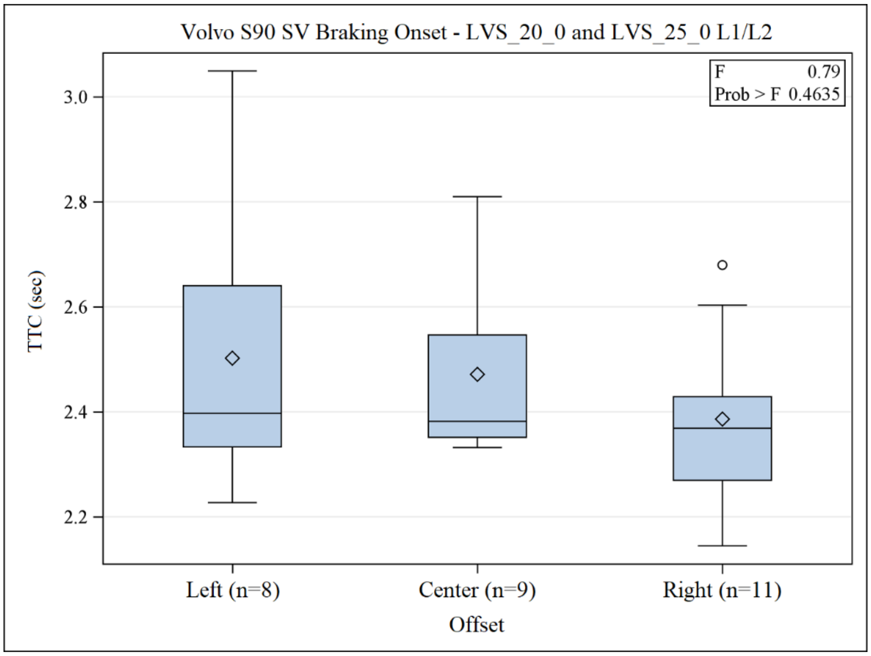

Figure A-7. Volvo S90 LVS_25_0 driving automation levels 1 and 2 SV braking onset TTCs (Figure 39 repeated)

Hypothetically, had the ACC non-activations in Figure A-6 been combined with the ACC-based SV braking onset values just examined, the resulting data would have distorted the box plots and thereby masked what was actually happening in the underlying data (i.e., that the combined data set was not normally distributed). Figure A-8 shows the distorted box plots to the left-hand side of each left, center, and right offset box plot combinations just shown in Figure A-6. The reader can see that the data from the orange and gray box plots of the left offset combined to form the blue box plot on the far left. The data from the light blue and green box plots of the center data combined to form the yellow box plot in the middle of the chart, while the data from the brown and red box plots of the right offset combined to form the dark blue box plot. As was the case with Figure A-6, the ACC non-activations at the bottom are labeled "CIB" in the legend of Figure A-8.

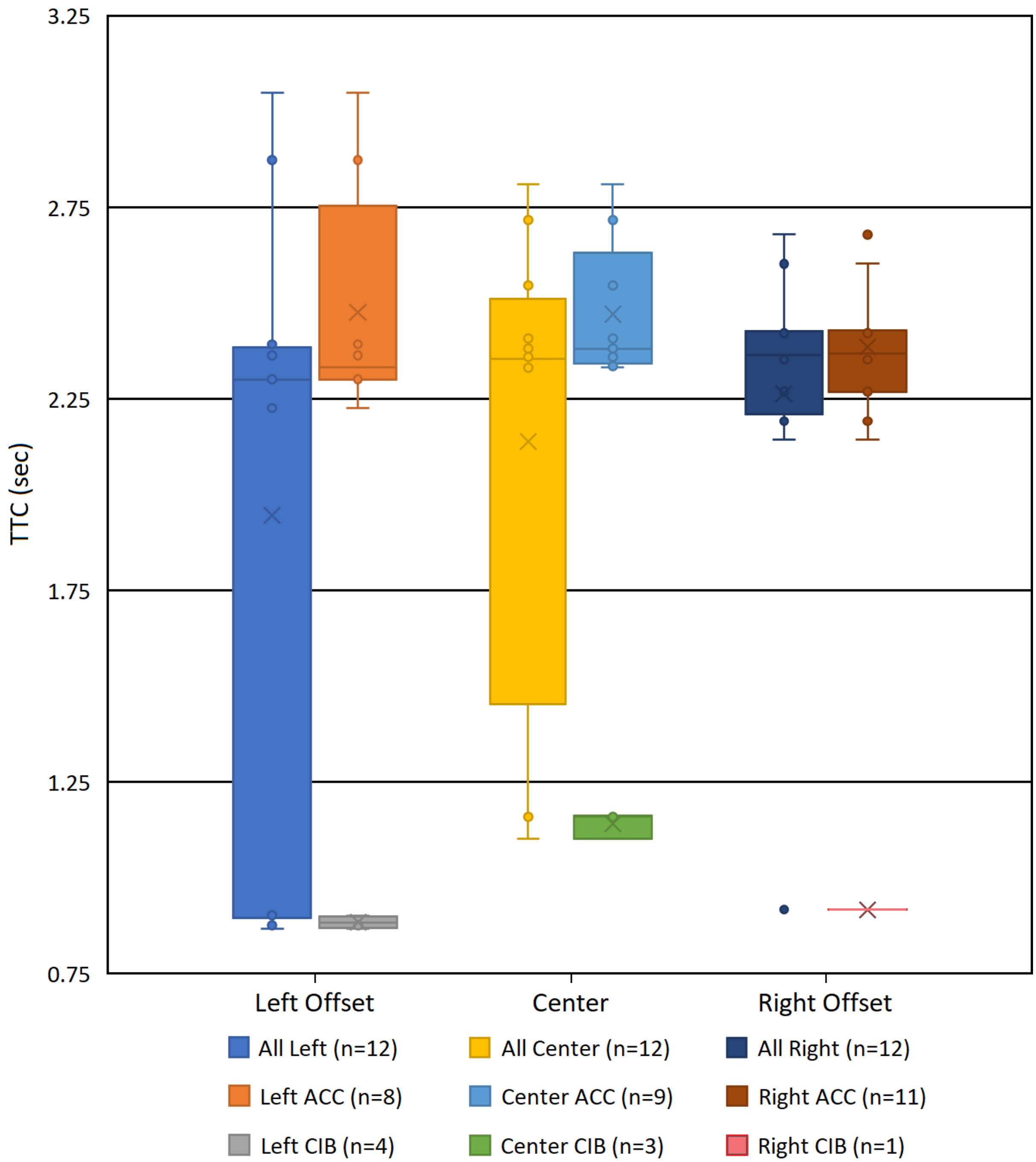

Figure A-8. Volvo S90 LVS driving automation levels 1 and 2 SV braking onset TTCs, collapsed across speed, level of automation, and ACC non-activations (within offset)

If an attempt was made to analyze the combined dataset (ACC-based SV braking onset values and ACC non-activation values) using SAS, the software will produce box plots like that shown in Figure A-9. The reader will observe that the box plots contained therein match the blue, yellow, and dark blue box plots in Figure A-8. However, such an attempt would be inappropriate.

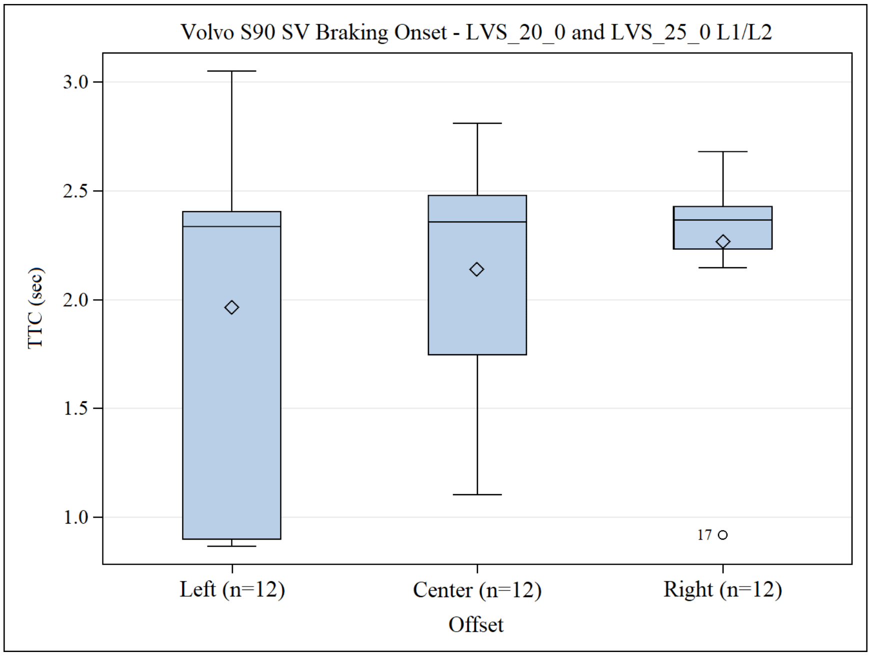

Figure A-9. Volvo S90 LVS_25_0 driving automation levels 1 and 2 SV braking onset TTCs, incorrectly combined

The underlying assumptions of ANOVA and the general linear model (GLM) are that the data be independent, "normally distributed" and have homogeneity of variance. The center and left offset data, when combined as shown in Figure A-9, have the data clustered into two groups (one at each end of the box plot), which contravenes the normally distributed assumption. There is little chance that the three sets of offset data have homogeneity of variance either, though there was no reason to formally verify that. Therefore, ACC non-activations could not be combined with the ACC-based SV braking onset TTC's since it would create a non-normal distribution.

The lone ACC non-activation observed within the Nissan Leaf's LVS_25_0 left test series uncovers another subtlety of statistics, that of hypothesis testing (see Testing Box Plots, above). To start, Figure 33 is replotted as Figure A-10. This comparison follows the stated research objective, asking "Are the center and right offset SV braking onset TTC's in driving automation level 1 equal?". There is validity to this approach because the center and right offsets were all ACC-based SV braking onsets and therefore directly comparable.

If an attempt was made to include the ACC non-activation alongside the other five ACC-based SV braking onset TTC's in one analysis, the SAS software would produce box plots like that shown in Figure A-11. This too would be inappropriate, not due to non-normality of the distributions but for different reasons.

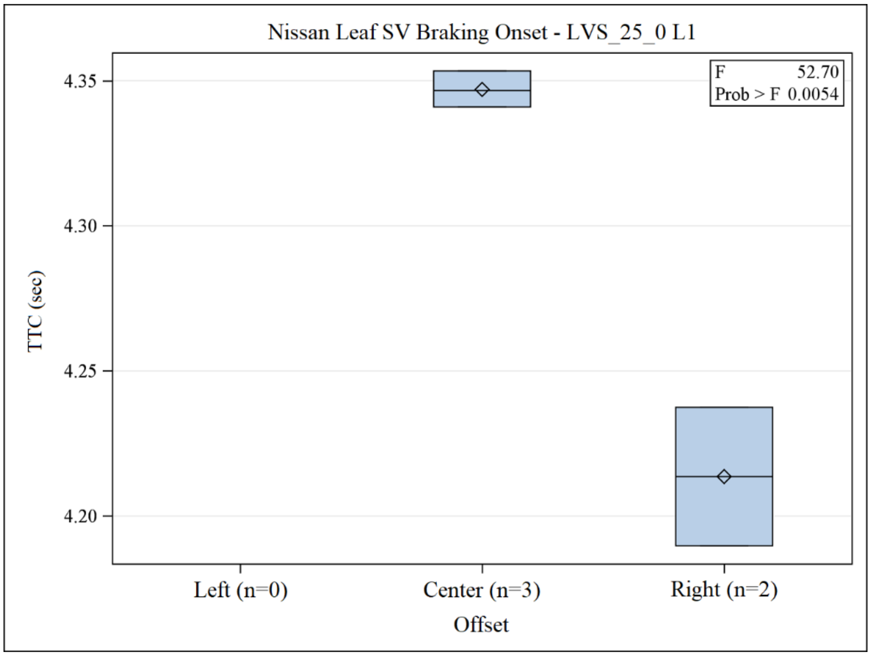

Figure A-10. Nissan Leaf LVS_25_0 driving automation level 1 SV braking onset TTCs (Figure 33 repeated)

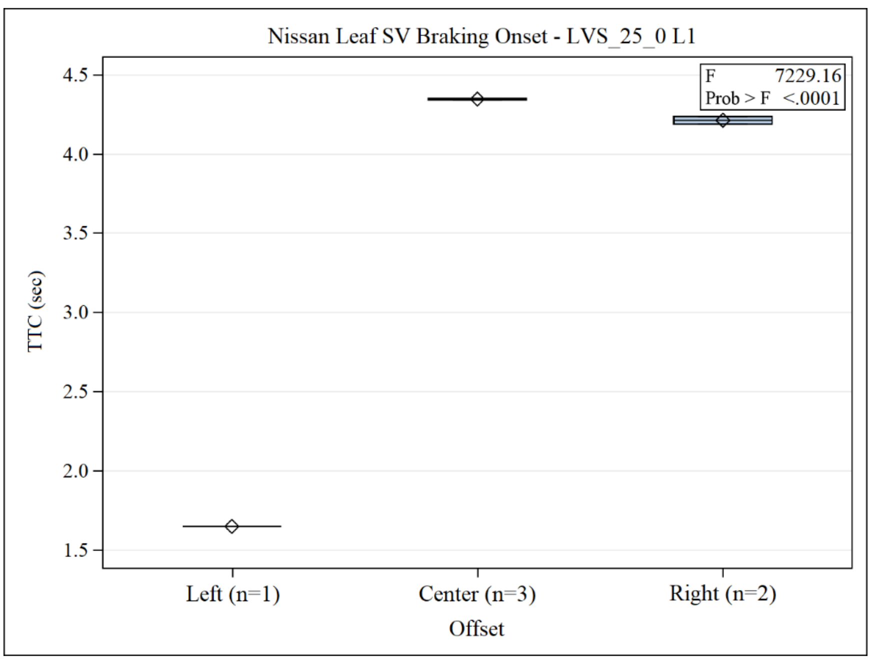

Figure A-11. Nissan Leaf LVS_25_0 driving automation level 1 SV braking onset TTCs with ACC non-activation included

Although the data are all SV braking onset TTC's (by way of the naming convention chosen), the CIB-based SV braking onset (i.e., ACC non-activation) occurred so much later in the pre-crash timeline that its inclusion distorts the analysis, making it appear to be highly significant. The inclination would be to reject the null hypothesis, except that the null hypothesis has been changed. The analysis does not compare the same thing (ACC-based SV braking onsets) across the three levels of POV offset. Instead, it compares a left ACC non-activation (CIB-based SV braking onset) to center and right offset ACC-based SV braking onsets.

Besides altering the hypothesis, another problem arises when one factor in the analysis (i.e., the left ACC non-activation) over-contributes to the error variance. Any difference that might be attributed to the center and right POV offset positions is thoroughly marginalized because the difference between the two types of SV braking onsets (CIB-based and ACC-based) completely overwhelms the analysis. This can be seen by comparing Figures A-10 and A-11. Figure A-10 suggests the center and right offset data are reasonably different. Figure A-11 suggests that the left offset data is very different than the center and right offset data, while the center and right offset data are relatively close when compared to each other.

Since the hypothesis does not match the research objective, and since combining such different types of data obscures the interpretation of this stated objective, the Nissan Leaf's sole ACC non-activation was removed from the data discussed in the Driving Automation Level 1 and 2 SV Braking Onset Results section in the third chapter.

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