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# A Test Track Comparison of the Global Vehicle Target and NHTSA's Strikeable Surrogate Vehicle

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16. Abstract

The primary objective of the work described in this report was to compare the forward collision warning (FCW) alert and crash imminent braking (CIB) intervention onset timing elicited by the Global Vehicle Target Revision E (GVT) to that observed during identical tests performed with NHTSA's Strikeable Surrogate Vehicle (SSV) benchmark. Three light vehicles and three rear-end crash scenarios were used for this evaluation. A secondary objective of this study was to describe some of the test track based use considerations related to the GVT, namely the dynamic stability and in-the-field reconstruction time after being struck by a test vehicle. GVT stability was assessed using straight line and curved path maneuvers at various speeds and lateral accelerations. Reconstruction times were examined using different impact speeds, directions of impact, and assembly crew sizes.

Multiple approaches were used to evaluate the data from this research. These analyses suggest that the Mercedes C300 and Volvo S90 responded similarly to both the GVT and SSV, with the Volvo S90 responses being the most consistent of these vehicles. The Tesla Model S test results suggest that there may have been minor differences in how it responded to the two targets, however a firmware update that occurred during testing made it unclear whether these potential differences were due to perceived dissimilarities in the targets or operational differences of the vehicle's firmware. This uncertainty meant the Tesla Model S data could not be incorporated into the final assessment of the two test targets. Going forward, this serves to highlight the importance of software control in testing a vehicle over extended periods. The GVT was physically stable and remained affixed to the robotic platform used to facilitate its movement during the high-speed longitudinal tests as well as those performed at the limit of the platform's lateral road holding capacity. Reassembly tests demonstrated that five people could reassemble the GVT significantly faster than three people (6.1 to 7.7 minutes versus 7.9 to 10.1 minutes). However, if the robotic platform needed to be re-initialized after the GVT is dislodged from it, the actual time between test trials was closer to 20 minutes regardless of reassembly team size.


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# CONVERSION FACTORS

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

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

## GLOSSARY

| | |
|---|---|
| ACC | Adaptive Cruise Control |
| AEB | Automatic Emergency Braking |
| CIB | Crash Imminent Braking |
| DBS | Dynamic Brake Support |
| Euro NCAP | European New Car Assessment Program |
| FCW | Forward Collision Warning |
| GAWR | Gross Axle Weight Rating |
| GVWR | Gross Vehicle Weight Rating |
| GST | Guided Soft Target |
| GVT | Global Vehicle Target |
| L2AV | Level 2 Automated Vehicle |
| Lidar | Light Detection and Ranging |
| 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 |
| NHTSA | National Highway Traffic Safety Administration |
| POV | Principal Other Vehicle |
| Radar | Radio Detection and Ranging |
| SRR | Short Range Radar |
| SSV | Strikeable Surrogate Vehicle |
| SAE | Society of Automotive Engineers |
| SV | Subject Vehicle |
| TPS | Throttle Position Sensor (data reported as a percentage of WOT) |
| TTC | Time to Collision |
| V2V | Vehicle-to-Vehicle Communication |
| VDA | Vehicle Dynamics Area |
| WOT | Wide Open Throttle (maximum accelerator pedal displacement) |

# EXECUTIVE SUMMARY

The primary objective of the work described in this report was to compare the forward collision warning (FCW) alert and crash imminent braking (CIB) intervention onset timing elicited by the Global Vehicle Target Revision E (GVT) to that observed during identical tests performed with NHTSA's Strikeable Surrogate Vehicle (SSV) benchmark. Three light vehicles (a 2015 Mercedes C300, a 2015 Tesla Model S 85D, and a 2017 Volvo S90) and three rear-end crash scenarios (lead vehicle stopped, lead vehicle moving, and lead vehicle decelerating) were used for this evaluation.

A second objective of this study was to describe some of the test track-based use considerations related to the GVT, namely the dynamic stability and in-the-field reconstruction time after an impact occurs. GVT stability was assessed using straight line and curved path maneuvers at various speeds and lateral accelerations. Reconstruction times after impact were examined using different impact speeds, directions of impact, and assembly crew sizes.

Multiple approaches were used to evaluate the data from this research. These analyses suggest that the Mercedes C300 and Volvo S90 responded similarly to both the GVT and SSV, with the Volvo S90 responses being the most consistent of these vehicles. Practically speaking, results from the Mercedes C300 and Volvo S90 indicate that, for these vehicles, any differences that might exist between the test targets were small enough not to appreciably influence the outcome of the tests described in this report.

The Tesla Model S test results suggest that there may have been minor differences in how it responded to the GVT and SSV, however a firmware update that occurred midway through the Tesla Model S evaluation made it unclear whether these potential differences were due to perceived dissimilarities in the test targets or operational differences of the vehicle's firmware. This uncertainty meant the Tesla Model S data could not be incorporated into the final assessment of the two test targets. Going forward, this serves to highlight the importance of software control in testing a vehicle over extended periods. Of the three used in this study, this vehicle was the only one to exhibit non-activations of FCW and CIB during testing, and they occurred during tests performed with each test target.

The two functional evaluations demonstrated that the GVT was physically stable and remained affixed to the robotic platform used to facilitate its movement during the high-speed longitudinal tests and the high-g J-turn tests performed in this study. After averaging all tests with the same team size, the reassembly time results showed that five people could reassemble the GVT significantly faster (6.1 to 7.7 minutes) than three people (7.9 to 10.1 minutes). However, if the robotic platform needed to be re-initialized after the GVT was dislodged from it, the actual time between test trials was closer to 20 minutes, regardless of assembly team size.

# 1.0 RESEARCH OBJECTIVE

The primary objective of the work described in this report was to compare the forward collision warning (FCW) and crash imminent braking (CIB) onset timing observed during tests performed with the Global Vehicle Target Revision E (GVT) to that observed during the same tests performed with NHTSA's Strikeable Surrogate Vehicle (SSV) benchmark. The three scenarios used were the lead vehicle stopped (LVS), lead vehicle moving (LVM), and lead vehicle decelerates (LVD).

A secondary objective of this study was to describe some of the test track-based use considerations related to the GVT, namely the dynamic stability while performing test maneuvers, and in-the-field reconstruction time after being struck by a test vehicle (the Subject Vehicle, or SV). GVT stability was assessed using straight line and curved path maneuvers performed at different speeds and lateral accelerations. Reconstruction times were examined following tests performed from different impact speeds and directions of impact, and with two assembly crew sizes.

# 2.0 TEST PROTOCOL

## 2.1 Test Targets

### 2.1.1. NHTSA Strikeable Surrogate Vehicle

NHTSA designed its SSV, shown in Figure 1, to facilitate safe, accurate, and repeatable test track-based automatic emergency braking (AEB) evaluations and is presently being used by the agency's New Car Assessment Program (NCAP) to objectively assess CIB and DBS performance [1]. The SSV provides visual and dimensional characteristics representative of an actual vehicle when approached from the rear to promote appropriate identification and classification by the AEB system of the vehicle being evaluated. Since the SSV body was based on a dimensional scan of a 2011 Ford Fiesta, its height and width dimensions are inherently realistic, and its carbon fiber and Kevlar composition provides radar return characteristics like those of an actual vehicle. To maximize visual realism, the SSV shell is wrapped with a commercially available vinyl material to simulate paint on the body panels and rear bumper, and a tinted glass rear window. The SSV is equipped with a simulated United States specification rear license plate. The taillights, rear bumper reflectors, and third brake light installed on the SSV are original equipment from the production vehicle. The SSV's rigid body structure allows it to maintain a consistent shape over time (i.e., visually, dimensionally, and from a radar-sensing perspective). A foam bumper is attached to the rear of the SSV to reduce the peak forces realized immediately after an impact from a test vehicle occurs.

The Michigan Transportation Research Institute (MTRI) and the University of Michigan Transportation Research Institute have assessed the radar-return characteristics for the SSV at different elevation aspects and azimuths. Results from this evaluation, documented in a report titled Radar Measurements of NHTSA's Surrogate Vehicle SSV [2], indicated that the SSV exhibited automobile-like radar-scattering characteristics at the tail-aspect for both 24 GHz and 77 GHz radar bands, and that it was suitable for evaluating radar-based detection systems.

**Figure 1: NHTSA's SSV (right) shown with the Tesla Model S evaluated in this study (left).**

### 2.1.2. Dynamic Research Inc. Guided Soft Target

The Guided Soft Target (GST) system was developed by Dynamic Research Inc. (DRI) to safely evaluate crash avoidance technologies beyond those designed to address rear-end crashes only. The GST system is comprised of two main parts, the Low Profile Robotic Vehicle (LPRV) shown in Figure 2, and the GVT shown in Figure 3. This system provides accurate closed loop control of the GST relative to a Subject Vehicle (SV) and because it is strikeable from any approach aspect it can be incorporated into nearly any pre-crash scenario. Multiple fail-safe measures are designed to ensure the safe operation of the GST. NHTSA uses a 20-ft (6.1 m) long enclosed trailer to transport its GST system to and from the test track. With the GVT already assembled to the top of the LPRV, it takes three people approximately 20 minutes to unload and initialize the GST.

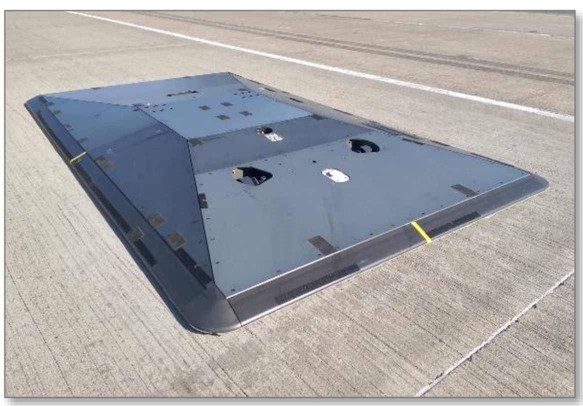


**Figure 2: DRI GST LPRV.**

**Figure 3: GVT (revision E) atop of the LPRV.**

### 2.1.2.1 Low Profile Robotic Vehicle

The LPRV contains the batteries, drive motors, GPS receiver, and most of the control electronics for the GST system. It is approximately 110” L × 60” W × 4” H (2.8 m × 1.5 m × 0.1 m), weighs just over 700 lbs (318 kg), and can be driven over by most passenger cars and heavy vehicles with axles loaded up to 20,000 lbf (9071.8 kg). The LPRV has a pneumatic suspension that compresses when 150 lbf (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 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.

### 2.1.2.2 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 the skins are attached to. 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 (see Figure 4).

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, a series of five public workshops and three radar tuning meetings were held from August 2015 through 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.

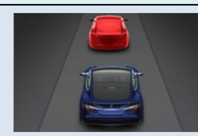
After feedback from the automotive vehicle manufacturers and suppliers had been incorporated into the design of the GVT (known at the time as revision E), a series of high-resolution radar scans were performed by MTRI using the same equipment previously used to measure the radar characteristics of the SSV 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 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 [3].


**Figure 4: GVT reassembly sequence example (left to right, top to bottom).**

## 2.2 Subject Vehicles

A brief overview of the subject vehicles used for the work described in this report, their sensing technologies, and the visual FCW alert presented in their respective instrument panels, is provided in Table 1 and Sections 2.2.1, 2.2.2, and 2.2.3. Vehicle test weights are provided in **Appendix A**.

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

| Subject Vehicle | Sensing Technology | | FCW Visual Alert |
|---|---|---|---|
| | Radar | Vision | |
| 2017 Volvo S90 T6 AWD | One LRR (77 GHz) | Mono-camera |  |
| 2015 Mercedes C300 4MATIC | Two SRR (24 GHz) One LRR (77 GHz) | Stereo-cameras |  |
| 2015 Tesla Model S 85D | One LRR (77 GHz) | Mono-camera |  |

### 2.2.1. 2017 Volvo S90 T6

The 2017 Volvo S90 T6 (Volvo S90) is an all-wheel drive, four-door passenger car equipped with Volvo Intellisafe ACC, AEB, and level 2 automated vehicle driving capability. Automatic speed reductions achieved by this vehicle are produced by the combination of ACC, AEB, transmission downshifting, and engine braking. A description of the forward-looking sensors used by the Volvo S90 is provided in Table 1.

The Volvo S90 features three driver-selectable “Individual Drive Mode” settings: Eco, Comfort, and Dynamic. The tests described in this report were conducted in “Dynamic Mode” so that the vehicle’s “Auto Start/Stop” feature was disabled.[1]

A full FMVSS No. 135 brake burnish was performed to condition the Volvo S90 brake pads and rotors prior to the evaluations performed in this study.

[1] “Auto Start/Stop” is a fuel-saving feature that shuts the engine down whenever the car is brought to a stop. When the car restarts, a brief drop in voltage can potentially cause the instrumentation installed in the vehicle to reboot (including the GPS), requiring reinitialization. To eliminate the potential for this to unnecessarily extend the time needed for testing, the stop/start feature was turned off. The Volvo website indicated that Dynamic Mode also changes transmission shifting, steering response, shock dampening and ride height. There was no indication therein that Dynamic Mode altered AEB functionality.

### 2.2.2. 2015 Mercedes C300 4MATIC

The 2015 Mercedes C300 4MATIC (Mercedes C300) is an all-wheel drive, four-door passenger car equipped with adaptive cruise control (ACC), AEB,[2] and SAE level 2 automated vehicle driving capability. When presented with a potential rear-end crash scenario, the Mercedes C300 automatically reduces speed using a combination of ACC, AEB, transmission downshifting, and engine braking. A description of the forward-looking sensors used by the Mercedes C300 is provided in Table 1.

Before the evaluations described in this report were performed, the Mercedes C300 was used in a NHTSA test program that required an FMVSS No. 135 brake burnish be performed. Therefore, since a full burnish was not necessary for the tests described in this report, an FMVSS No. 126 “mini-burnish” was used to re-condition the brake pads and rotors [4]. This process ensured an objective baseline from which the vehicle’s AEB braking performance could be assessed without incurring the time or expense of performing a second (and unnecessary) FMVSS No. 135 burnish.

### 2.2.3. 2015 Tesla Model S 85D

The 2015 Tesla Model S 85D (Tesla Model S) is a full-sized, all-electric five-door passenger car with level 2 automated vehicle driving and parking capabilities. A unique version[3] of firmware 7.1 was installed during the SSV-based AEB tests described in this report, whereas Tesla production firmware version 8.0.2.42.40 was used for the GVT-based evaluations. The automatic speed reductions achieved by the Tesla Model S are produced by a combination of ACC, AEB, and regenerative braking. A description of the forward-looking sensors used by the Tesla Model S is provided in Table 1.

A full FMVSS No. 135 brake burnish was performed to condition the Tesla Model S brake pads and rotors prior to the evaluations performed in this study [5].

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

[3] To facilitate testing within the confines of the Transportation Research Center, Inc. proving grounds, this version (7.1.103.14.1) relaxed certain software restrictions used on public roadways, which. The adjustments made by Tesla are not believed to have had any effect on the operation or functionality of the vehicle’s FCW and AEB systems, or the outcome of the tests described in this report.

## 2.3 Crash Avoidance Technologies

The Tesla Model S, Mercedes C300, and Volvo S90 were each equipped with crash avoidance technologies inclusive of AEB systems containing FCW, CIB, and DBS. While the specific system responses of an AEB system depend on a combination of the vehicle manufacturer's implementation and the driving situation, they typically use an FCW to alert the driver of the imminent collision, then automatically provide a CIB or DBS intervention (if necessary) to prevent or mitigate the rear-end crash. DBS was not used for the tests described in this report, therefore only details about FCW and CIB system operation are described Sections 2.3.1 and 2.3.2.

### 2.3.1. Forward Collision Warning

An FCW system utilizes forward-looking sensors[4] to monitor the range and range rate between a moving vehicle (i.e., the SV) and another vehicle or object in its forward path. If the system determines a collision is likely, an FCW is presented to the driver by means of an auditory, visual, and/or haptic alert. The timing of an FCW alert relative to an imminent rear-end collision is intended to provide the driver with enough time to acknowledge the alert, assess the potential hazard, and respond with the appropriate combination of braking and/or steering needed to avoid a crash.

### 2.3.2. Crash Imminent Braking

A CIB system uses forward-looking sensor data to determine when automatic braking is necessary to mitigate or avoid a crash, typically in situations where the driver fails to apply any braking or steering in response to an FCW alert. Depending on the system design and driving circumstances, a CIB system may apply up to the maximum braking available from the vehicle's foundation brakes.

## 2.4 Driver-Configurable Settings

The Tesla Model S and Volvo S90 were both equipped with driver-configurable FCW alert settings. In the case of the Tesla Model S, the driver also had the option to select one of two regenerative braking modes. This was important because the setting selected was capable of directly effecting the vehicle speed at the time of a CIB intervention; a factor that may determine whether crash avoidance was achieved or not. Details about which settings were used for the tests described in this report are provided in Sections 2.4.1 and 2.4.2.

### 2.4.1. FCW Settings

The Tesla Model S, Mercedes C300, and Volvo S90 were each equipped with an FCW system designed to activate before a CIB intervention. The Tesla Model S and Volvo S90 systems allowed the driver to manually choose from one of three proximity settings. Prior to performing

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

any of the tests trials described in this report, NHTSA experimenters confirmed that the most conservative FCW setting had been specified. These settings, shown in Figures 5 and 6, allowed the alerts to be presented at the longest possible time-to-collision (TTC); i.e., the earliest possible alert timing. For a given SV, the same FCW settings were used during evaluations performed with each surrogate vehicle.


**Figure 5: Tesla Model S FCW settings. The "earlier" setting was selected for all tests described in this report.**

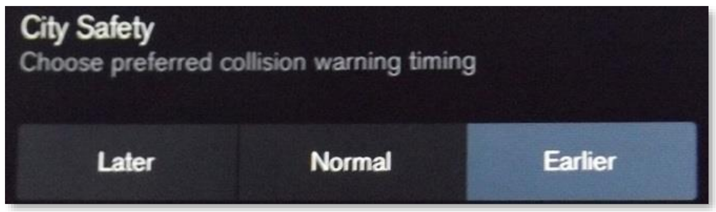


**Figure 6: Volvo S90 FCW settings. The "early" setting was selected for all tests described in this report.**

For each vehicle, the FCW included auditory and visual components, and the alerts were presented concurrently. The visual alerts (previously shown in Table 1) were presented in the center of the respective instrument panels. The auditory alerts of the Tesla Model S and Volvo S90 FCW were presented through the audio system speakers, whereas the Mercedes C300 alert used a piezoelectric speaker located behind the instrument panel.

### 2.4.2. Regenerative Braking Setting

The Tesla Model S was equipped with a regenerative braking system. When the driver releases the accelerator pedal, the electric drive motors function as generators to convert kinetic energy into electricity to charge the vehicle's batteries. The Tesla Model S allows the driver to select one of the two regenerative braking modes shown in Figure 7. From a braking perspective, the "standard" mode provides a greater deceleration (approximately 0.14g or 1.37 $m/s^2$). All Tesla Model S tests described in this report were performed using the "standard" regenerative braking mode.

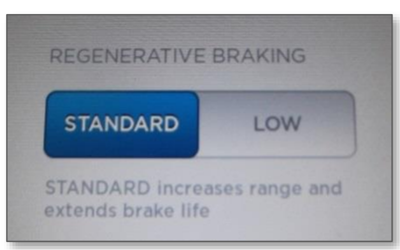


**Figure 7: Tesla Model S regenerative brake settings. Selection is available from a menu on the center display touchscreen.**

## 2.5 Test Scenarios and Speeds

Tables 2 through 5 list the test maneuver speeds used for this study. Table 2 presents the speed combinations of the three rear-end pre-crash scenarios used to evaluate FCW and CIB onset timing, where the test targets each functioned as the Principal Other Vehicle (POV). Tables 4 and 5 describe the functional evaluations. Each test condition (scenario and test speed combination) described in Table 2 was repeated three times. Each test conditions described in Tables 3 through 5 was performed once.

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

| Pre-Crash 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) |

**Table 3. GVT Straight Line Stability Test Speeds (n=1 per test condition)**

| Maneuver | Nominal Test Speeds in mph (km/h) | | | |
|---|---|---|---|---|
| Straight Line Stability | 10 (16.1) | 20 (32.2) | 30 (48.3) | 40 (64.4) |

**Table 4. GVT Cornering Stability Test Speeds (n=1 per test condition)**

| Maneuver | Commanded Lateral Accelerations in g (m/s$^2$) | | | |
|---|---|---|---|---|
| J-Turn Stability at 25 mph (40.2 km/h) | 0.3 (2.9) | 0.4 (3.9) | 0.5 (4.9) | 0.6 (5.9) |

**Table 5. GVT Reconstruction Time Matrix (n=1 per test condition)**

| Direction of Impact | Nominal Test Speeds | | | |
|---|---|---|---|---|
| | 10 mph (16.1 km/h) | | 25 mph (40.2 km/h) | |
| Front | 3 people | 5 people | 3 people | 5 people |
| Side | 3 people | 5 people | 3 people | 5 people |
| Rear | 3 people | 5 people | 3 people | 5 people |

The LVS, LVM, and LVD tests used for the work described in this report were based on those specified in the NHTSA NCAP FCW and CIB test procedures [6,7], but were adjusted to include a greater number of SV and POV speed combinations, and included three repeated trials per test condition rather than seven. Each LVS, LVM, and LVD test condition used in this study was designed to conclude with an SV-to-POV impact if the SV did not brake automatically. The FCW and CIB responses were used as dependent measures.

Test tolerances for the LVS, LVM, and LVD tests, during an interval from TTC = 5.0 seconds to the onset of the FCW alert, were as follows:

- 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 maneuvers 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.

## 2.6 Test Locations

The tests described in this report were performed from July 26, 2016 to May 15, 2017 at the Transportation Research Center, Inc. (TRC) proving grounds, in East Liberty, OH. The concrete surface of the Skid Pad and the Skid Pad North Loop were used for the FCW and CIB assessments, facilities with nominal peak and slide frictional coefficients of 0.93 and 0.88, respectively. The GVT stability tests were run on the Vehicle Dynamics Area, an asphalt-paved surface with nominal peak and slide frictional coefficients of 0.92 and 0.87, respectively. All tests were performed on dry pavement at temperatures above 40°F (4.4°C).

# 3.0 TEST RESULTS

For each test condition, two AEB-based metrics were used to compare the SV response to the GVT versus the SSV benchmark:  FCW alert onset and CIB intervention onset. Both onsets were measured in time to collision, or TTC. Examining these metrics provided a practical and objective way to assess how similar the rear aspect of each surrogate vehicle appeared to the SV without having to directly access, monitor, or analyze the AEB control algorithms (which was not possible given their proprietary nature). When an SV responds similarly to both targets, then there is some certainty that any differences between targets were small enough not to influence test outcome. Section 3.1 discusses the FCW and CIB onset results.

**Note:**  Although the appearance of a test target can also affect SV speed reduction and frequency of impact, a comparative analysis using these two metrics is not be included in this report.
The GVT stability results are included in Section 3.2. The reconstruction time results were also included in the GVT Notice of Availability but are briefly discussed in Section 3.3.

## 3.1 FCW Onset and CIB Onset Responses

Section 3.1 presents an examination of the FCW and CIB onset TCC ranges for each combination of SV and test condition. In Section 3.1.1, a tabular summary of the onset TTC ranges is presented. Section 3.1.2 uses the data introduced in Section 3.1.1 to visually demonstrate how the onset TTCs were distributed within their respective ranges, and the extent to which the onset TTC ranges from the two targets overlapped within each combination of SV and test condition. Section 3.1.3 considers the same data using a different approach; it presents the median values of the three tests nominally performed within each test condition, by each SV. Section 3.1.4 uses the unequal variance t-test as an analytical method to assess whether there is a statistical difference between the vehicles' response to SSV and GST.

### 3.1.1. Tabular Summary of FCW and CIB Onset TTCs

The FCW and CIB onset TTC ranges observed for each combination of SV, test condition, and surrogate vehicle are provided in Tables 6 and 7, respectively. Three vehicles completed nine test conditions for each target, generating 27 sets of onset TTC ranges to compare. **Adjacent pairs of SSV and GVT data are colored identically to indicate whether the FCW or CIB onset TTC ranges overlapped or not.** Cells that are shaded green indicate that there was overlap in the two targets' data, whereas yellow cell shading indicates that a gap exists between the data ranges (i.e., they were separated).

**Note:** The Tesla Model S failed to produce FCW and/or CIB responses during some test trials. These nonexistent responses are excluded from the TTC onset ranges shown in Tables 6 and 7 because using zero as the lower bound creates an abnormally wide TTC range that would be overly inclusive and thereby bias subsequent comparisons.

The FCW onset TTC range data presented in Table 6 were grouped into two categories, overlap and separation.

- Overlap was present in 16 of the 27 FCW onset TTC range comparisons.
  - The upper bound of one range was 0.001 second greater than the lower bound of the other in two of these comparisons (i.e., the least amount of overlap).
  - One range was entirely within the other in 6 of the 27 comparisons (i.e., complete overlap was observed).
  - The remaining eight comparisons had varying amounts of overlap that fell between the two previous extremes.
- Eleven comparisons had separation between the ranges.
  - The Volvo S90 had one comparison with a separation between the FCW onset TTC ranges of 0.031 seconds (LVS_20_0).
  - The Mercedes C300 had separations between four of its FCW onset TTC range comparisons, ranging from 0.002 to 0.012 seconds.
  - The Tesla Model S had separations between six of its FCW onset TTC range comparisons, ranging from 0.001 to 0.092 seconds.

The CIB onset TTC range data presented in Table 7 were also grouped into categories of overlap and separation.

- Overlap was present in 19 of the 27 CIB onset TTC range comparisons.
  - One range was entirely within the other in 13 of the 27 comparisons (i.e., complete overlap).[5]
  - One of these comparisons had an overlap that was only 0.005 seconds (LVS_25_0 tests performed with the Mercedes C300), which was the least amount of overlap of the CIB onset TTC ranges.
  - The remaining five comparisons had varying amounts of overlap that fell between the two previous extremes.
- Eight CIB onset TTC range comparisons had separation between the ranges.
  - The Volvo S90 had separations between two of its CIB onset TTC range comparisons; one was 0.013 seconds and the other was 0.029 seconds.
  - The Mercedes C300 also had separations between two of its CIB onset TTC range comparisons; one was 0.024 seconds and the other was 0.046 seconds.
  - The Tesla Model S had separations between four of its CIB onset TTC range comparisons, ranging from 0.003 to 0.067 seconds.
  - Separation was observed for each of the LVS_15_0 scenario comparisons (i.e., for each of the SVs evaluated in this report).

[5] The 13 instances of CIB onset overlap include two test conditions (LVM_25_10 and LVM_35_20) where the Tesla Model S did not activate CIB for any of the trials. Overlap was said to exist for these conditions because the vehicle's lack of response was the same for both test targets. These non-activations differ from those noted earlier in this section because the deceleration produced by the Tesla Model S regenerative braking system the after release of the accelerator pedal was great enough to avoid impacting either of the two test targets.

**Table 6. GVT Versus SSV FCW Onset Range Summary**

| Crash Imminent Test Conditions | | | Range of FCW onset TTCs (seconds) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pre-Crash Scenario | Test Speeds (mph) | | 2017 Volvo S90 | | 2015 Mercedes C300 | | 2015 Tesla Model S | |
| | SV | POV | SSV | GVT | SSV | GVT | SSV | GVT |
| Lead Vehicle Stopped (LVS) | 15 | 0 | 2.130 – 2.145 | 2.139 – 2.229 | 1.621 – 1.643 | 1.647 – 1.709 | 2.021 – 2.100 | 2.031 – 2.151 |
| | 20 | 0 | 2.309 – 2.441 | 2.472 – 2.510 | 1.797 – 1.842 | 1.854 – 1.894 | 2.363 – 2.446 | 2.423 – 2.554 |
| | 25 | 0 | 2.632 – 2.643 | 2.642 – 2.728 | 1.953 – 2.006 | 1.967 – 2.021 | 2.721 – 2.776 | 2.803 – 2.866 |
| Lead Vehicle Moving (LVM) | 25 | 10 | 2.011 – 2.044 | 2.043 – 2.125 | 1.421 – 1.867 | 1.483 – 1.825 | 2.643 – 2.739 | 2.831 – 2.845 |
| | 35 | 10 | 2.846 – 2.942 | 2.674 – 2.857 | 2.233 – 2.333 | 2.341 – 2.502 | 3.201 – 3.355 | 3.193 – 3.288 |
| | 35 | 20 | 2.240 – 2.454 | 2.222 – 2.337 | 2.149 – 2.185 | 2.040 – 2.185 | 3.058 – 3.214 | 3.215 – 3.283 |
| | 45 | 20 | 2.752 – 2.801 | 2.684 – 2.775 | 2.332 – 2.357 | 2.359 – 2.444 | 3.131 – 3.185 | 3.203 – 3.239 |
| Lead Vehicle Decelerates (LVD) | 25 | 25 | 1.934 – 2.632 | 1.982 – 2.055 | 1.735 – 1.908 | 1.541 – 1.936 | 2.043 – 2.052[1] | 2.067 – 2.198 |
| | 35 | 35 | 2.060 – 2.230 | 2.065 – 2.209 | 2.055 – 2.149 | 1.866 – 2.231 | 1.860 – 2.145 | 2.221 – 2.393[2] |

[1] No FCW alert was presented during Test 107.
[2] Only two valid tests were performed in this series (Tests 312 and 316).

**Table 7. GVT Versus SSV CIB Onset Range Summary**

| Crash Imminent Test Conditions | | | Range of CIB onset TTCs (seconds) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pre-Crash Scenario | Test Speeds (mph) | | 2017 Volvo S90 | | 2015 Mercedes C300 | | 2015 Tesla Model S | |
| | SV | POV | SSV | GVT | SSV | GVT | SSV | GVT |
| Lead Vehicle Stopped (LVS) | 15 | 0 | 0.651 – 0.721 | 0.734 – 0.780 | 0.688 – 0.744 | 0.768 – 0.811 | 0.402 – 0.454 | 0.316 – 0.371 |
| | 20 | 0 | 0.799 – 0.841 | 0.822 – 0.854 | 0.870 – 0.919 | 0.965 – 0.976 | 0.420 – 0.515 | 0.350 – 0.495 |
| | 25 | 0 | 1.004 – 1.048 | 1.040 – 1.044 | 0.990 – 1.029 | 1.024 – 1.071 | 0.594 – 0.615 | 0.488 – 0.527[4] |
| Lead Vehicle Moving (LVM) | 25 | 10 | 0.834 – 0.882 | 0.848 – 0.882 | 0.450 – 0.928 | 0.509 – 0.824 | –[2] | –[2] |
| | 35 | 10 | 1.063 – 1.140 | 1.127 – 1.158 | 1.128 – 1.196 | 1.149 – 1.211 | 0.474 – 0.553 | 0.458 – 0.539 |
| | 35 | 20 | 0.735 – 0.836 | 0.830 – 0.834[1] | 1.147 – 1.213 | 1.080 – 1.233 | –[2] | –[2] |
| | 45 | 20 | 1.129 – 1.199 | 1.126 – 1.155 | 1.148 – 1.227 | 1.184 – 1.221 | 0.468 – 0.518 | 0.385 – 0.465 |
| Lead Vehicle Decelerates (LVD) | 25 | 25 | 1.188 – 1.360 | 1.258 – 1.293 | 0.815 – 1.109 | 0.554 – 1.124 | 0.508[3] | 0.452 – 0.497 |
| | 35 | 35 | 1.132 – 1.215 | 1.244 – 1.353 | 1.181 – 1.332 | 0.952 – 1.520 | 0.489 – 0.567 | 0.498 – 0.500[5] |

[1] Valid CIB onset data were only available for two tests performed in this series (Tests 121 and 122).
[2] No CIB activation was observed for any of the three tests in this scenario.
[3] No CIB activation was observed during Tests 106 and 107.
[4] No CIB activation was observed during Test 280.
[5] Only two valid tests were performed in this series (Tests 312 and 316).

### 3.1.2. Graphical Presentation of FCW and CIB Onset TTCs

This section contains a series of figures to help the reader visualize how the FCW and CIB onset TTCs shown in Tables 4 and 5 were distributed within the respective ranges for each combination of SV, test condition, and surrogate vehicle. For these figures, the two measures are presented as X (FCW onset) and Y (CIB onset) coordinates. This plotting technique was simply used as an efficient way to present a significant amount of data, not to infer the operation of one system is dependent on that of the other.

Results from tests performed with the Volvo S90 are shown in Figures 8 through 10. Data produced during evaluation of the Mercedes C300 are shown in Figures 11 through 13. Tesla Model S results are presented in Figures 14 through 16 (including the trials inclusive of an FCW alert but no CIB intervention). For all plots, the GVT- and SSV-based data points are represented using round (●) and square markers (■), respectively. Marker color is used to group tests performed with the same combination of SV and POV speeds per scenario.

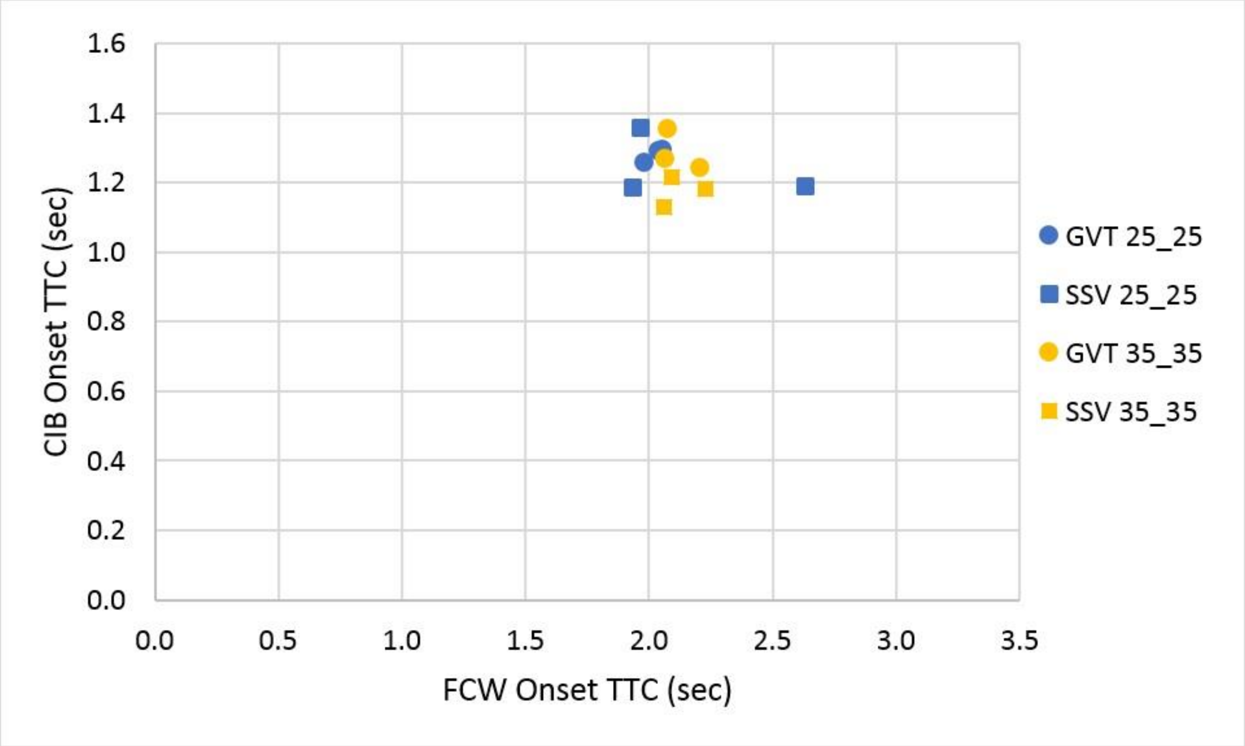


**Figure 8: FCW and CIB onset timings to both targets during LVD scenario (Volvo S90).**

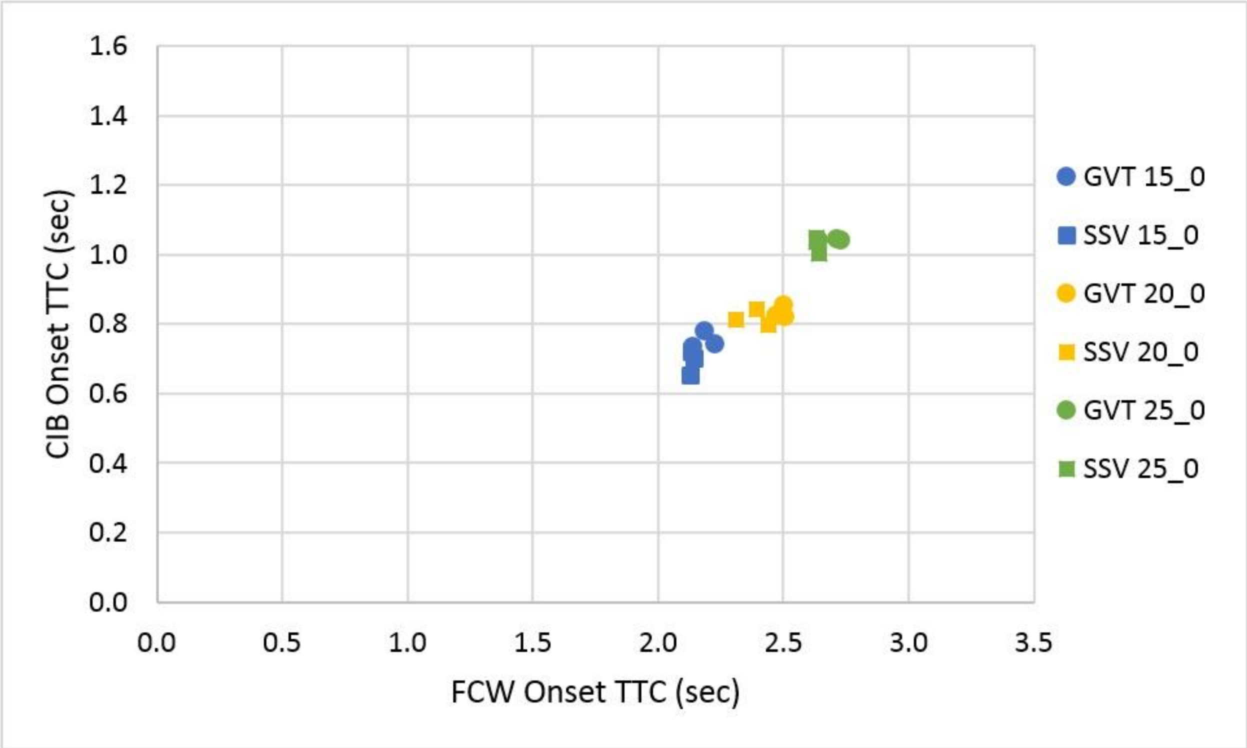


**Figure 9: FCW and CIB onset timings to both targets during LVS scenario (Volvo S90).**

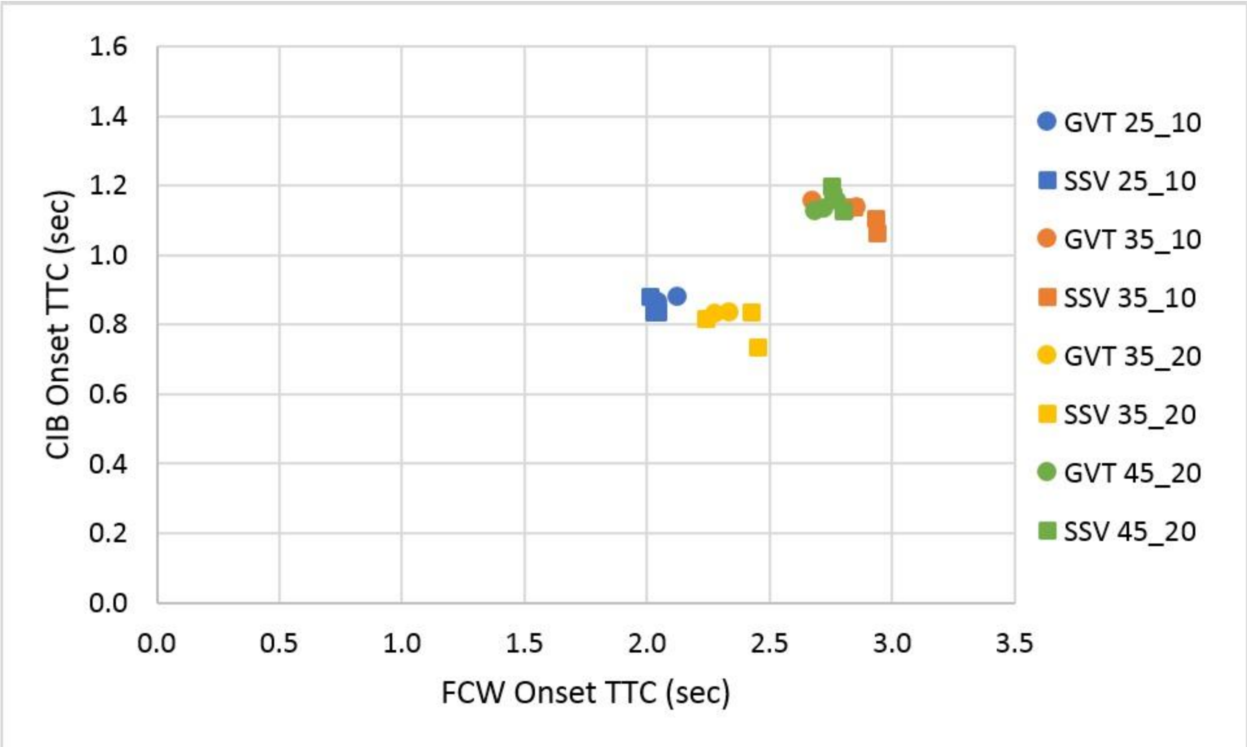


**Figure 10: FCW and CIB onset timings to both targets during LVM scenario (Volvo S90).**

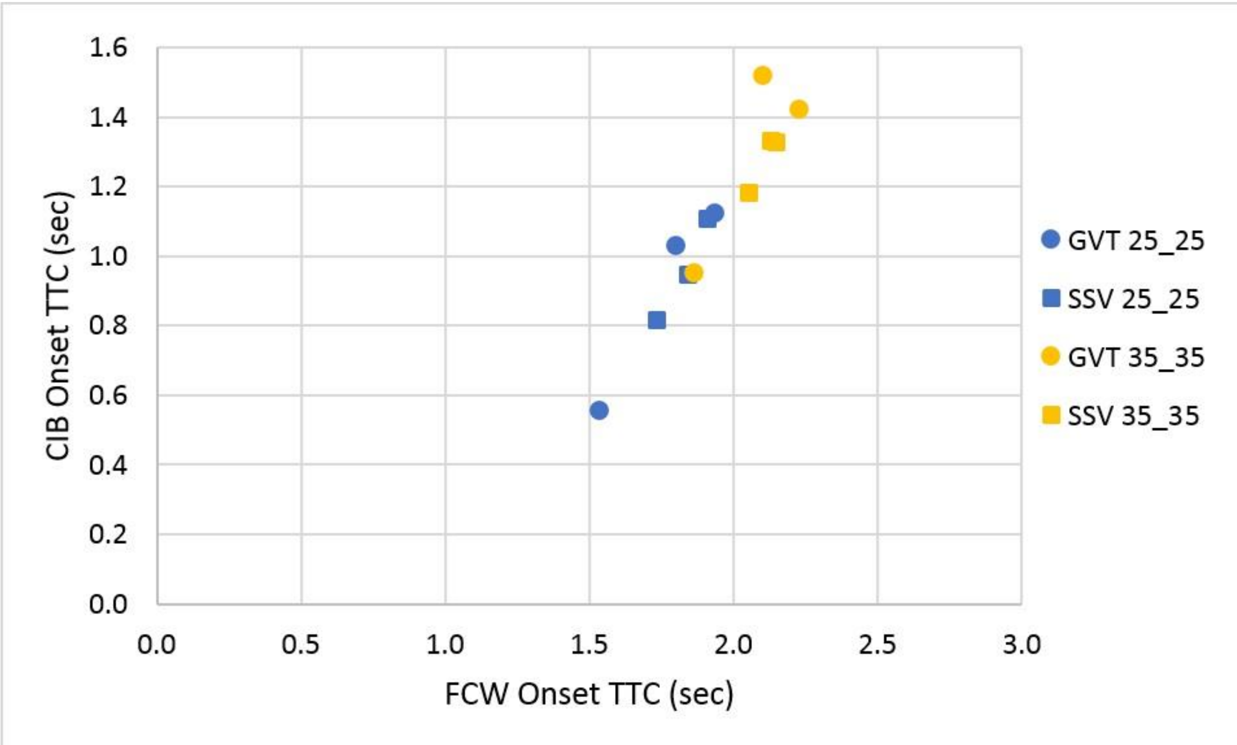


**Figure 11: FCW and CIB onset timings to both targets during LVD scenario (Mercedes C300).**

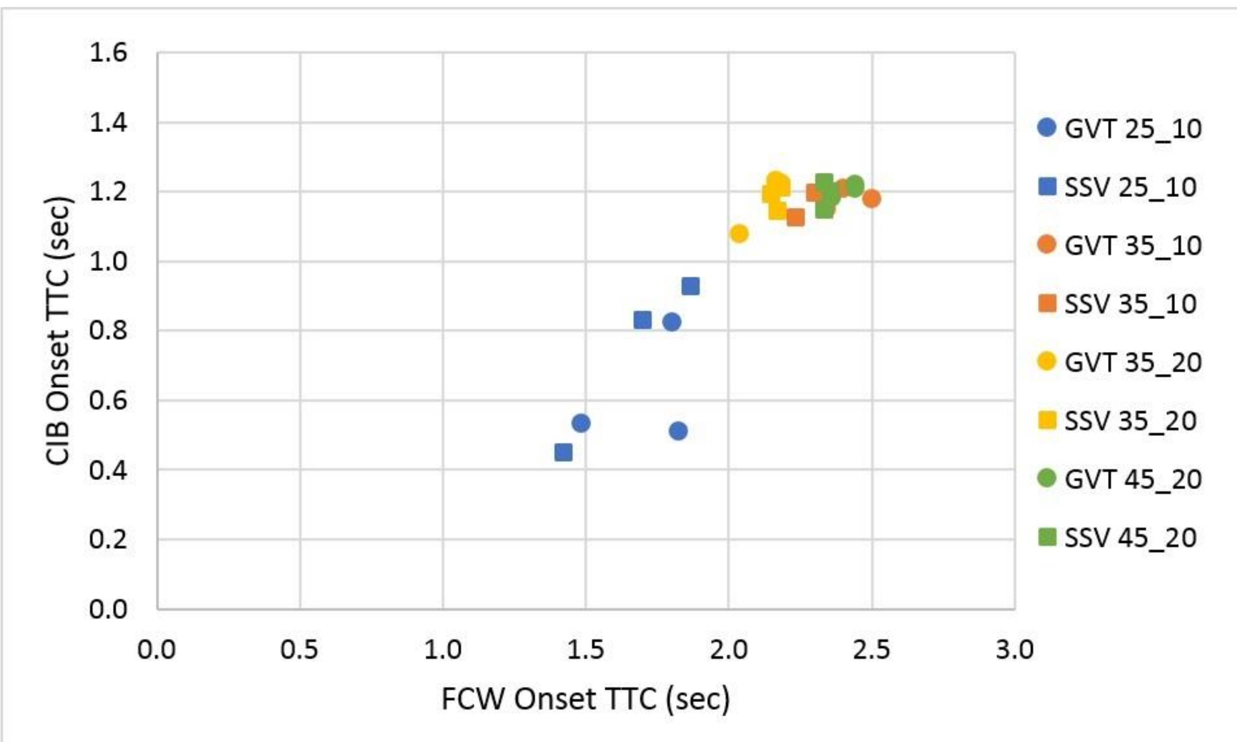


**Figure 12: CW and CIB onset timings to both targets during LVM scenario (Mercedes C300).**

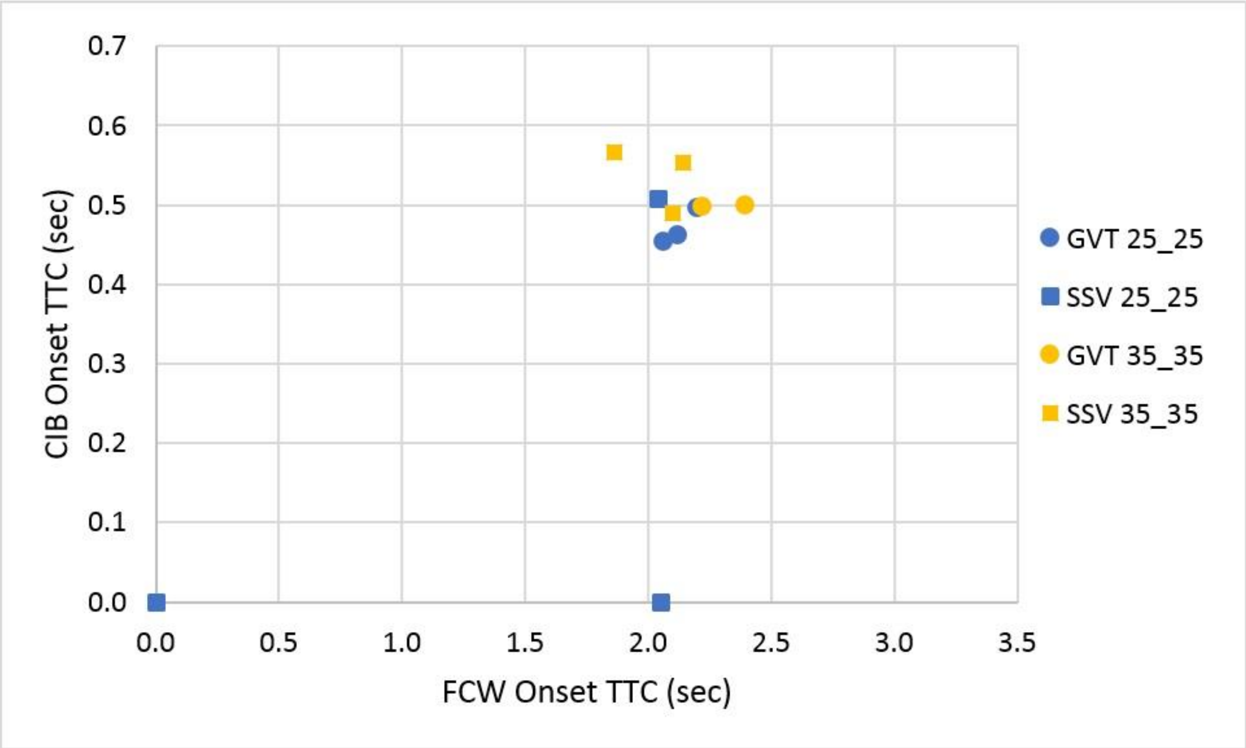


**Figure 13: FCW and CIB onset timings to both targets during LVS scenario (Mercedes C300).**

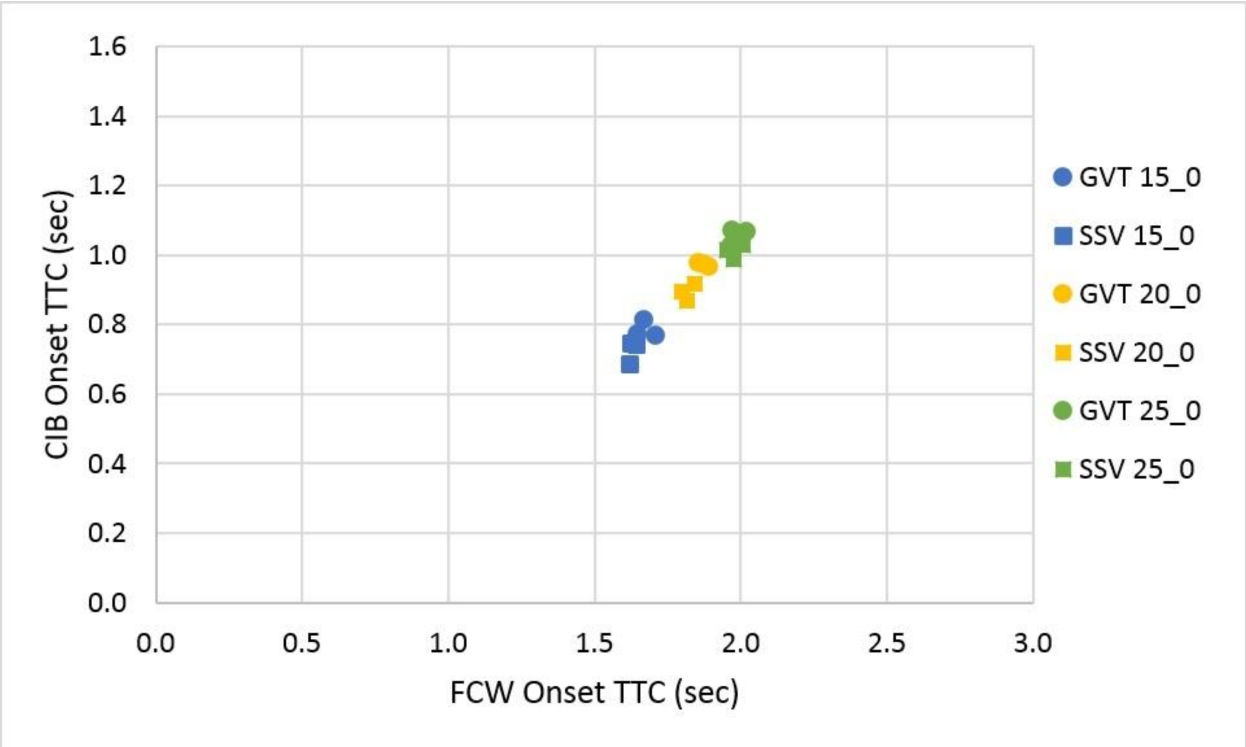


**Figure 14: FCW and CIB onset timings to both targets during LVD scenario (Tesla Model S).**

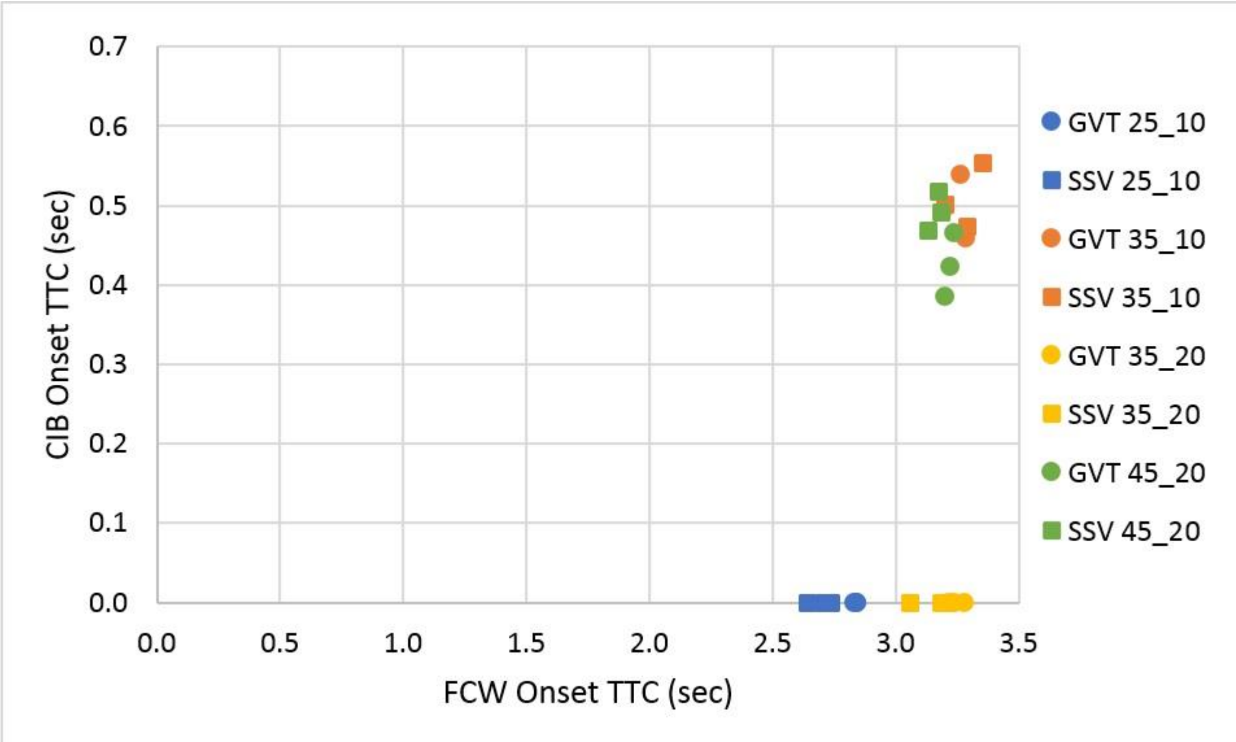


**Figure 15: FCW and CIB onset timings to both targets during LVM scenario (Tesla Model S).**

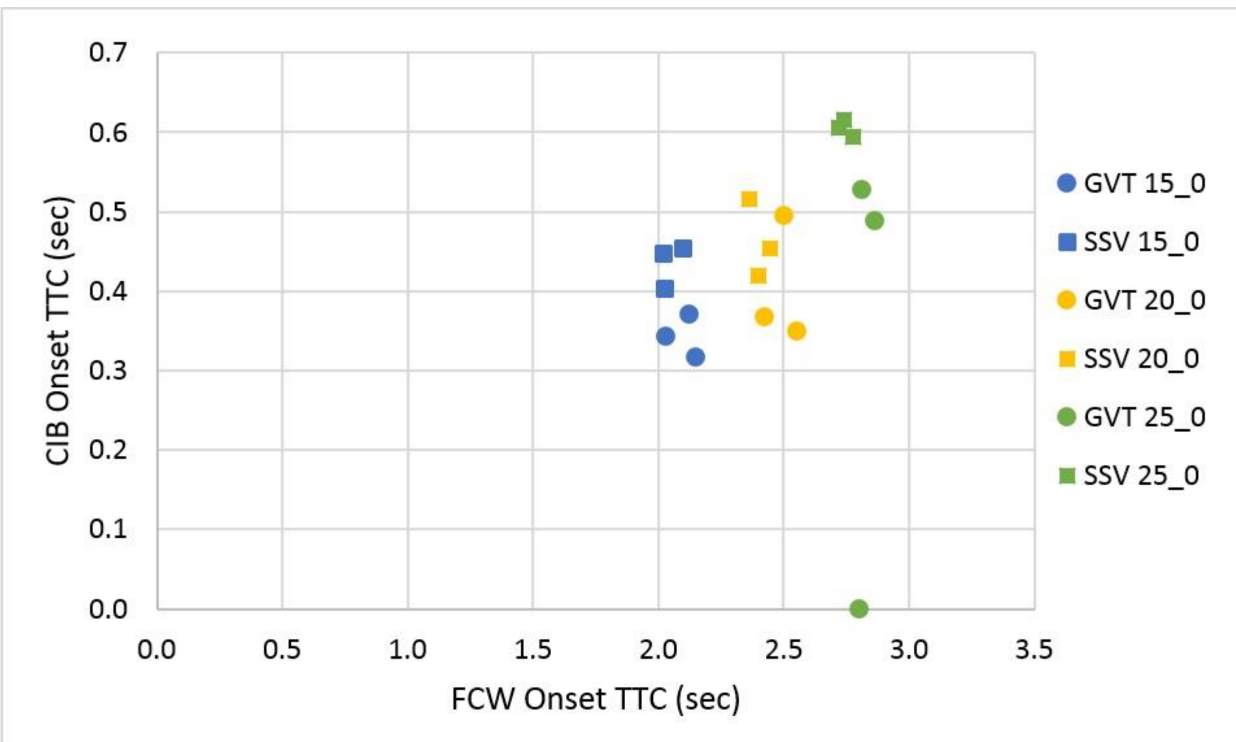


**Figure 16: FCW and CIB onset timings to both targets during LVS scenario (Tesla Model S).**

### 3.1.3. Median Analysis

The analysis described in this section compares the median values of each FCW and CIB onset TTC range for the same test condition (SV, scenario, and test speeds). Whereas the overlap analysis presented in Sections 3.1.1 describe the variability of the data, the median value analysis is used to estimate the central tendency of the onset TTC value within those ranges.

For each combination of SV, test maneuver, and speed, the median value from the SSV data set was subtracted from the median value of the equivalent GST data set (i.e., a positive value indicates the GST-based onset occurred before that of the respective SSV-based onset for that comparison). When only two TTC values were available for a given combination of test target and test condition, the median value was interpolated as the average of the two. When only one TTC value was available for a given combination of target and test condition, it was used in lieu of the median value.

The results from these comparisons are shown in Table 8. As a point of reference, the cell shading used in Table 8 matches that previously used in Tables 6 and 7 (i.e., where green and yellow were used to indicate the presence of range overlap and separation, respectively).

The nine test condition comparisons per onset TTC category were averaged to calculate two overall assessments per SV, and are shown in the bottom row of Table 8. Since the Tesla Model S tests performed in the LVM_25_10 and LVM_35_20 scenarios did not produce CIB activations (regardless of target), the data from these trials were not included in the average difference between median values. In summary:

- The average difference in the FCW onset TTC median values was 0.005 seconds for the Volvo S90, 0.037 seconds for the Mercedes C300, and 0.084 seconds for the Tesla Model S.
- The average difference in the CIB onset TTC median values was 0.032 seconds for the Volvo S90, 0.010 seconds for the Mercedes C300, and -0.067 seconds for the Tesla Model S.
- In 18 of the 27 possible FCW onset TTC median value comparisons, FCW alerts were presented earlier when the GVT was used. The maximum median difference was 0.208 seconds.
- In 16 of the 18 possible CIB onset TTC median values from the Volvo S90 and Mercedes C300 data, CIB activated earlier when the GVT was being used. The maximum difference in median values was -0.299 seconds. This trend was not observed for the Tesla Model S, however, where all seven of the non-zero median value differences showed that CIB activated earlier when the SSV was being used. The maximum difference in median values for the Tesla was -0.104 seconds.

**Table 8. Difference in Onset TTC Median Values**

| Crash Imminent Test Conditions | | | Difference in Onset TTC Median Values (GVT-SSV, expressed in seconds) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pre-Crash Scenario | Test Speeds (mph) | | 2017 Volvo S90 | | 2015 Mercedes C300 | | 2015 Tesla Model S | |
| | SV | POV | FCW | CIB | FCW | CIB | FCW | CIB |
| Lead Vehicle Stopped (LVS) | 15 | 0 | 0.052 | 0.040 | 0.045 | 0.029 | 0.100 | -0.104 |
| | 20 | 0 | 0.107 | 0.010 | 0.055 | 0.079 | 0.103 | -0.087 |
| | 25 | 0 | 0.082 | 0.002 | -0.004 | 0.055 | 0.069 | -0.098 |
| Lead Vehicle Moving (LVM) | 25 | 10 | 0.015 | 0.027 | 0.102 | -0.299 | 0.131 | – |
| | 35 | 10 | -0.117 | 0.033 | 0.100 | 0.018 | -0.028 | -0.009 |
| | 35 | 20 | -0.117 | 0.015 | -0.005 | 0.030 | 0.053 | – |
| | 45 | 20 | -0.036 | -0.035 | 0.107 | 0.005 | 0.048 | -0.069 |
| Lead Vehicle Decelerates (LVD) | 25 | 25 | 0.073 | 0.103 | -0.038 | 0.082 | 0.208 | -0.054 |
| | 35 | 35 | -0.015 | 0.089 | -0.024 | 0.092 | 0.072 | -0.046 |
| Average Difference in Median Values | | | 0.005 | 0.032 | 0.037 | 0.010 | 0.084 | -0.067 |

### 3.1.4. Analysis Using the T-Test

This section uses the t-test to compare FCW and CIB onset TTC responses between the SSV and GST for each combination of SV, test maneuver, and speed. Specifically, an unequal variance t-test with a two-tailed distribution was selected because the box and whisker plots of the data in Appendix 6.2 suggested that some of the comparisons may have unequal variances (i.e., some ranges were wider than others). The unequal variance t-test has the following underlying assumptions:

- The data is continuous
- The data is a simple, random sample from its population
- The data follow a normal probability distribution

The first assumption of continuous data is valid since the measurement used was onset TTC. The second assumption of a random sample from a population is also valid, but it is noted that with such a small sample size (n=3), there is the possibility that the selected random sample is not representative of the overall population, and that this could result in inaccurate t-test results. The final assumption of a normal probability distribution cannot be validated with such a small sample size per test condition, so it remains an un-validated assumption that the vehicles' response to the two targets for each combination of test maneuver and speed would follow a normal distribution.

Each set of FCW and CIB onset TTC ranges were analyzed using the t-test described above. Each individual data set had equal sample sizes of n=3 tests unless noted otherwise. The null hypothesis for this t-test was that the means of the vehicles' FCW and CIB onset TTC responses between the SSV and GST were equal. For the analysis discussed in this report, a significance level of $\alpha = 0.05$ was used (i.e., the results have a confidence level of 95 percent).

The output of the t-test is a t-score. This score was converted to a p-value based on the degrees of freedom, which in this case was one less than sample size, or two. If the p-value was less than the significance level of 0.05, the null hypothesis was rejected. Conversely, if the p-value was greater than the significance level, the null hypotheses failed to be rejected. For the onset TTC data discussed in this report, rejection of the null hypothesis for a given test condition meant that the SV responded differently to the two targets for that comparison.

The results from the t-test are shown in Table 9. Cells are colored green if the t-test results indicated that the SV response to the two targets was not different. Cells are colored yellow if the t-test results indicated that the SV response to the two targets was different.

**Table 9. Results of Unequal Variance t-test**

| Crash Imminent Test Conditions | | | Results of Unequal Variance t-test (α = 0.05) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pre-Crash Scenario | Test Speeds (mph) | | 2017 Volvo S90 | | 2015 Mercedes C300 | | 2015 Tesla Model S | |
| | SV | POV | FCW | CIB | FCW | CIB | FCW | CIB |
| Lead Vehicle Stopped (LVS) | 15 | 0 | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Reject |
| | 20 | 0 | Fail to Reject | Fail to Reject | Reject | Reject | Fail to Reject | Fail to Reject |
| | 25 | 0 | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Reject | Fail to Reject |
| Lead Vehicle Moving (LVM) | 25 | 10 | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Reject | – [1] |
| | 35 | 10 | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject |
| | 35 | 20 | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | – [1] |
| | 45 | 20 | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject |
| Lead Vehicle Decelerates (LVD) | 25 | 25 | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | – [2] |
| | 35 | 35 | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject | Fail to Reject |

[1] No CIB activation was observed for any of the six tests in this scenario, however the response to the two targets was equal.
[2] No CIB activation was observed for two of the three SSV tests in this scenario.

Of the 54 possible FCW and CIB onset TTC comparisons, the null hypothesis was rejected five times (i.e., t-test indicated that for five test conditions, the response to the two targets was different). That said, the range separations associated with these five comparisons differed by no more than 0.092 seconds.

- The Mercedes C300 accounted for two of the five rejections due to its FCW and CIB onset TTC responses in the LVS_20_0 scenario.
- The Tesla Model S accounted for the other three rejections due to its CIB onset TTC responses in the LVS_15_0 scenario, and the FCW responses in the LVS_25_0 and LVM_25_10 scenarios.

Three CIB onset TTC comparisons for the Tesla Model S did not have enough data to calculate the t-test, including the LVM_25_10 and LVM_35_20 tests where CIB did not activate, and the LVD_25_25 maneuver where CIB failed to activate during two of the SSV-based trials. The Volvo S90 had similar FCW and CIB onset TTC responses to both targets, and was the only vehicle to avoid hitting both targets in all test scenarios.

### 3.2 Stability Testing

The physical stability of the GVT while attached to the LPRV platform was assessed using two path-following maneuvers: straight line and constant-radius curve. During the straight-line tests, the GVT was commanded to accelerate at approximately 0.1 g (1 $m/s^2$) to a speed of 10, 20, 30, or 40 mph (16.1, 32.2, 48.3, and 64.4 km/h) and maintain that speed until reaching a preset stopping point.

For the constant-radius curve tests, the commanded maneuver speed was a constant 25 mph (40.2 km/h). The GVT was accelerated to the desired speed and executed one of four different J-turn (180-degree turn) maneuvers using path radii capable of producing nominal lateral accelerations of 0.3, 0.4, 0.5, or 0.6 g (2.9, 3.9, 4.9, and 5.9 $m/s^2$). Wind speed remained below 20 mph (32.2 km/h) throughout testing. Data collection consisted of video recordings of each test trial. Review of these videos demonstrated that the GVT remained stable and affixed to the LPRV throughout all the stability assessment tests.

### 3.3 Reassembly Time Results

A fully crossed test matrix consisting of two teams (three and five people), two tests speeds (10 and 25 mph, or 16.1 and 40.2 km/h) and three approach aspects (front, side, and rear) was used to assess the time needed to reassemble the GVT after it had been struck by an SV. One test was conducted for each of the twelve conditions. After averaging all tests with the same team size, the reassembly times ranged from 6.1 to 7.7 minutes when five people performed the task, and between 7.9 to 10.1 minutes with three people.

That said, reconstruction time is not the only factor that affects the length of time between tests. Every time the GVT is hit hard enough to alter its position on the LPRV, the following steps must be completed before testing resumes, a process that can take approximately 20 minutes:

1. The GVT must be repositioned or reassembled on the LPRV, depending on impact speed;
2. The LPRV GPS antenna quick-disconnect connector may become unplugged. If this occurs, the antenna must be reconnected and the GPS re-initialized by driving the LPRV in circles;
3. The reported distance from the SV to GVT (e.g., the longitudinal range from the front of the SV to the rear of the GVT) must be checked, and adjusted if necessary. Following this confirmation, a static calibration data file is collected;
4. The GST system must be driven back to the pre-test staging location after each trial; and
5. Depending on the type of test being performed, the SV brakes may need to be brought back up to testing temperature (since they would have likely cooled by the time the aforementioned steps had concluded).

By comparison, the SSV takes less than one minute to reset, and NHTSA's many years of performing AEB tests using the SSV have shown that they may be performed at a rate of approximately one test every five minutes. This interval often coincides with the time needed to cool the SV brakes to an acceptable level following an AEB test.

## 3.4 Additional Comments

In addition to the tests performed in support of the research described in this report, NHTSA has had extensive experience using the GVT during other test track evaluations. During these tests, the following observations have been made:

- Since the maximum speed of the GST system is nominally 50 mph (80.5 km/h), it is recommended that if the GVT is driven into a headwind, the GVT speed plus that of the headwind should not exceed 50 mph (80.5 km/h). This is to reduce the likelihood of having the GVT separate from the top of the LPRV.
- Striking the GVT with the SV in the presence of high wind speeds, regardless of direction, has the potential to significantly lengthen reassembly time. This due to a much larger debris field created by wind carrying the pieces of the GVT through the air and the outer skins being difficult to constrain while trying to secure them to the GVT's foam frame.
- There is a potential for parts of the GVT to be blown into test areas used occupied by other facility users (e.g., those performed in adjacent test lanes). For this reason, precautions should be taken when using the GVT during periods of high wind if impacts are anticipated.

# 4.0 CONCLUDING REMARKS

Multiple approaches were used to examine the FCW and CIB onset TTC data from this research:

- The extent of overlap or separation of the data ranges
- The difference between the median values
- The unequal variance t-test

Taken collectively, results from the three analyses suggest that the FCW and CIB onset timing observed during rear-end tests performed with the GVT was similar to that elicited by the SSV baseline. Practically speaking, the results from the Mercedes C300 and Volvo S90 indicate that, for these vehicles, any differences that might exist between the test targets were small enough not to appreciably influence the outcome of the tests described in this report.

The Tesla Model S FCW and CIB results suggest that there may have been minor differences in how it responded to the GVT and SSV, however a firmware update that occurred midway through the Tesla Model S evaluation made it unclear whether these potential differences were due to perceived dissimilarities in the test targets or operational differences of the vehicle's firmware. This uncertainty meant the Tesla Model S data could not be incorporated into the final assessment of the two test targets. Going forward, this serves to highlight the importance of software control in testing a vehicle over extended periods. Of the three vehicles used in this study, the Tesla was the only one to exhibit non-activations of FCW and CIB during testing, and they occurred during tests performed with each test target.

Two functional evaluations were performed to evaluate some of the practical aspects of using the GST system during test track evaluations. The GVT was stable and remained affixed to the LPRV during straight line and J-turn tests performed up to the limits of the GVTs intended use. The reassembly time results showed that five people could reassemble the GVT appreciably faster (6.1 to 7.7 minutes) than three people (7.9 to 10.1 minutes), but that the actual time burden to a research program was closer to 20 minutes between tests whenever the GVT was dislodged from the LPRV between test trials. By comparison, the SSV took less than one minute to reset, and facilitated testing at a rate of approximately once every five minutes, albeit in rear-end crash scenarios only. This limitation highlights one of the most important attributes of the GVT: that it can be struck from any SV approach aspect, not just from the rear.

## 5.0 REFERENCES

[1] 80 FR No. 214, p. 68604 (2015, November 5) New Car Assessment Program (NCAP), Docket No. NHTSA-2015-0006-0024. Available at www.regulations.gov/contentStreamer?documentId=NHTSA-2015-0006-0024&contentType=pdf

[2] Buller, W., Wilson, B., Ebling, J., van Nieuwstadt, L. (2017, May). *Radar Measurements of NHTSA's Surrogate Vehicle SSV* (Docket No. NHTSA-2012-0057-0034). Ann Arbor, MI: Michigan Tech Research Institute. Available at https://www.regulations.gov/contentStreamer?documentId=NHTSA-2012-0057-0034&attachmentNumber=1&contentType=pdf

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# APPENDIX A. ADDITIONAL TEST VEHICLES SPECIFICATIONS

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

| Subject Vehicle | Vehicle Weight Information (lbs.) | | | |
|---|---|---|---|---|
| | Baseline[1] | Overall[2] (GVWR) | Front Axle[2] (GAWR) | Rear Axle[2] (GAWR) |
| 2015 Tesla Model S 85D (5YJSA1H2XFF0xxxxx) | 4,848[3] | 5,321 (5,820) | 2,655 (2,813) | 2,666 (3,307) |
| 2015 Mercedes C300 4MATIC (55SWF4KB3FU0xxxxx) | 3,594[3] | 4,180 (4,773) | 2,142 (2,348) | 2,038 (2,480) |
| 2017 Volvo S90 T6 AWD (YV1A22MK6H10xxxxx) | 4,124 | 4,756 (5,200) | 2,437 (2,620) | 2,319 (2,690) |

[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).**

| Subject Vehicle | Vehicle Weight Information (kg) | | | |
|---|---|---|---|---|
| | Baseline[1] | Overall[2] (GVWR) | Front Axle[2] (GAWR) | Rear Axle[2] (GAWR) |
| 2015 Tesla Model S 85D (5YJSA1H2XFF0xxxxx) | 2,199.0[3] | 2,413.6 (2,549.2) | 1,204.3 (1,276.0) | 1,209.3 (1,500.0) |
| 2015 Mercedes C300 4MATIC (55SWF4KB3FU0xxxxx) | 1,630.2[3] | 1,896.0 (2,165.0) | 971.6 (1,065.0) | 924.4 (1,124.9) |
| 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) |

[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

# APPENDIX B. ONSET TTC BOX AND WHISKER PLOTS

The following plots rely on three data points (n=3) unless noted in the legend.

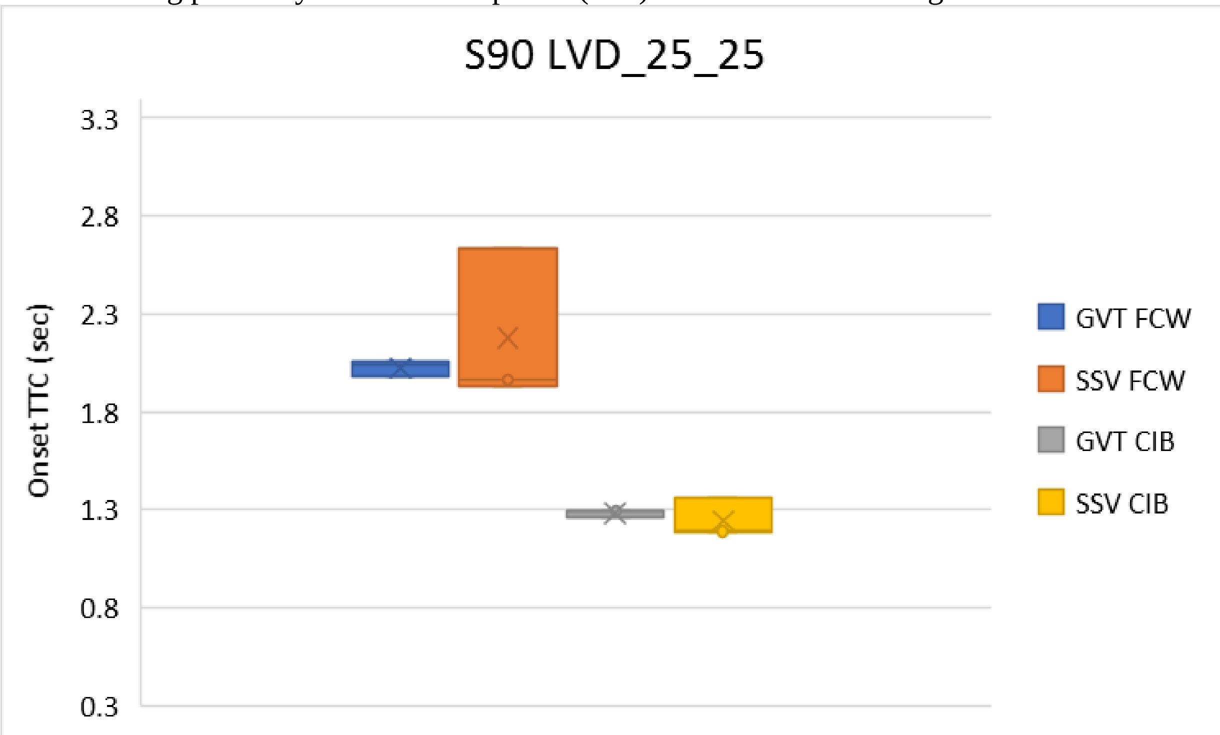


**Figure B-1: FCW and CIB onset timings to both targets during LVD_25_25 scenario (Volvo S90).**

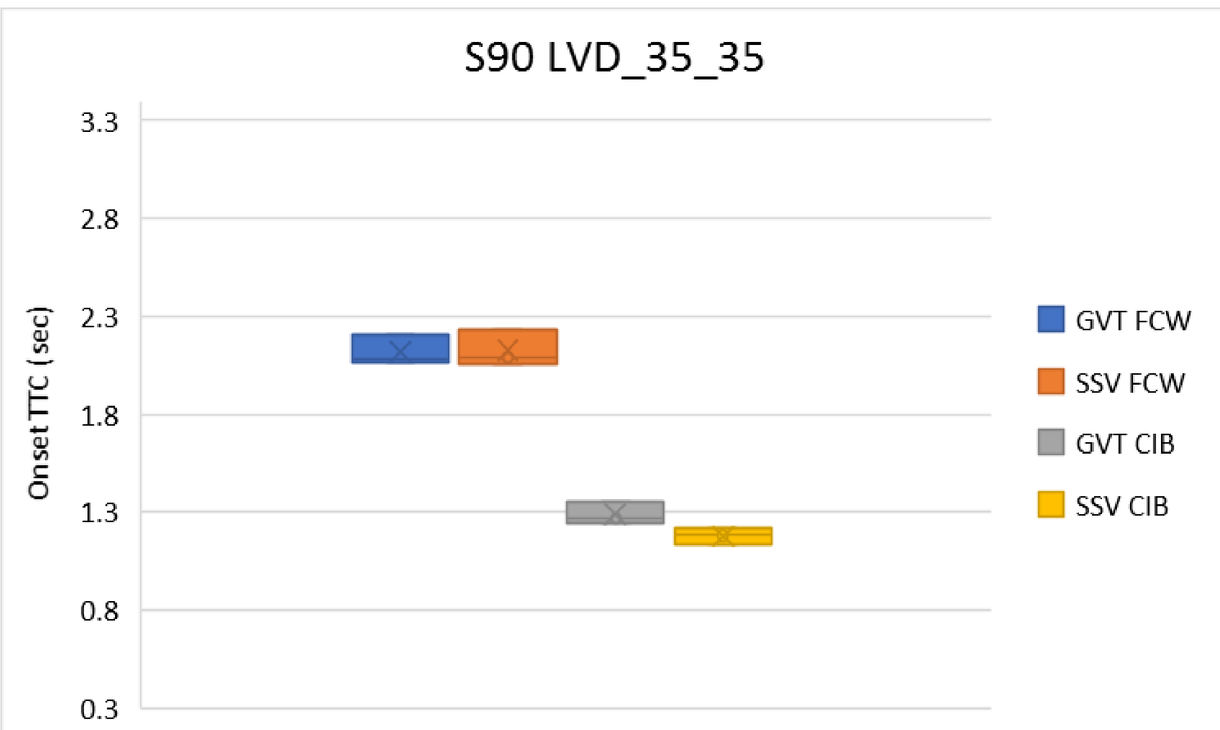


**Figure B-2: FCW and CIB onset timings to both targets during LVD_35_35 scenario (Volvo S90).**

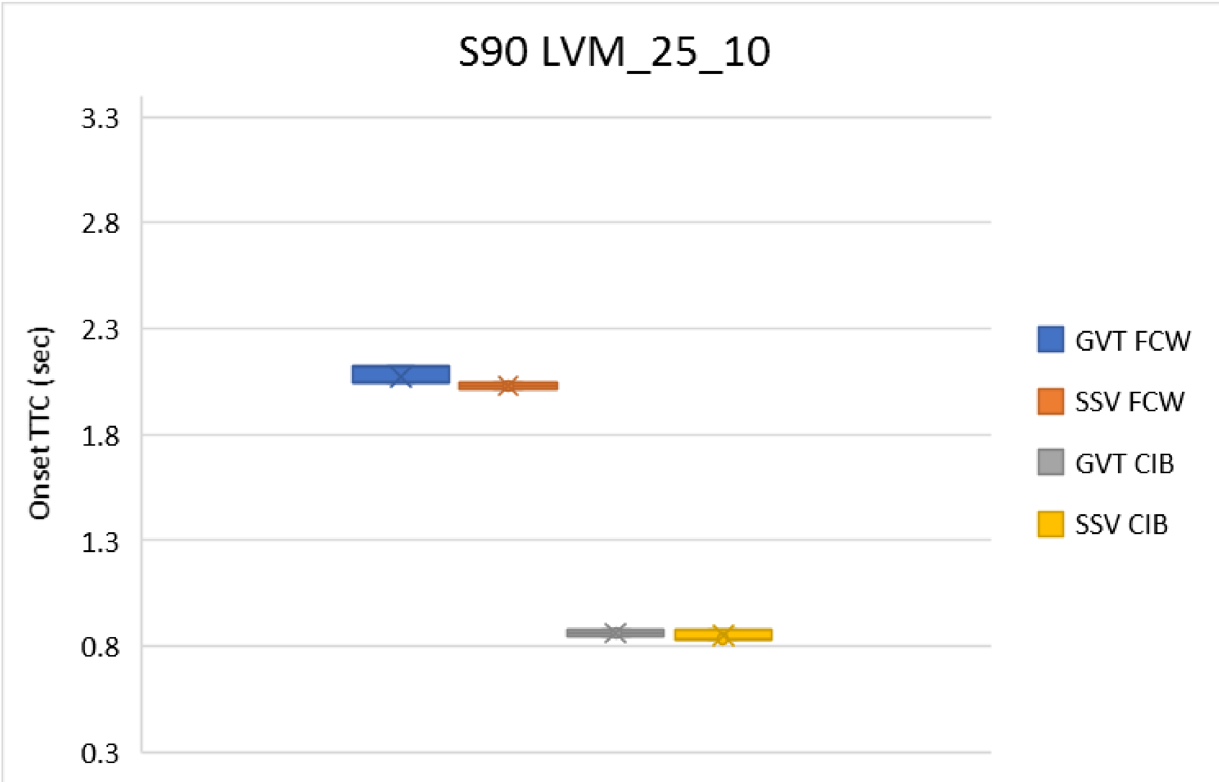


**Figure B-3: FCW and CIB onset timings to both targets during LVM_25_10 scenario (Volvo S90).**


**Figure B-4: FCW and CIB onset timings to both targets during LVM_35_10 scenario (Volvo S90).**

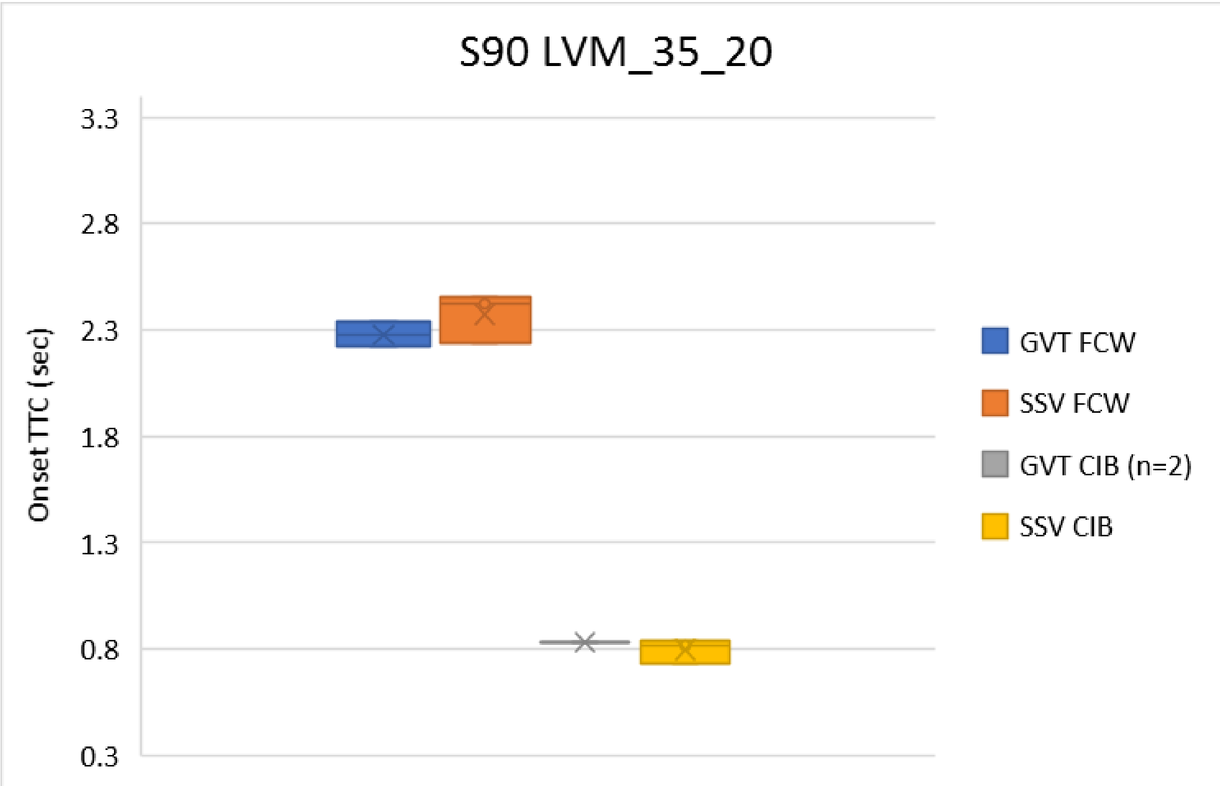


**Figure B-5: FCW and CIB onset timings to both targets during LVM_35_20 scenario (Volvo S90).**


**Figure B-6: FCW and CIB onset timings to both targets during LVM_45_20 scenario (Volvo S90).**

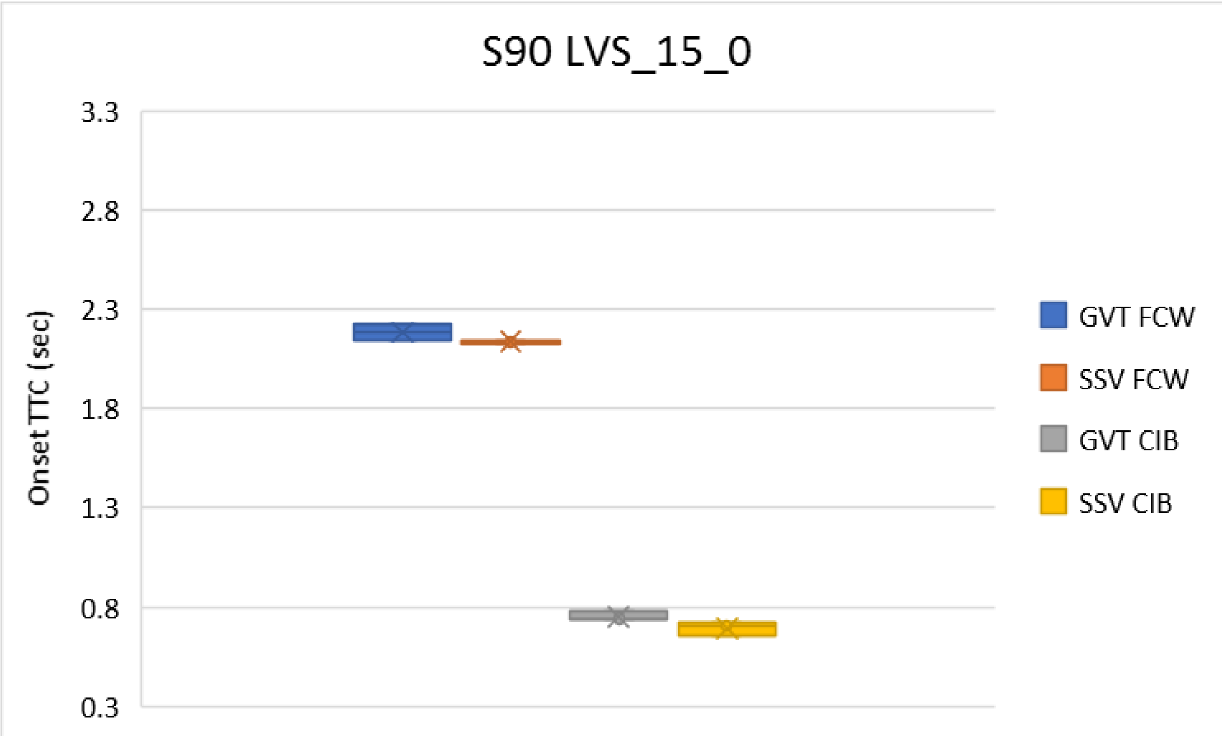

**Figure B-7: FCW and CIB onset timings to both targets during LVS_15_0 scenario (Volvo S90).**

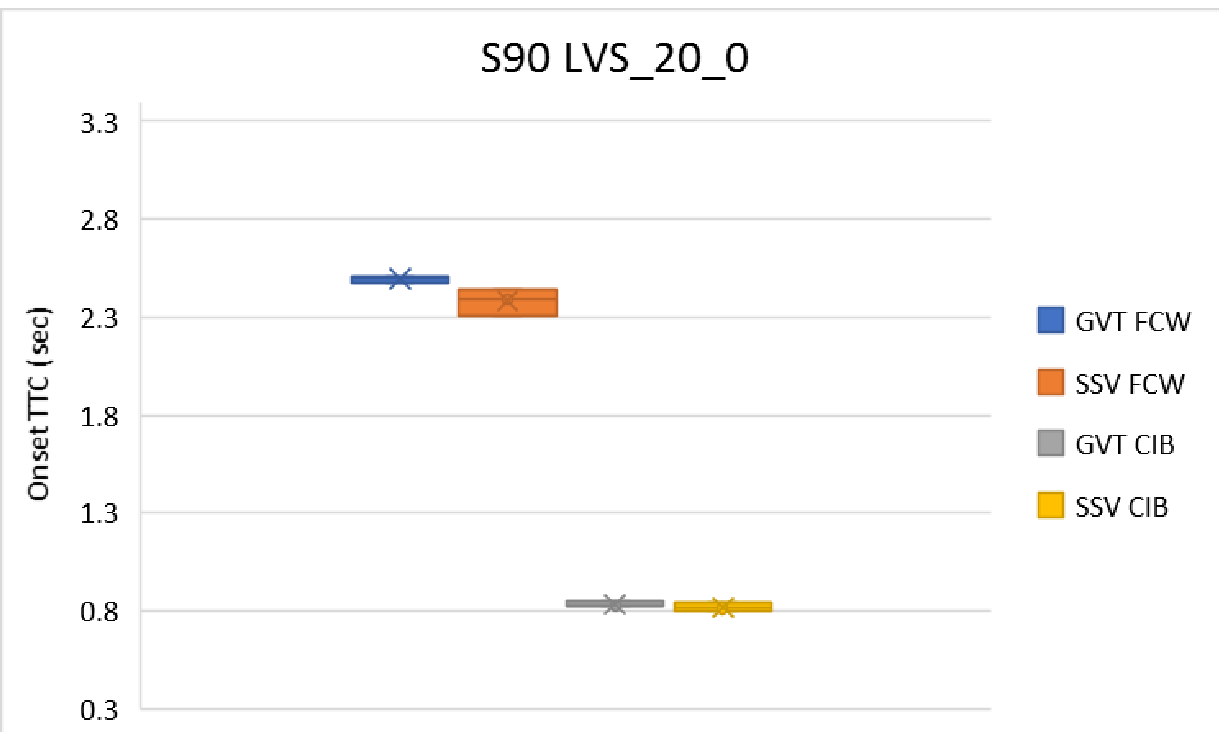

**Figure B-8: FCW and CIB onset timings to both targets during LVS_20_0 scenario (Volvo S90).**

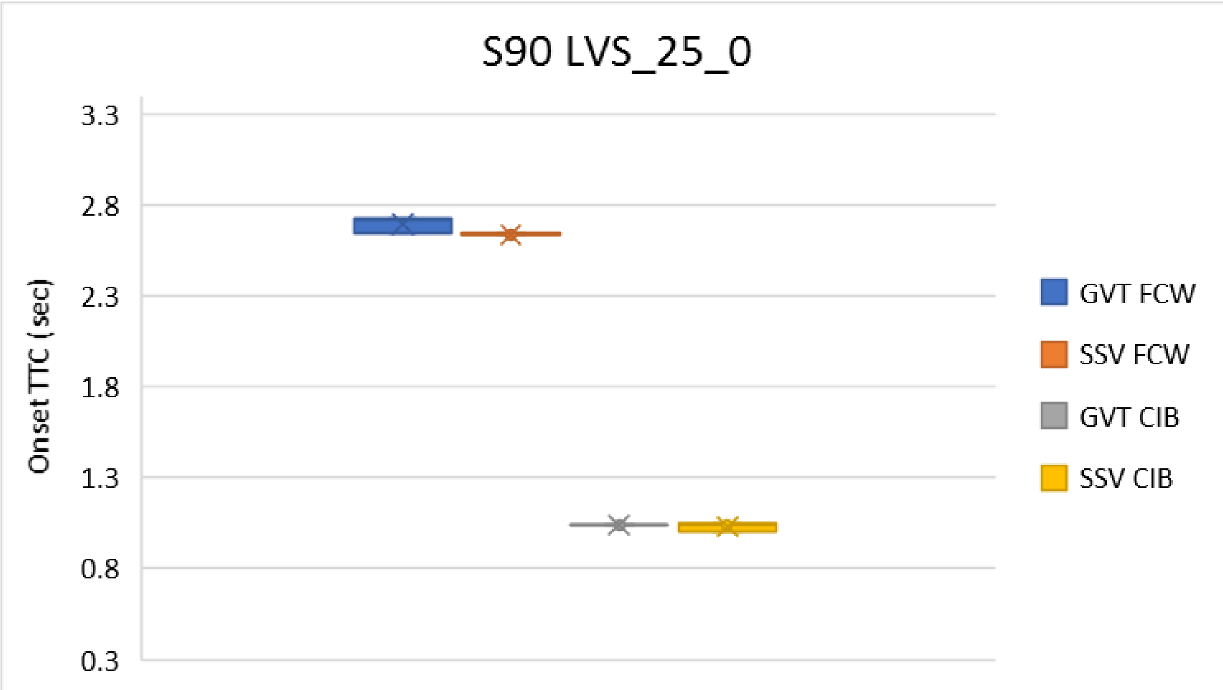

**Figure B-9: FCW and CIB onset timings to both targets during LVS_25_0 scenario (Volvo S90).**

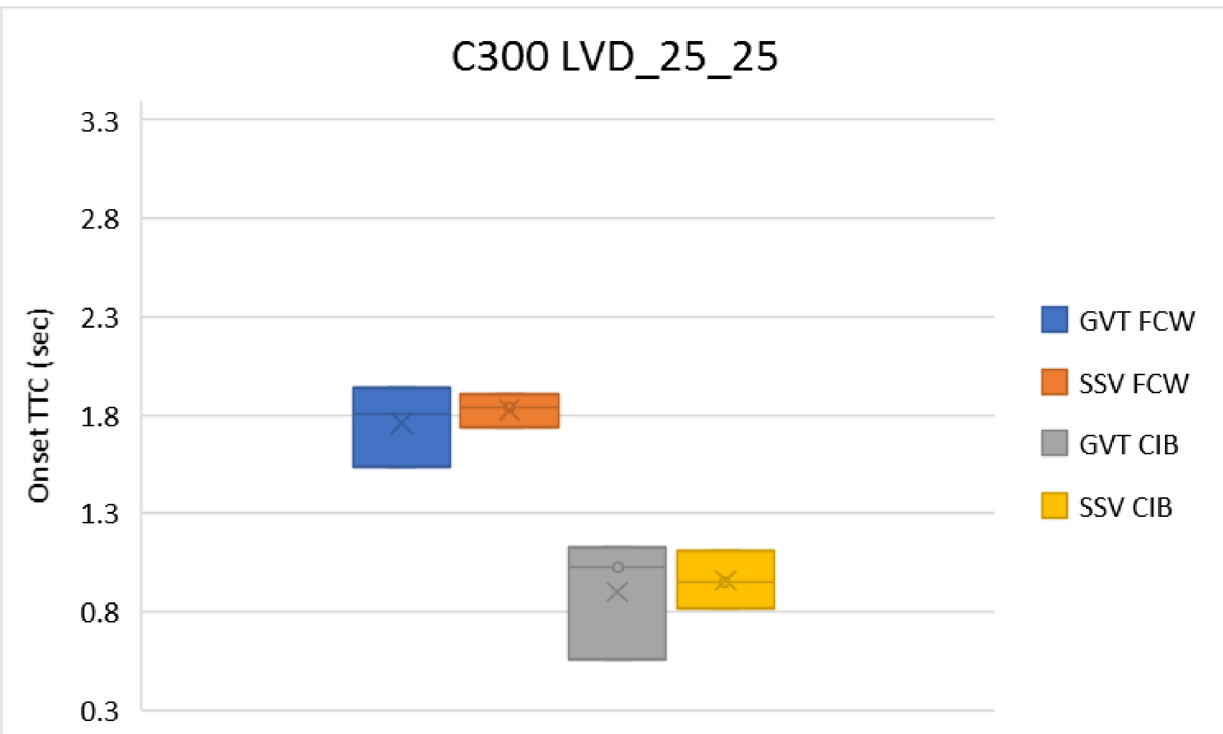

**Figure B-10: FCW and CIB onset timings to both targets during LVD_25_25 scenario (Mercedes C300).**

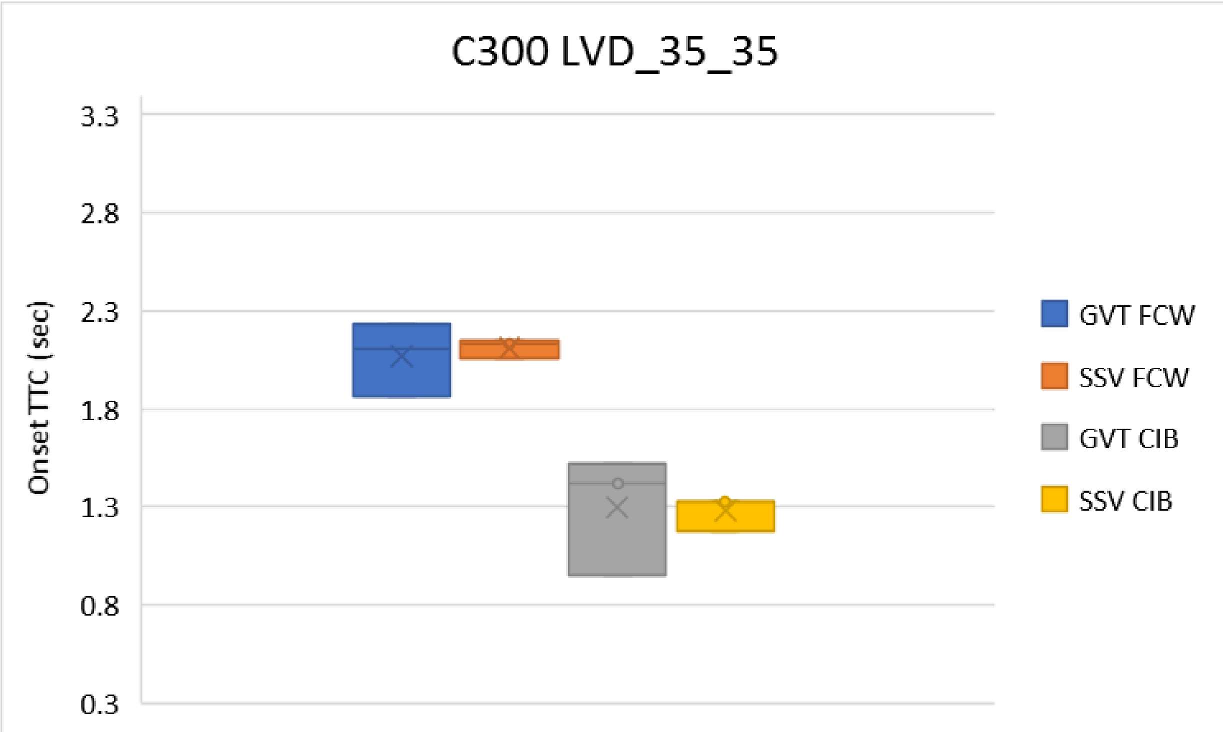


**Figure B-11: FCW and CIB onset timings to both targets during LVD_35_35 scenario (Mercedes C300).**


**Figure B-12: FCW and CIB onset timings to both targets during LVM_25_10 scenario (Mercedes C300).**


**Figure B-13: FCW and CIB onset timings to both targets during LVM_35_10 scenario (Mercedes C300).**

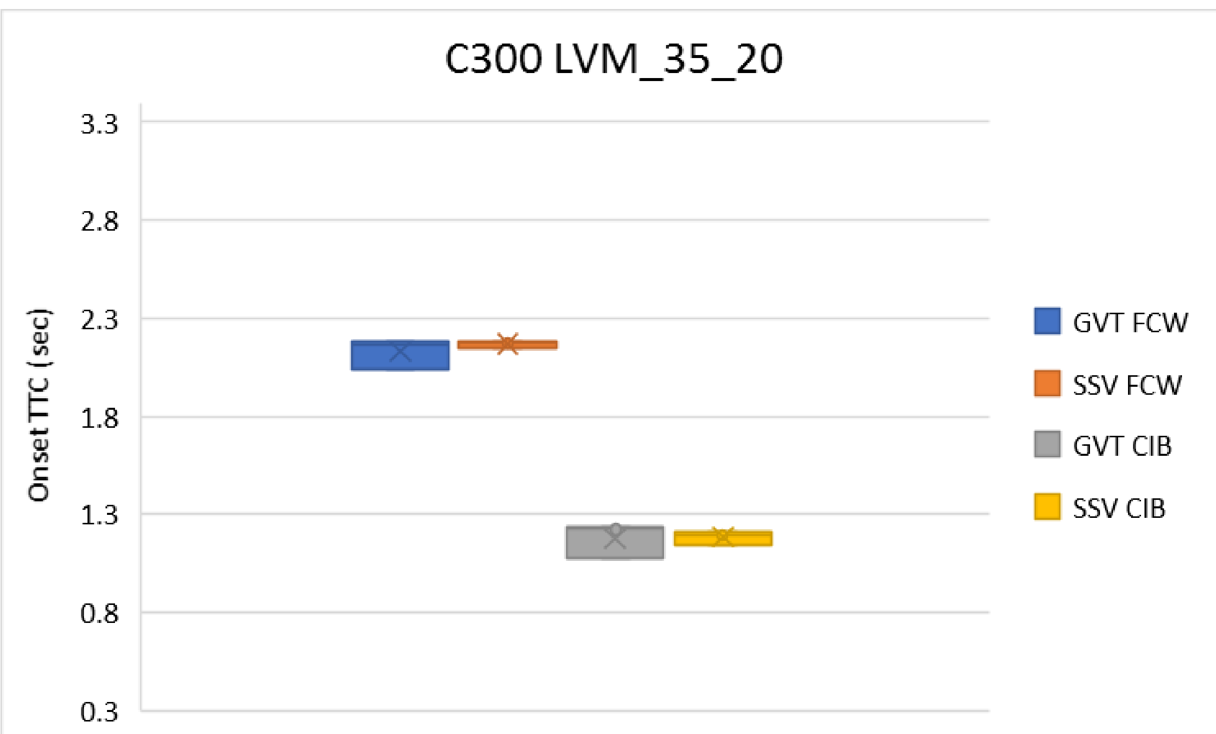


**Figure B-14: FCW and CIB onset timings to both targets during LVM_35_20 scenario (Mercedes C300).**


**Figure B-15: FCW and CIB onset timings to both targets during LVM_45_20 scenario (Mercedes C300).**

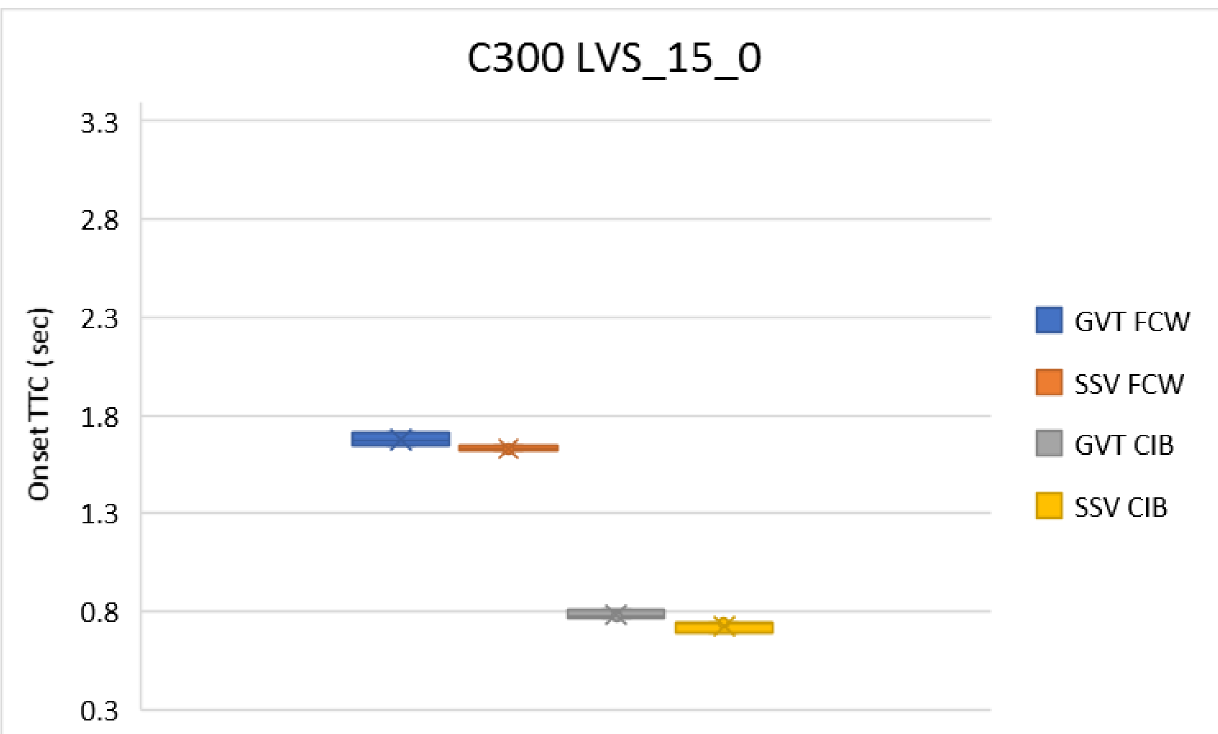


**Figure B-16: FCW and CIB onset timings to both targets during LVS_15_0 scenario (Mercedes C300).**

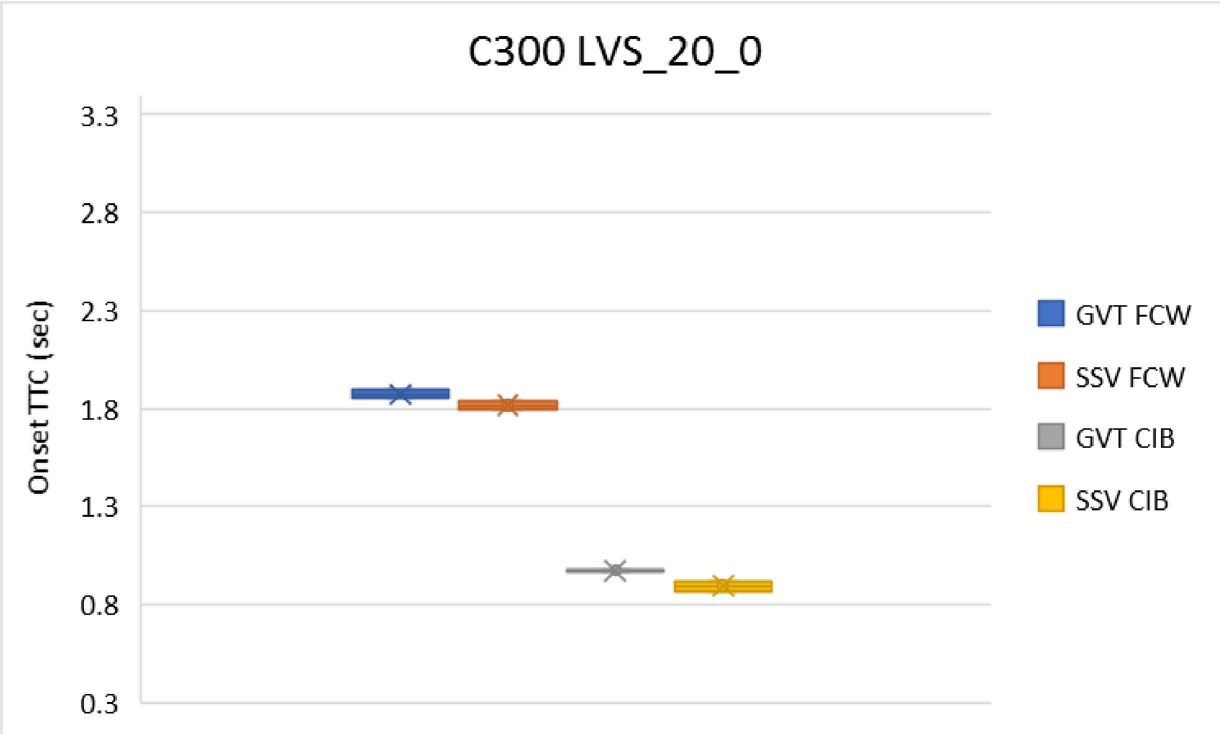

**Figure B-17: FCW and CIB onset timings to both targets during LVS_20_0 scenario (Mercedes C300).**

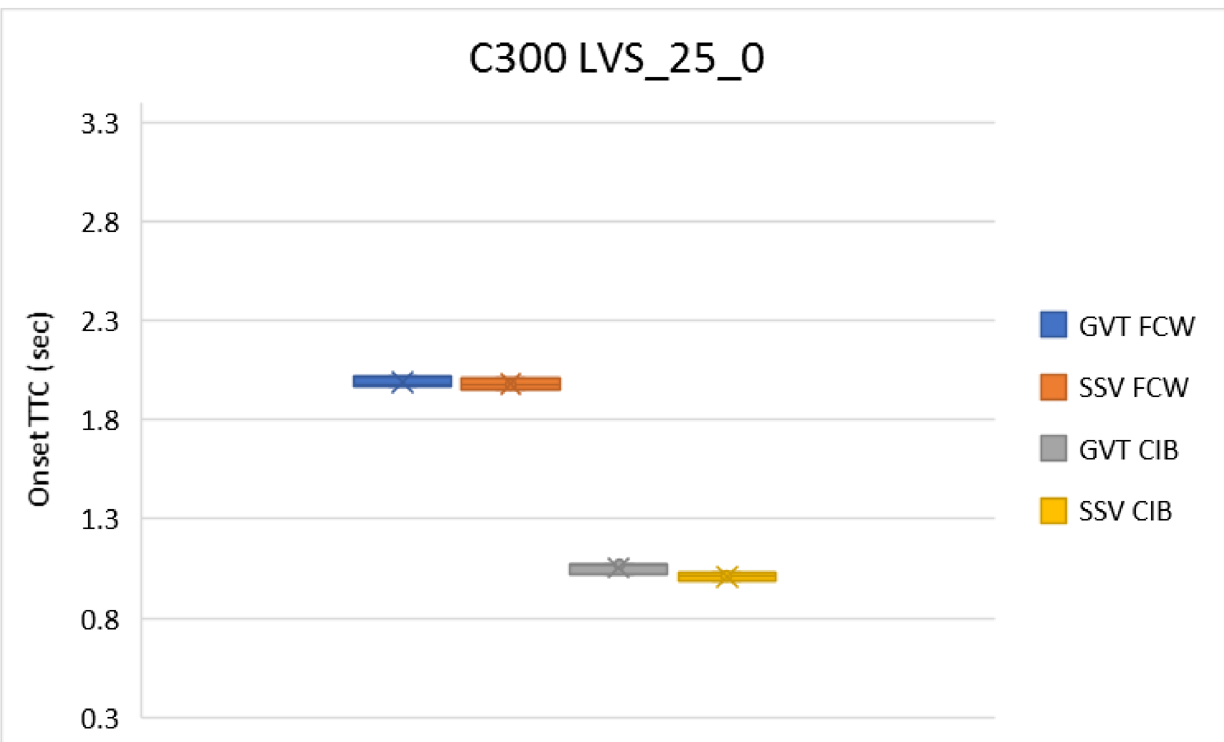

**Figure B-18: FCW and CIB onset timings to both targets during LVS_25_0 scenario (Mercedes C300).**

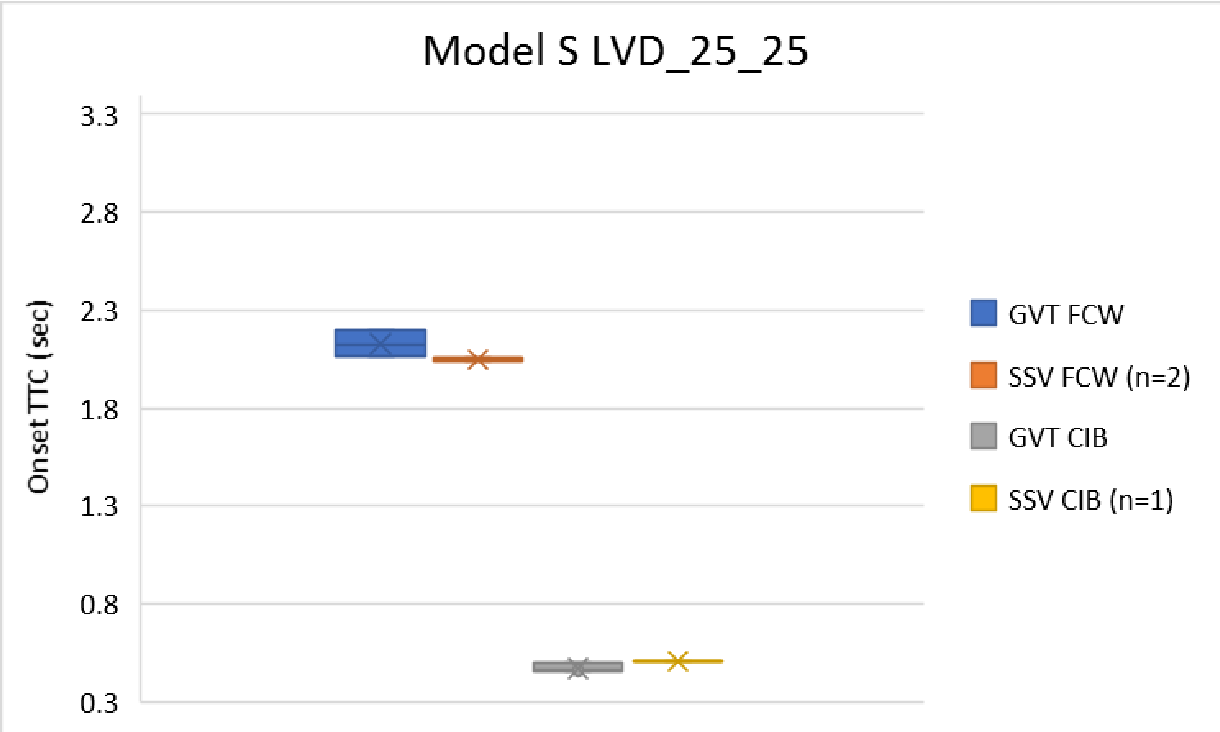


**Figure B-19: FCW and CIB onset timings to both targets during LVD_25_25 scenario (Tesla Model S).**

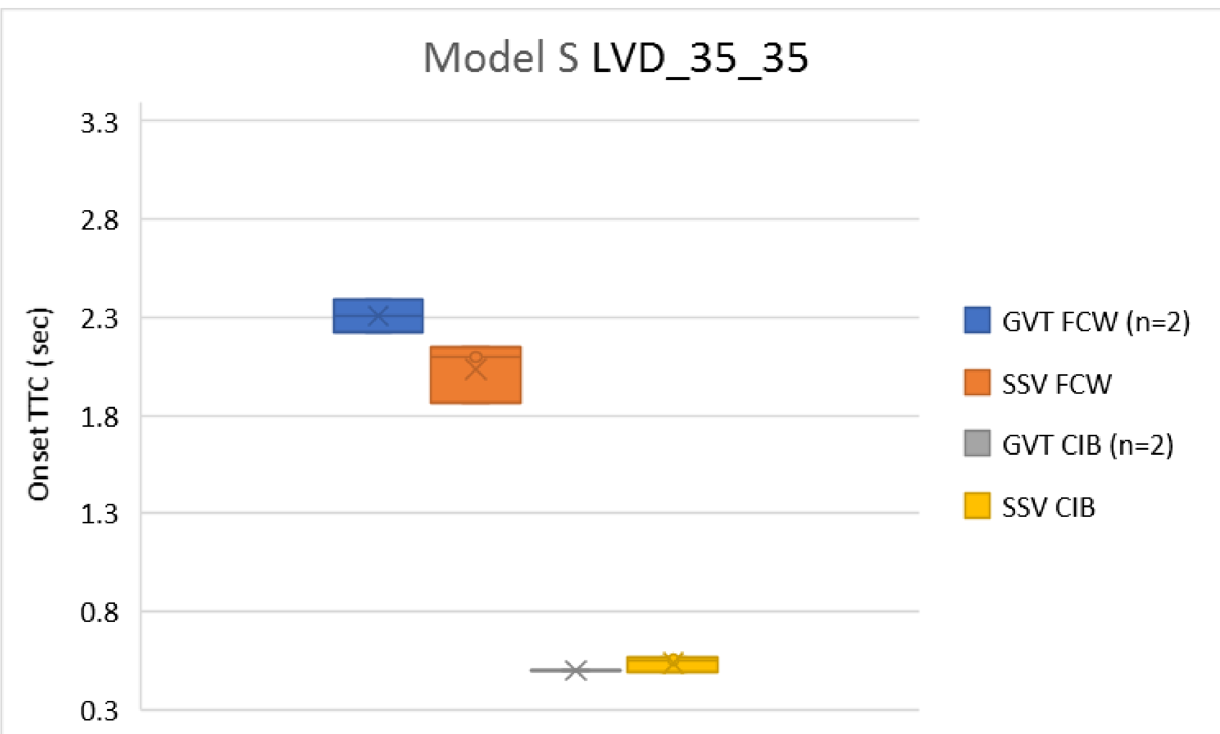


**Figure B-20: FCW and CIB onset timings to both targets during LVD_35_35 scenario (Tesla Model S).**


**Figure B-21: FCW and CIB onset timings to both targets during LVM_25_10 scenario (Tesla Model S).**

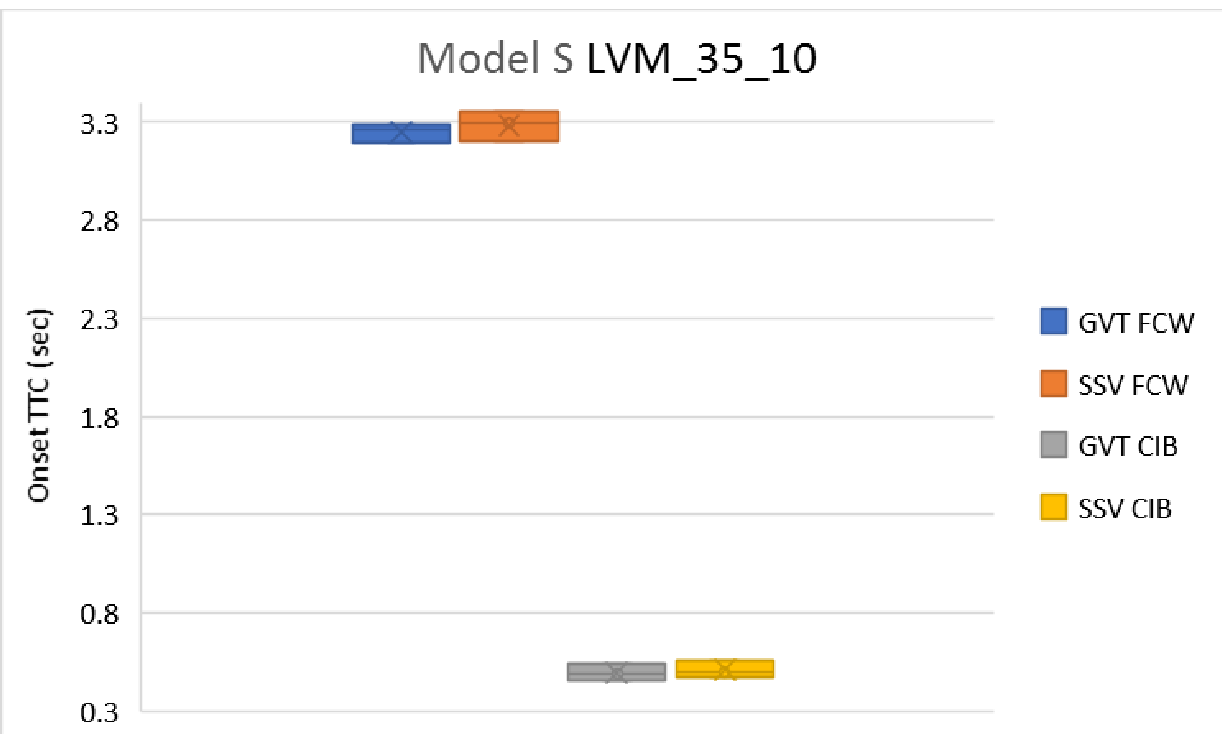


**Figure B-22: FCW and CIB onset timings to both targets during LVM_35_10 scenario (Tesla Model S).**

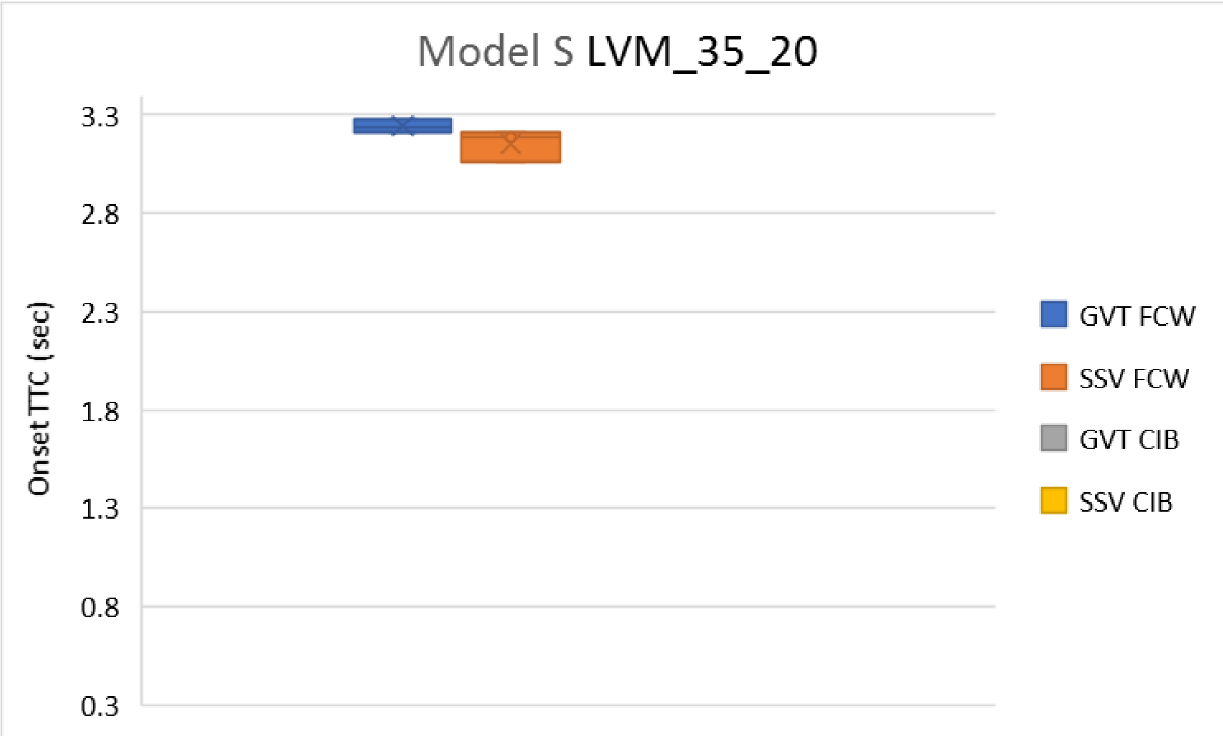


**Figure B-23: FCW and CIB onset timings to both targets during LVM_35_20 scenario (Tesla Model S).**


**Figure B-24: FCW and CIB onset timings to both targets during LVM_45_20 scenario (Tesla Model S).**

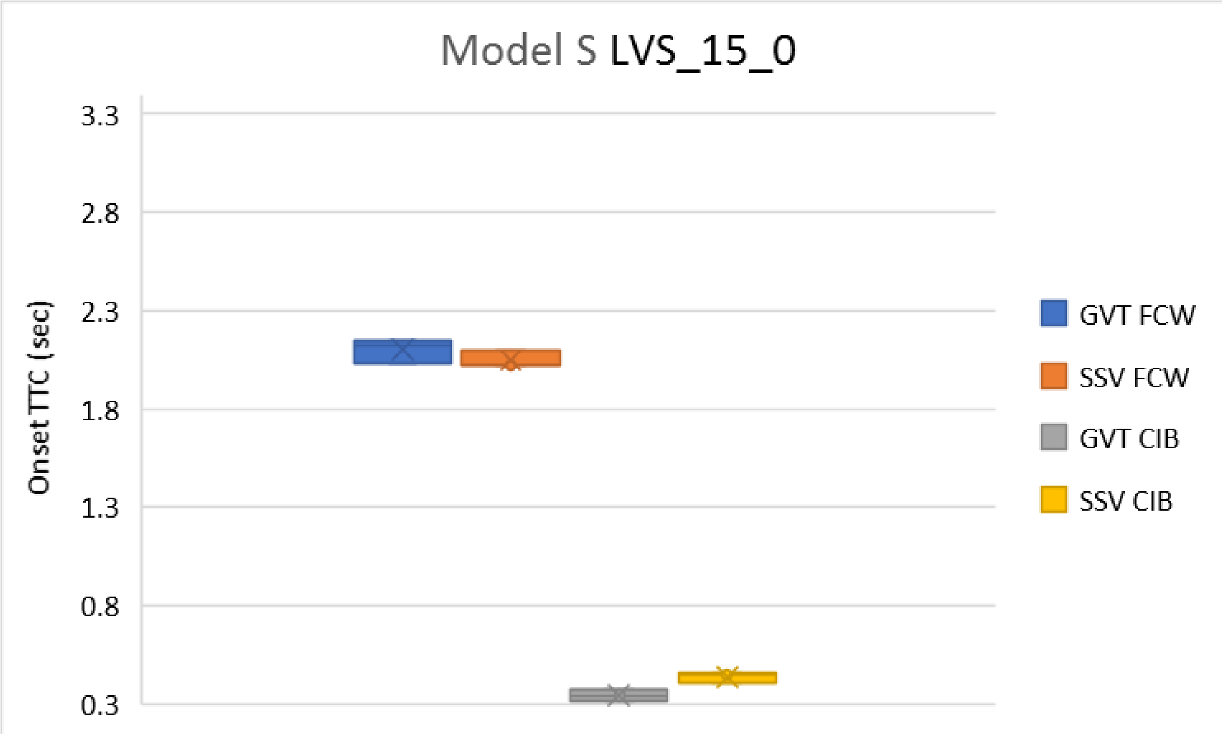


**Figure B-25. FCW and CIB onset timings to both targets during LVS_15_0 scenario (Tesla Model S).**

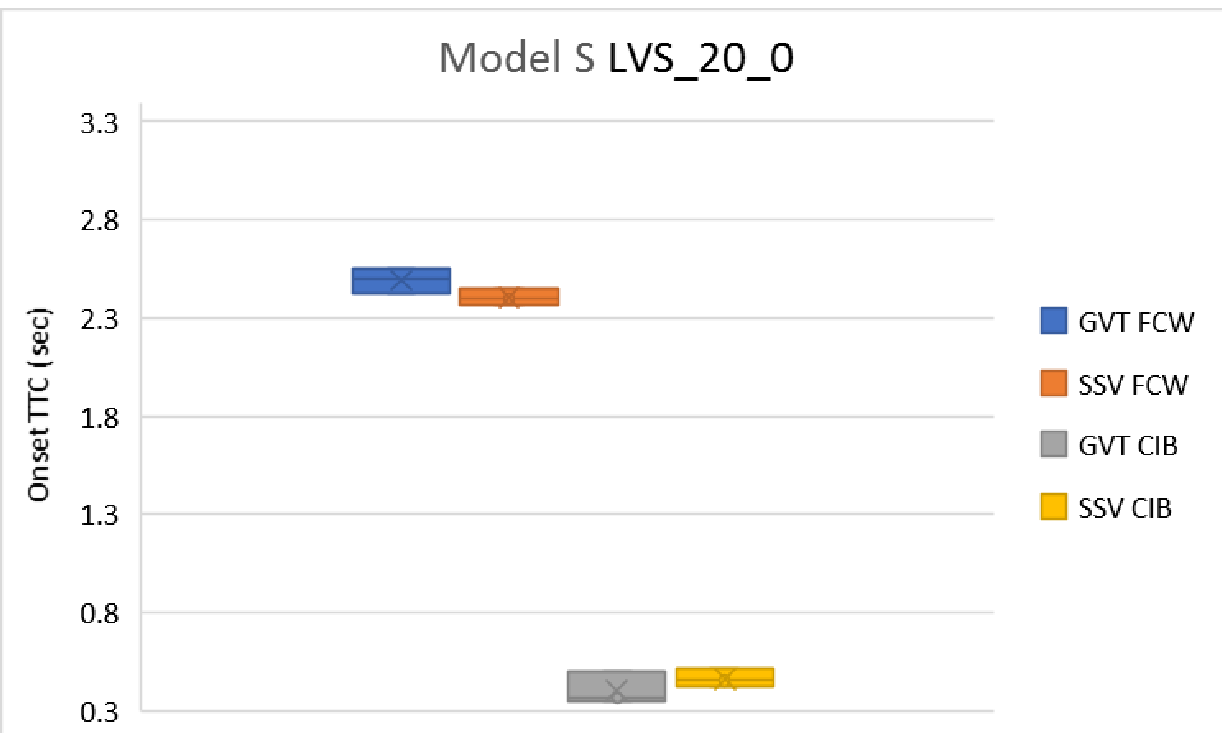


**Figure B-26: FCW and CIB onset timings to both targets during LVS_20_0 scenario (Tesla Model S).**

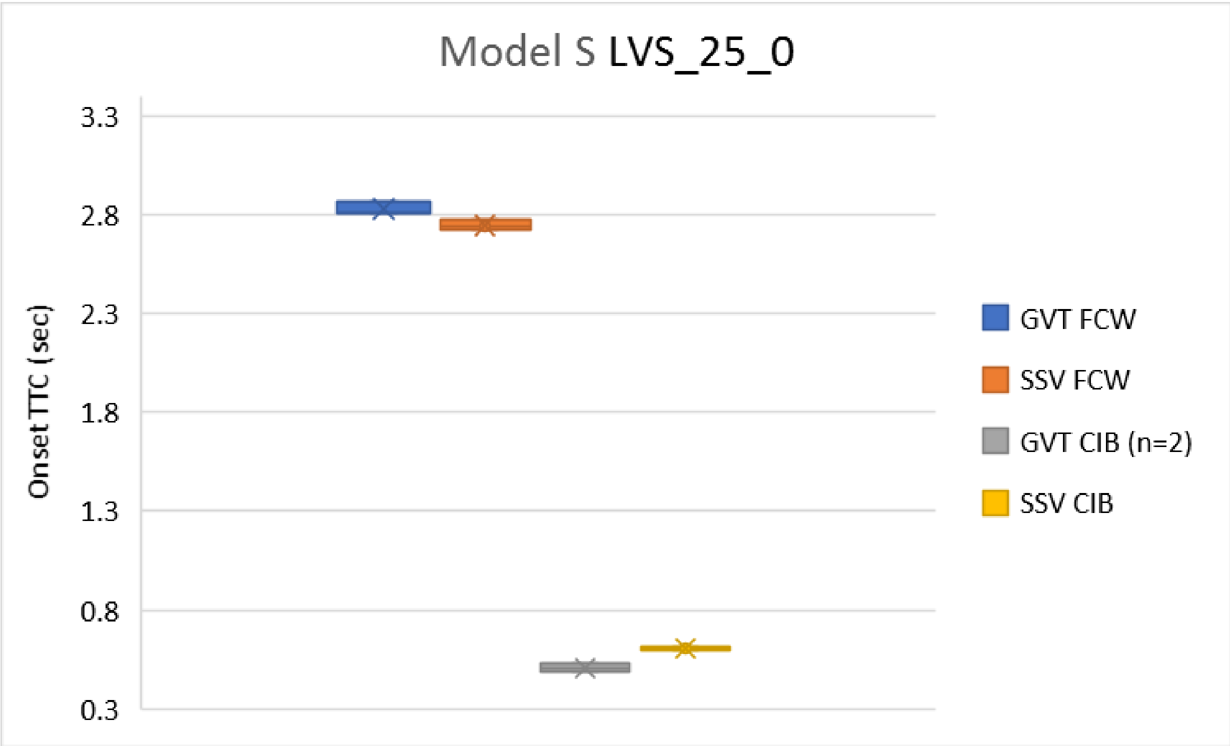


**Figure B-27: FCW and CIB onset timings to both targets during LVS_25_0 scenario (Tesla Model S).**

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