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NHTSA's 2014 Automatic Emergency Braking Test Track Evaluations

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16. Abstract
NHTSA's 2014 light vehicle automatic emergency braking (AEB) test program evaluated the ability of four vehicles, a 2014 Acura MDX, a 2014 BMW i3, a 2015 Hyundai Genesis, and a 2014 Jeep Grand Cherokee, to be tested with the agency's August 2014 draft crash-imminent braking (CIB) and dynamic brake support (DBS) test procedures. The maneuvers were successfully validated and the performance of the vehicles compared to a common set of draft assessment reference values (ARVs). None of the vehicles discussed in this report were able to satisfy all CIB ARVs if their performance was considered against a "seven of eight" evaluation criteria, and only the Jeep Grand Cherokee was able to satisfy the DBS ARVs during at least seven of eight trials for each test condition

The Jeep Grand Cherokee was evaluated with NHTSA's AEB test procedures once a month for four months to assess test repeatability and to examine the effect of nominal calendar month and ambient temperature. Statistically significant differences were present in month-to-month speed reductions for the lead vehicle stopped tests performed with CIB and for the lead vehicle decelerates-to-a-stop tests performed with DBS. However, these differences were < 1.0 mph (1.6 km/h), not believed to be practically significant, and did not affect the ability of the vehicle to satisfy the ARVs during at least seven of eight trials for each test condition. Ambient temperatures within a range of 49 to 81ºF (9.4 to 27.2ºC) were not found to have a meaningful effect on mean speed reduction or speed reduction variability.

The tests described in this report were based on the agency's August 2014 draft AEB procedures, but included some minor differences to address unique situations that occurred during test conduct. These differences were intended to provide clarification, not to affect (increase) test severity.

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CONVERSION FACTORS

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

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

LIST OF ACRONYNMS

AEB	Automatic Emergency Brake
ARV	Assessment Reference Value
BC	Brake Controller
CIB	Crash Imminent Braking
DBS	Dynamic Brake Support
EDR	Event Data Recorder
Euro NCAP	European New Car Assessment Program
FCAM	Forward Collision Avoidance and Mitigation
FCW	Forward Collision Warning
GAWR	Gross Axle Weight Rating
GVWR	Gross Vehicle Weight Rating
LRR	Long Range Radar
LVS	Lead Vehicle Stopped
LVM	Lead Vehicle Moving
LVD	Lead Vehicle Decelerating (general case)
LVD1	Lead Vehicle Decelerating (throughout duration of maneuver)
LVD2	Lead Vehicle Decelerating to a Stop
NHTSA	National Highway Traffic Safety Administration
POV	Principal Other Vehicle
RFC	Request for Comment
SSV	Strikeable Surrogate Vehicle
SV	Subject Vehicle
STP	Steel Trench Plate
TPS	Throttle Position Sensor (data reported as a percentage of WOT)
TTC	Time to Collision
WOT	Wide Open Throttle (maximum throttle pedal displacement)

EXECUTIVE SUMMARY

The National Highway Traffic Safety Administration's (NHTSA) 2014 light vehicle automatic emergency braking (AEB) test program evaluated the ability of four light vehicles, a 2014 Acura MDX, a 2014 BMW i3, a 2015 Hyundai Genesis, and a 2014 Jeep Grand Cherokee, to be tested with the agency's August 2014 draft crash imminent braking (CIB) and dynamic brake support (DBS) test procedures. Additionally, the Jeep Grand Cherokee was evaluated with these procedures once a month for four months to assess test repeatability.

In contrast to the agency's June 2012 draft CIB and DBS tests procedures, the August 2014 draft procedures[1]:

- Specify use of the brake burnish and initial brake temperatures (IBT) described in FMVSS No. 135
- Use the subject vehicle's (SV) forward collision warning (FCW) alert in the test chorography
- Contain revised SV throttle, brake, and load specifications
- Incorporate a series of relaxed test tolerances

The maneuvers were successfully validated and the performance of the vehicles compared to a common set of assessment reference values (ARVs). Repeatability was assessed by examining the effect of month and ambient temperature. In summary:

- None of the vehicles discussed in this report were able to satisfy all CIB ARVs if their performance was considered against a "seven of eight" evaluation criteria
- Only the Jeep Grand Cherokee was able to satisfy each DBS ARV.
- CIB false positives were observed with the Acura MDX during 1 of 8 steel trench plate (STP) tests performed from 25 mph (40 km/h).
- DBS false positives were observed during 6 of 8 STP tests performed from 25 mph (40 km/h) with the Acura MDX. From 45 mph (72 km/h), DBS false positives occurred during 8 of 8 tests performed with the Acura MDX and during 1 of 8 STP tests performed with the Jeep Grand Cherokee. The AEB systems of these vehicles were both based on a single long range radar (LRR) only.
- Statistically significant differences were present in month-to-month speed reductions for the LVS_25_0 tests performed with CIB and the LVD2_25_25 tests performed with DBS. However, these differences were < 1 mph (1.6 km/h), not believed to be

[1] The August 2014 draft CIB and DBS test procedures are identical to those described in the January 28, 2015 request for comment (RFC) used to announce NHTSA's plan to recommend these technologies in the New Car Assessment Program (NCAP).

practically significant, and did not affect the ability of the vehicle to satisfy the ARVs during at least seven of eight trials for each test condition.

- Ambient temperatures within a range of 49 to 81ºF (9 to 27ºC) were not found to have a meaningful effect on mean speed reduction or speed reduction variability.

The tests described in this report were based on the agency's August 2014 draft AEB procedures, but included some minor differences to address unique situations that occurred during test conduct. These differences, which were intended to provide clarification, not to affect (increase) test severity, were limited to:

- Inclusion of brake controller feedback selection process. This process is intended to help determine whether a vehicle's DBS performance should be evaluated with displacement or hybrid feedback. This process considers the relationship of brake pedal displacement, application force, and deceleration during DBS activation.
- Allowing a 250 ms overlap of throttle and brake application during DBS evaluation. This allowance addresses the situation where the SV's FCW alert occurs late in the pre-crash timeline. Without this provision it may not be possible to satisfy all DBS validity requirements for some vehicles, specifically those pertaining to throttle release-to-brake application timing.
- Specification of additional brake application tolerances. The intent of these tolerances is to ensure the brake pedal positions, forces, and rates described in the draft DBS test procedure are properly commanded, and that they can be practically achieved with the agency's brake controller.

A method to more accurately determine brake pedal displacement and application force needed to achieve a nominal deceleration magnitude with the vehicle's foundation brakes is discussed. However, at the time this report was published, NHTSA had not validated effectiveness of this method, or quantified how test burden will be affected by the additional steps it would require. This method was not used to evaluate the vehicles discussed in this report.

1.0 INTRODUCTION

1.1. Background

In August 2014, NHTSA published a research report documenting the agency's work with AEB systems, and the draft test procedures it has used to evaluate them [1,2,3]. AEB systems are a subset of what the agency refers to as Forward Crash Avoidance and Mitigation (FCAM) systems. Whereas the FCAM designation includes systems that provide Forward Collision Warning (FCW) only, AEB systems such as Crash Imminent Braking (CIB) and Dynamic Brake Support (DBS) are specifically designed to help drivers avoid, or mitigate the severity of, rear-end crashes. CIB systems provide automatic braking when forward-looking sensors indicate that a crash is imminent and the driver has not braked, whereas DBS systems provide supplemental braking when sensors determine that driver-applied braking is insufficient to avoid an imminent crash.

On January 22, 2015, Transportation Secretary Anthony Foxx announced NHTSA's plan to add Crash Imminent Braking (CIB) and Dynamic Brake Support (DBS) to the agency's New Car Assessment Program (NCAP). On January 28, a request for comment (RFC) was published to seek public comments on this plan [4]. The test procedures described in the RFC, those NHTSA has proposed to use for the objective evaluation CIB and DBS, are identical to the agency's August 2014 draft CIB and DBS test procedures. This document describes NHTSA's evaluation of four AEB-equipped late-model vehicles using these procedures. Additionally, one vehicle was used to evaluate AEB test output repeatability.

1.2. Vehicle Selection Rationale

The vehicles used for NHTSA's 2014 AEB evaluations are shown in Table 1-1, and were selected to complement the more complete vehicle list described in the August 2014 AEB report. Specifically, there was an interest in including vehicles from manufacturers that the agency had not evaluated in previous test efforts or whose AEB systems were first available in the United States during the 2014 or 2015 model year. The recent test vehicles were equipped with systems based on a 77 GHz long-range radar (LRR) and/or a mono-camera.

Each vehicle was equipped with an FCW system designed to operate ahead of CIB or DBS activation, and each system allowed the driver to manually choose from two to three FCW proximity settings. Prior to performing any of the CIB or DBS tests trials described in this report, NHTSA experimenters confirmed that the most conservative FCW mode had been specified in accordance with each vehicle's respective operator's manual. This mode allowed the alerts to be presented at the longest possible time to collision (TTC).

Note: The BMW i3 was the first electric vehicle (EV) with AEB technologies evaluated by NHTSA. To maximize the consistency of the braking output, the vehicle's battery charge was depleted so that its internal combustion "range extender" engine would operate throughout the entire test series. This precaution was used to reduce any confounding effect the battery's state-of-charge may have had on the BMW i3 AEB and/or foundation brake performance.

Figure 1-1 NHTSA's 2014 AEB Test Vehicle List

Vehicle	Vehicle Weights (lbs)[1]			AEB Sensing Technology	FCW Auditory Alert
	Overall (GVWR)	Front Axle (GAWR)	Rear Axle (GAWR)		
2015 Hyundai Genesis	5,150 (5,511)	2,520 (2,800)	2,630 (2,921)	One LRR (77 GHz) + Mono-camera	Hyundai_Genesis_FCW.mp3
2014 Acura MDX	4,760 (5,677)	2,670 (2,910)	2,090 (2,965)	One LRR (77 GHz)	Acura_MDX_FCW.mp3
2014 BMW i3	3,770 (3,815)	1,690 (1,785)	2,080 (2,205)	Mono-camera	BMW_i3_FCW.mp3
2014 Jeep Grand Cherokee	5,170 (6,500)	2,620 (3,200)	2,550 (3,700)	One LRR (77 GHz)	Jeep_Grand_Cherokee_FCW.mp3

[1] Includes the combination of a fully-fueled test vehicle plus driver, experimenter, and instrumentation.

1.3. Attempt to Quantify Repeatability

The CIB and DBS test series were both conducted once a month for four months using the Jeep Grand Cherokee. For these tests, the vehicle was equipped with the same instrumentation package and brake controller configuration (i.e., the equipment was not removed and re-installed each month). For the DBS tests, the foundation brake system was re-characterized each month using the process described in the August 2014 draft DBS test procedure. Results from each characterization were then used to perform a complete suite of NHTSA's draft DBS tests.

2.0 TEST PROTOCOL

2.1. NHTSA AEB Test Scenarios

NHTSA's August 2014 draft AEB test procedures were used for the work described in this report. An overview of each scenario is presented in Table 2-1.

Table 2-1 2014 AEB Test Matrix

Maneuver	Test Speeds; mph (km/h)		Initial Headway; ft (m)	Brake Apply Headway (DBS only); ft (m)
	SV	POV		
Stopped Lead Vehicle (LVS_25_0)	25 (40)	0	>187 (>57)	40 (12)
Slower Moving Lead Vehicle LVM_45_20	45 (72)	20 (32)	>183 (>56)	37 (11)
Slower Moving Lead Vehicle LVM_25_10	25 (40)	10 (16)	>34 (>110)	22 (7)
Decelerating Lead Vehicle LVD1_35_35	35 (56)	35 (56)	45 (14)	32 (10)
Decelerating Lead Vehicle (to a stop) LVD2_25_25	25 (40)	25 (40)	328 (100)	40 (12)
Steel Trench Plate STP_45	45 (72)	--	>337 (>106)	73 (22)
Steel Trench Plate STP_25	25 (40)	--	>187 (>57)	40 (12)

As highlighted in the report documenting NHTSA's 2013 AEB research activities [5], and in contrast to previously-released drafts [6,7], the August 2014 draft procedures specify the brake burnish and initial brake temperatures (IBT) described in FMVSS No. 135 be used[2] [8]. The procedures were also revised in the following areas:

- Use of the SV forward collision warning (FCW) alert in the test chorography
- SV throttle management specification
- SV brake application specifications (for DBS evaluations)
- SV load specification
- Miscellaneous test tolerances

[2] The FMVSS 135 IBT range is 149ºF(65ºC) ≤ IBT ≤ 212ºF(100ºC)

2.1.1. Use of FCW Alert

The SV auditory FCW alerts were used for the tests described in this report. The output of a microphone secured near the origin of the alert (to maximize the signal to noise ratio to the greatest extent possible) was used to determine the onset timing.

2.1.2. SV Throttle Management

The SV driver was required to maintain vehicle speed from the onset of the validity period (the beginning of the time when test tolerances must be maintained) to the onset of the SV FCW alert. Using the onset of FCW to define the end of the constant speed interval was a change.

2.1.3. SV Brake Applications

SV brake applications occurred at SV-to-POV headways representative of nominal TTC defined in the August 2014 draft test procedures. Each SV was evaluated with a series of 45 mph (72 km/h) slower moving lead vehicle (LVM) tests performed with a programmable brake controller and two control algorithms. The output of these tests was used to determine which mode to use for the vehicle's respective DBS evaluation. Section 2.3 describes this process in detail.

2.1.4. SV Loading

Each SV was fully fueled and loaded with instrumentation, a driver, and a rear seat experimenter. Their respective front/rear axle and gross vehicle weight ratings (GVWR) were not exceeded. Section 2.4 provides the weights measured for each SV prior to test conduct.

2.2. Draft Assessment Reference Values (ARV)

The draft assessment reference values specified in the August 2014 draft test procedures were used to compare the SV braking performance of each SV to a common reference. These ARVs are provided in Table 2-2.

Table 2-2 CIB and DBS Draft Assessment Reference Values (ARVs)

AEB System	LVS 25_0	LVM 45_20	LVM 25_10	LVD1 35_35	LVD2 25_25	STP_45 (FP)	STP_25 (FP)
CIB	Speed Reduction ≥ 9.8 mph (15.8 km/h)	Speed Reduction ≥ 9.8 mph (15.8 km/h)	Crash Avoidance	Speed Reduction ≥ 10.5 mph (16.9 km/h)	Speed Reduction ≥ 9.8 mph (15.8 km/h)	No Activation[1]	
DBS	Crash Avoidance					No Activation[2]	

[1] CIB activation is said to occur if SV deceleration ≥ 0.25g within the validity period

[2] DBS activation is said to occur if SV deceleration ≥ 125% of a baseline average

2.3. DBS Brake Application Methods

Any test method used to evaluate a vehicle's test track performance should not affect the test outcome or, more specifically, the ability of the vehicle to accurately demonstrate its performance. In the case of DBS evaluations, the manner in which force is applied to the vehicle's brake pedal is very important.

The August 2014 DBS draft test procedure includes a provision for the SV to be evaluated with one of two brake application methods. Each method requires the use of a programmable brake controller, automated SV-to-POV headway-based brake applications, and position control to bring the SV brake pedal from its natural resting position to that capable of producing a deceleration of 0.3g during the brake characterization process described in the draft DBS test procedure at a rate of 10 in/s (254 mm/s). Once at this position,

- "Displacement feedback" requires the brake controller to maintain a constant actuator position throughout the test trial, or
- "Hybrid feedback" switches to an application force-based control known as "force feedback." Once in the force feedback mode the brake controller (1) commands a fallback rate of 56 lbf/s (250 N/s) to reduce force to the level capable of producing a deceleration of 0.3g during brake characterization, then (2) attempts to maintain force at that level for the remainder of the test trial.

The AEB NCAP notice states that "the agency will work with manufacturers to understand their preference of the optional hybrid feedback or displacement-based feedback during NHTSA's evaluation of their vehicles." However, for the work described in this report, NHTSA did not ask the vehicle manufacturers which brake application method would be best suited to evaluate the AEB performance of their respective vehicles. Instead, the agency used the process described in Section 2.3.1 to objectively select what was believed to be the most appropriate control feedback method for subsequent testing.

2.3.1. Control Feedback Selection Process

When DBS is engaged, the vehicle's brake gain, the deceleration realized for a given brake pedal input, always increases. However, NHTSA has observed that the relationship between applied force and brake pedal position during DBS operation varies. For some vehicles, DBS activation causes the brake pedal to fall towards the floor. For others, it causes the brake pedal to rise up against the driver's foot. Identifying how the brake pedal responds to DBS operation is the primary way to determine whether a vehicle should be evaluated with displacement or hybrid feedback.

The control feedback selection process used during the 2014 DBS tests described in this report is summarized in two ways. First, the three steps used by the process are defined. Secondly, a flow chart is presented in Figure 2-1.

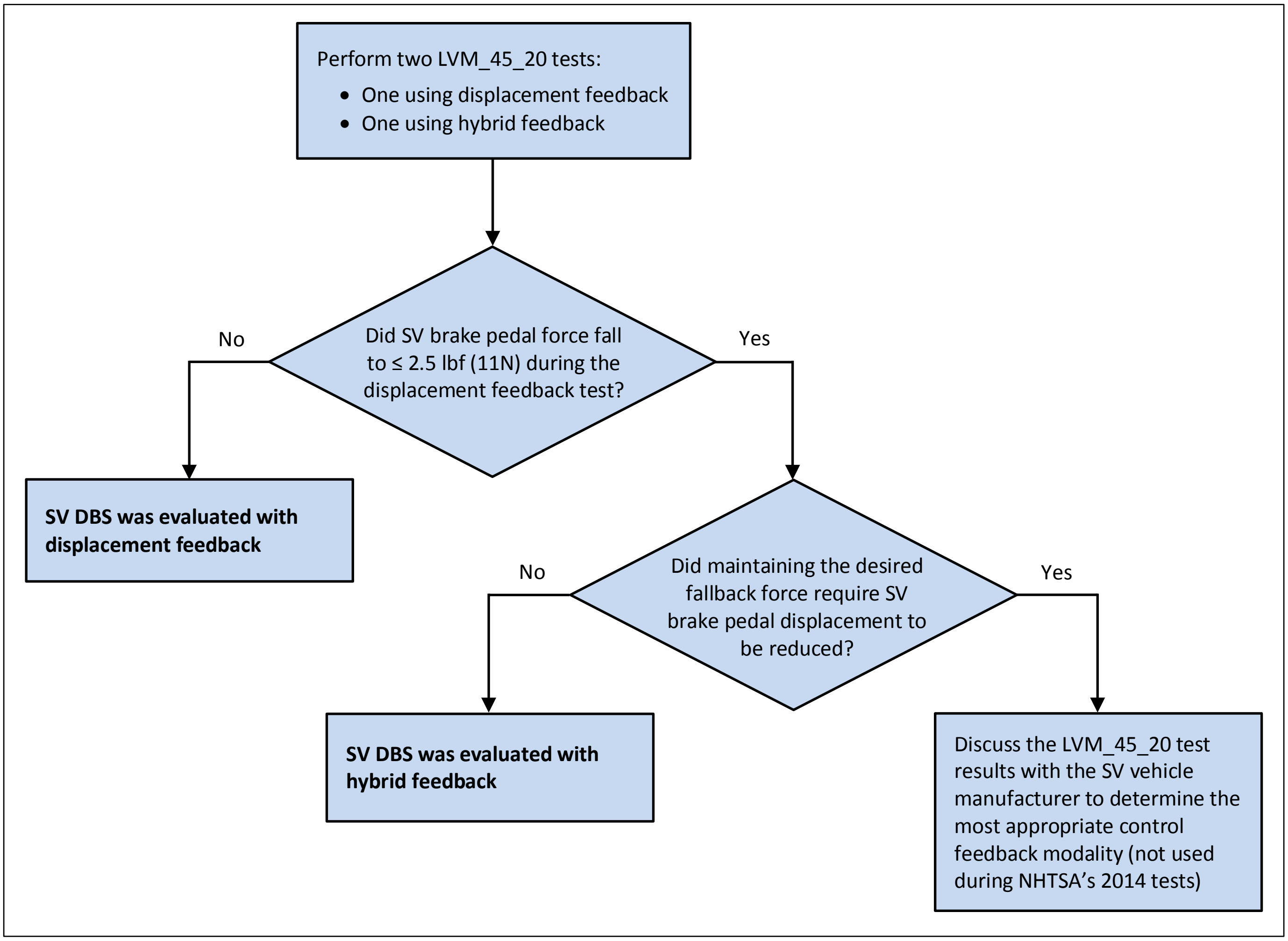
Step 1. Perform a short series of LVM 45_20 tests. The August 2014 draft DBS test procedure specifies seven individual test scenarios. Of those, the LVM test performed from 45 mph (72 km/h) appears to provide the most universal and practical way to demonstrate how a vehicle's DBS system operates[3]. Although only one LVM 45_20 test performed with each feedback loop[4] is necessary, NHTSA researchers performed three trials per feedback loop for the vehicles described in this report. The repeated trials allowed the consistency of each application method to be assessed.

Step 2. Review SV brake pedal position, brake pedal force, and vehicle deceleration test data. For the tests performed with displacement feedback, the position of the brake controller actuator should remain constant once it reaches the desired magnitude. If brake pedal force fell to a level ≤ 2.5 lbf (11 N) during these tests, hybrid feedback was used to evaluate the vehicle's DBS system. Otherwise, displacement feedback was used.

Step 3. Confirm control feedback selection. For tests performed with hybrid feedback, the position of the brake controller actuator is first increased from rest to that capable of producing 0.3g during brake characterization. Immediately after that, brake force should fall at a nominal rate of 56 lbf/s (250 N/s) to the magnitude needed to produce 0.3g during brake characterization, after which time it should remain constant. If maintaining this pedal force magnitude required the brake controller to reduce the actuator position magnitude (i.e., partially release the brake pedal), displacement feedback was used to evaluate the vehicle's DBS system. If the brake controller required actuator position be increased to maintain the force needed to produce 0.3g during brake characterization, hybrid feedback was used to evaluate the vehicle's DBS system.

[3] Some vehicles do not respond to the LVS scenario, and the LVD tests are more difficult to perform.

[4] Brake application magnitudes and surrogate vehicle specifications are included within the August 2014 draft DBS test procedure.



2.3.2. Commanded Displacement

DBS systems typically require a series of crash-imminent threshold conditions to be satisfied prior to system operation. Specifically, SV-to-POV range, closing velocity, deceleration, and brake application rate are all factors NHTSA has observed that potentially affect the likelihood of DBS activation.

The operational requirements and tight test tolerances described in the August 2014 DBS draft test procedure address the first three of these criteria. To ensure brake application rate was accurately achieved, the SV brake pedal was instrumented with a string (linear) potentiometer, shown in Figure 2-2, so the relationship between commanded brake controller actuator and actual brake pedal positions could be calculated. Using this relationship, the controller was programmed to output an actual brake pedal velocity of 1 ± 0.5 in/s (25 ± 12.7 mm/s) during brake system characterization and 10 ± 1 in/s (254 ± 25 mm/s) during the DBS evaluations.

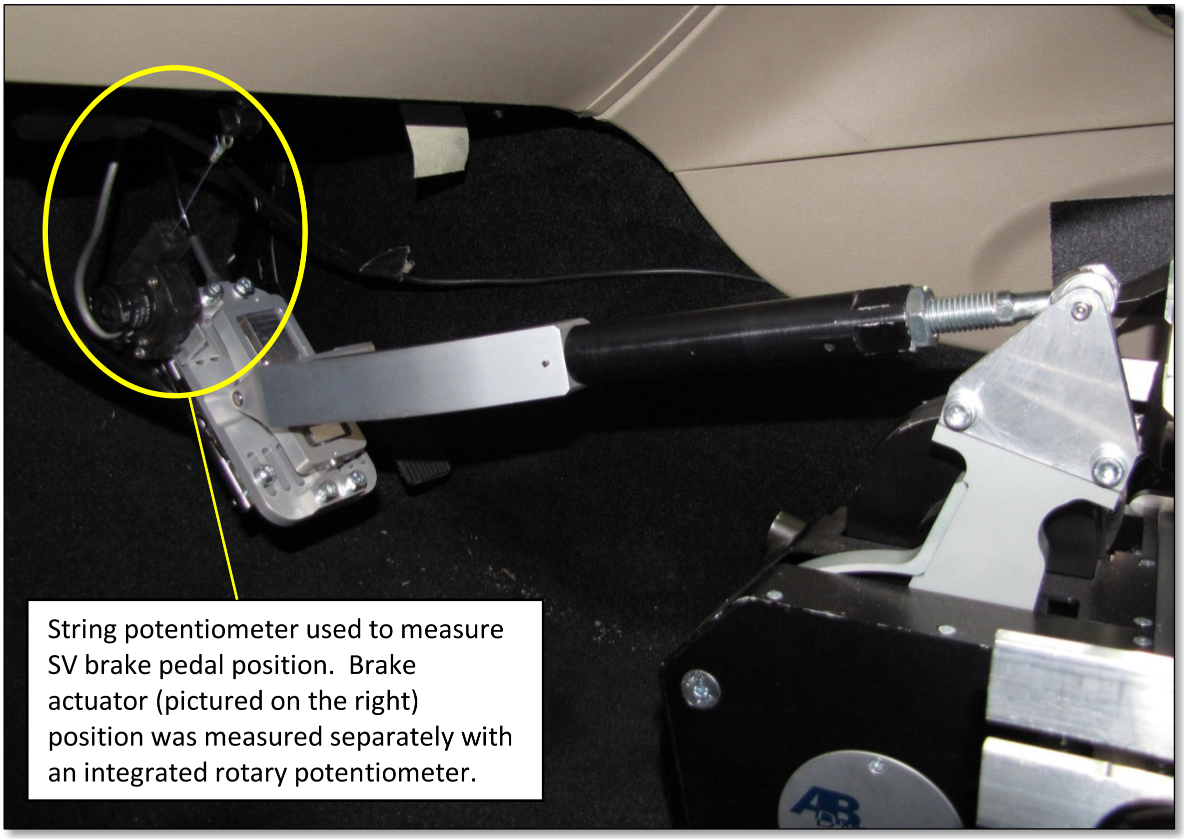


Figure 2-2 Brake controller and linear potentiometer installation.

2.4. Surrogate Vehicle

The NHTSA Strikeable Surrogate Vehicle (SSV), shown in Figure 2-3, was used for all CIB and DBS evaluations described in this report. The SSV is an artificial vehicle with visual, dimensional, and reflective (for scans from radar, lidar, etc. sensors) characteristics representative of an actual passenger car when approached from the rear aspect. Its carbon fiber construction is physically and dimensionally stable in the presence of wind gusts and during dynamic maneuvers, and is able to withstand repeated impacts of approximately 20 mph (32.2 km/h) without damage. Multiple validation efforts (performed by NHTSA, vehicle manufacturers, and suppliers) have concluded the SSV should be appropriately identified and classified as a genuine vehicle by all forward-looking AEB sensors/systems presently installed on production vehicles. More detailed descriptions of the SSV are available at [1,9,10,11].

Figure 2-3 NHTSA's Strikeable Surrogate Vehicle (SSV)

2.4.1. SSV Rear Brake Light Activation

One aspect contributing to the inherent visual realism of the SSV is the use of brake and taillights from an actual production vehicle (a 2011 Ford Focus hatchback). Although they were not illuminated directly during the evaluations described in NHTSA's 2014 AEB report [1], the plastic lenses were reflective, symmetrically oriented, and provided areas of high contrast relative to the SSV's white exterior, elements important to proper camera and/or lidar-based system performance.

Recognizing the opportunity to further enhance the realism of the SSV during the LVD tests, NHTSA researchers enabled the rear brake lights during the 2014 AEB evaluations. Specifically:

- LED light bulbs were installed within the SSV taillights in lieu of the standard incandescent equivalents (lower power consumption and no filaments to break during impacts; see Figure 2-4).
- A receiver, a lightweight battery, and a NHTSA-developed electronics box were installed in the cavity of the SSV shell.
- An RF transmitter was installed in the SSV tow vehicle to broadcast when braking was initiated (when the tow vehicle brake lights were illuminated).

Figure 2-4 SSV brake light illumination comparison.

2.4.2. Comments Regarding SSV Durability

Prior to NHTSA's 2013 AEB tests, a number of important SSV design revisions were implemented to improve its ability to withstand repeated high-severity impacts [1]. NHTSA researchers believe these revisions have indeed improved SSV durability, and retained their use throughout the 2014 testing described in this report. Additionally, a new load frame was constructed to address concerns that the bonding surface area in high-stress areas may be inadequate. Key elements of the new load frame include:

- Reinforced corners with larger corner gussets and horizontal tube stiffeners, shown in Figure 2-5
- Increased front vertical tube dimensions
- Hysol 9430 epoxy used as the bonding agent

These modifications allowed the SSV to be used with no load frame failures during the 2014 AEB testing, despite incurring multiple SV-to-SSV impacts at relative speeds over 20 mph (32.2 km/h). The latest SSV specifications, which include the 2014 revisions, are available in NHTSA's Forward-Looking Advanced Braking Technologies docket [10].

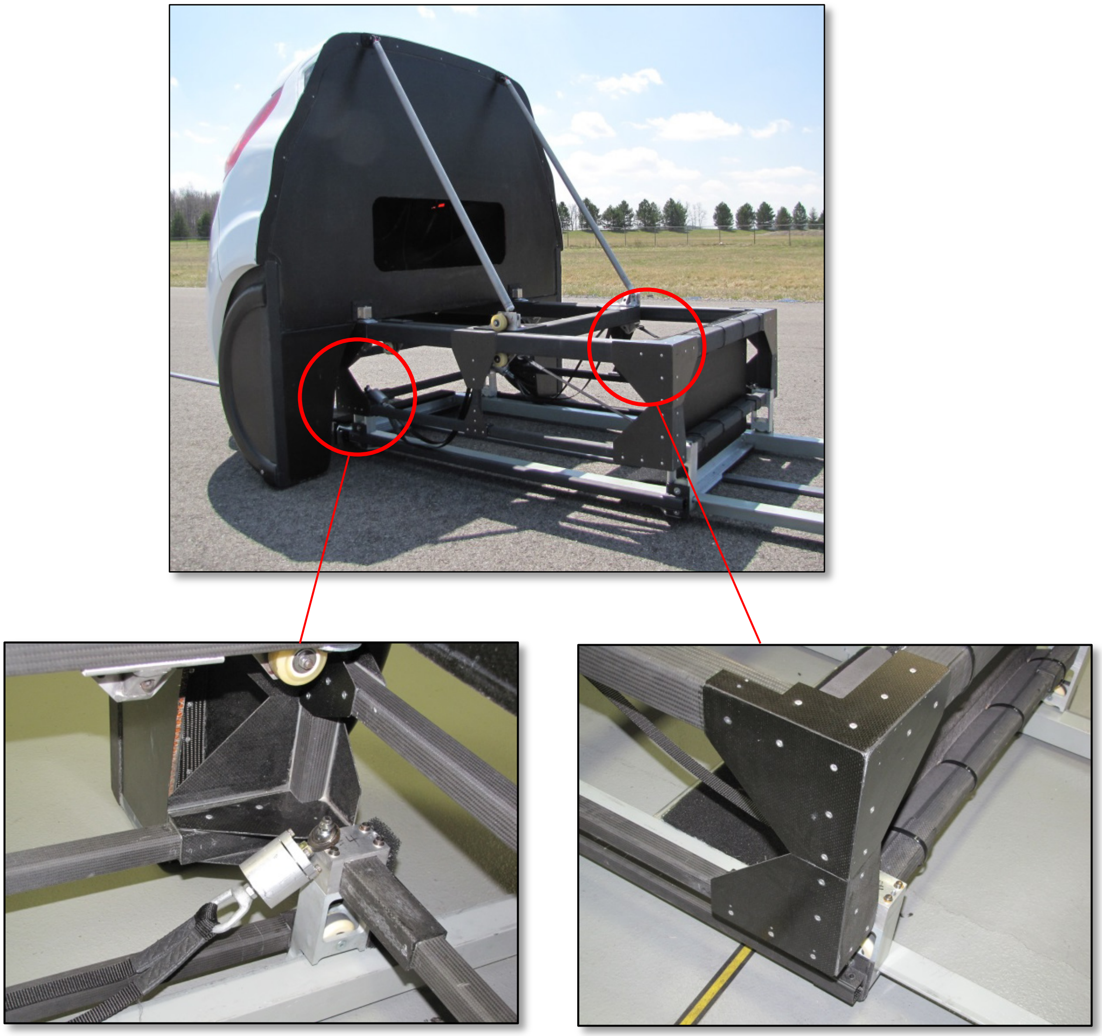


Figure 2-5 SSV load frame reinforcements. Note gussets.

3.0 TEST RESULTS

The results provided in this chapter are presented in seven sections. Section 3.1 describes the brake application feedback selection process for each vehicle. Section 3.2 lists the range of speed reductions observed for each vehicle as a function of AEB system and test scenario. Section 3.3 summarizes the SV-to-POV crash avoidance frequency. Section 3.4 presents a false positive assessment. Sections 3.5 and 3.6 discuss the ability of the SVs to satisfy the draft ARVs specified in the August 2014 draft test procedures and repeatability, respectively. Finally, Section 3.7 discusses challenges encountered during of conduct of the agency's draft test procedures, and ways they may be addressed.

3.1. Brake Actuator Control Feedback Selection

In this section, the data used to determine the most appropriate brake control feedback loop for each of the four vehicles evaluated in this report are shown. LVM_45_20 trials performed with displacement feedback in the presence of a POV (the SSV) are shown in solid red, whereas comparable hybrid feedback trials are shown in solid blue. For the sake of comparison, comparable baseline tests (i.e., those performed without anything in the forward path of the SV) initiated from 45 mph (72 km/h) are presented using the same color convention but with dashed lines for the Jeep Grand Cherokee, Hyundai Genesis, and Acura MDX[5]. For the tests performed with a POV, the minimum SV-to-POV range is indicated with a green asterisk. If an SV-to-POV impact was produced, it is indicated with a red asterisk.

3.1.1. Jeep Grand Cherokee

Figure 3-1 presents the data used to determine the most appropriate brake control feedback loop for the Jeep Grand Cherokee. For this vehicle,

- The deceleration data produced with a POV clearly indicates both feedback loops were able to activate DBS, whereas the baseline tests were not.
- With displacement feedback and the POV, brake pedal force (indicated as "BC Force") remains above 45 lbf (200 N) until minimum SV-to-POV range is achieved (i.e., the end of the test). Deceleration remained high from just after the brakes are applied until the end of the test.
- With hybrid feedback and the POV, the controlled reduction of brake pedal force was accompanied by a reduction of brake pedal position ≈ 800 ms after the brakes were applied, and continued until minimum SV-to-POV range was realized. Approximately 1.2 seconds after the brakes were applied, deceleration began to taper to the baseline magnitude.

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[5] Although a similar comparison was performed with the BMW i3 it was not meaningful since the contribution of DBS was not apparent during the DBS tests performed with a POV.

Based on these observations, NHTSA researchers determined that displacement feedback would best allow the Jeep Grand Cherokee to demonstrate its DBS braking capability. Although hybrid feedback also allowed the vehicle to avoid a POV impact, the extent to which this feedback loop required the brake pedal to be released (i.e., to less than an inch of displacement), and that the release ultimately coincided with DBS being switched off, was a concern. Since only one feedback loop could be retained for further testing, the most conservative decision was to use the application associated with what appeared to be the best braking performance.

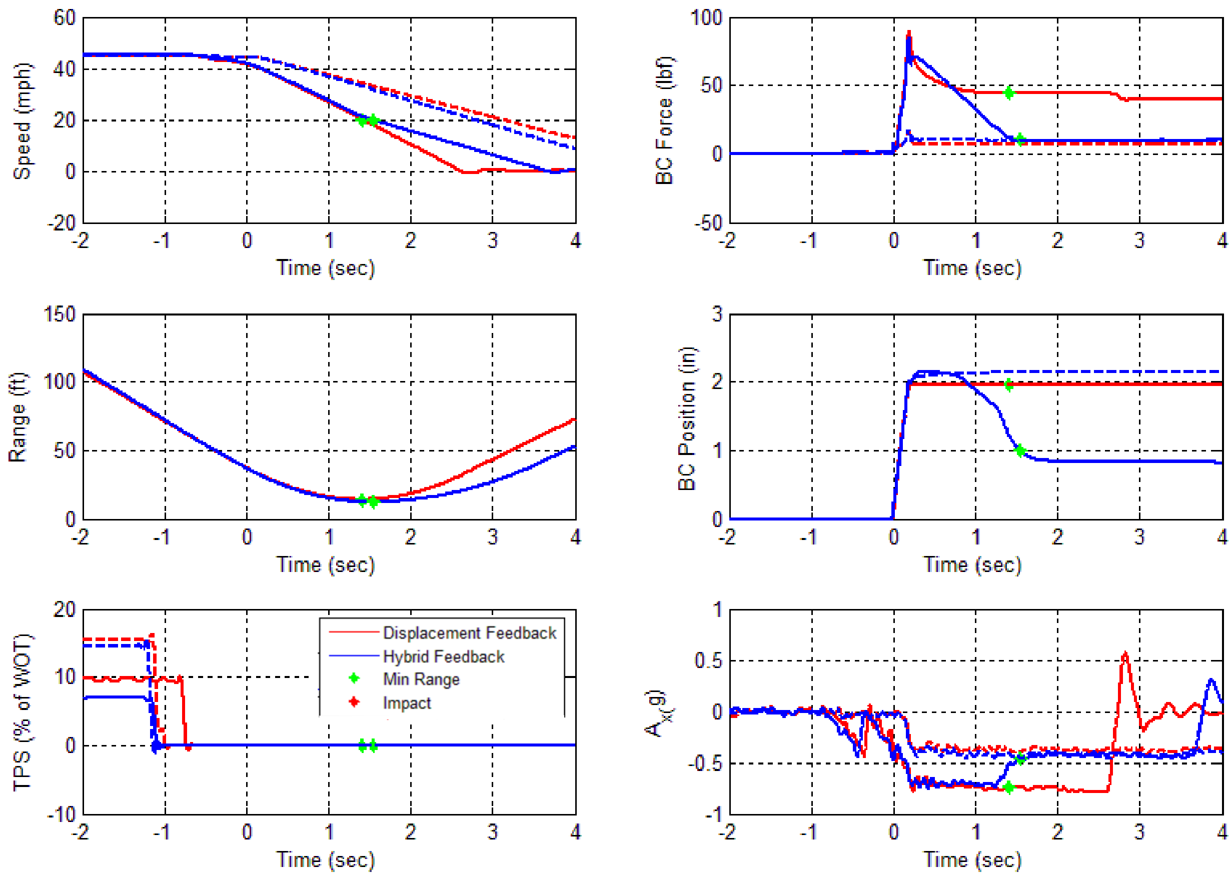

Figure 3-1 Jeep Grand Cherokee brake applications performed with and without a surrogate vehicle. Tests performed with the surrogate (solid lines) were intended to elicit DBS activation. Tests performed without the surrogate were not, and were used as baselines (dashed lines).

3.1.2. Hyundai Genesis

Figure 3-2 presents the data used to determine the most appropriate brake control feedback loop for the Hyundai Genesis. For this vehicle,

- The deceleration data produced with a POV clearly indicates both feedback loops were able to activate DBS, whereas the baseline tests were not. Interestingly, the baseline deceleration magnitudes differed significantly for the Hyundai Genesis, with hybrid feedback producing nearly twice the deceleration as that observed with displacement feedback.

- With displacement feedback and the POV, brake pedal force fell below 2.5 lbf (11.1 N) 279 ms after the initial brake application. However, 560 ms later it increased above 2.5 lbf (11.1 N), and ultimately reached 28.4 lbf (126.4 N) at the end of the test trial (when minimum SV-to-POV range occurs). Prior to minimum SV-to-POV range, a peak deceleration of 1.09g occurs 629 ms after the initial brake application. However, deceleration fell 39.2 percent to 0.66g 425 ms later, after which it increased until minimum range occurred.
- With hybrid feedback and the POV, the controlled reduction of brake pedal force was accompanied by a significant increase in brake pedal position immediately after that needed to produce a deceleration of 0.3g during characterization was achieved (from 1.5 to 2.7 in (38.7 to 69.3 mm), or 78.9 percent). That said, actuator position and deceleration did fall back prior to the occurrence of minimum SV-to-POV range, 20.0 and 9.3 percent, respectively.

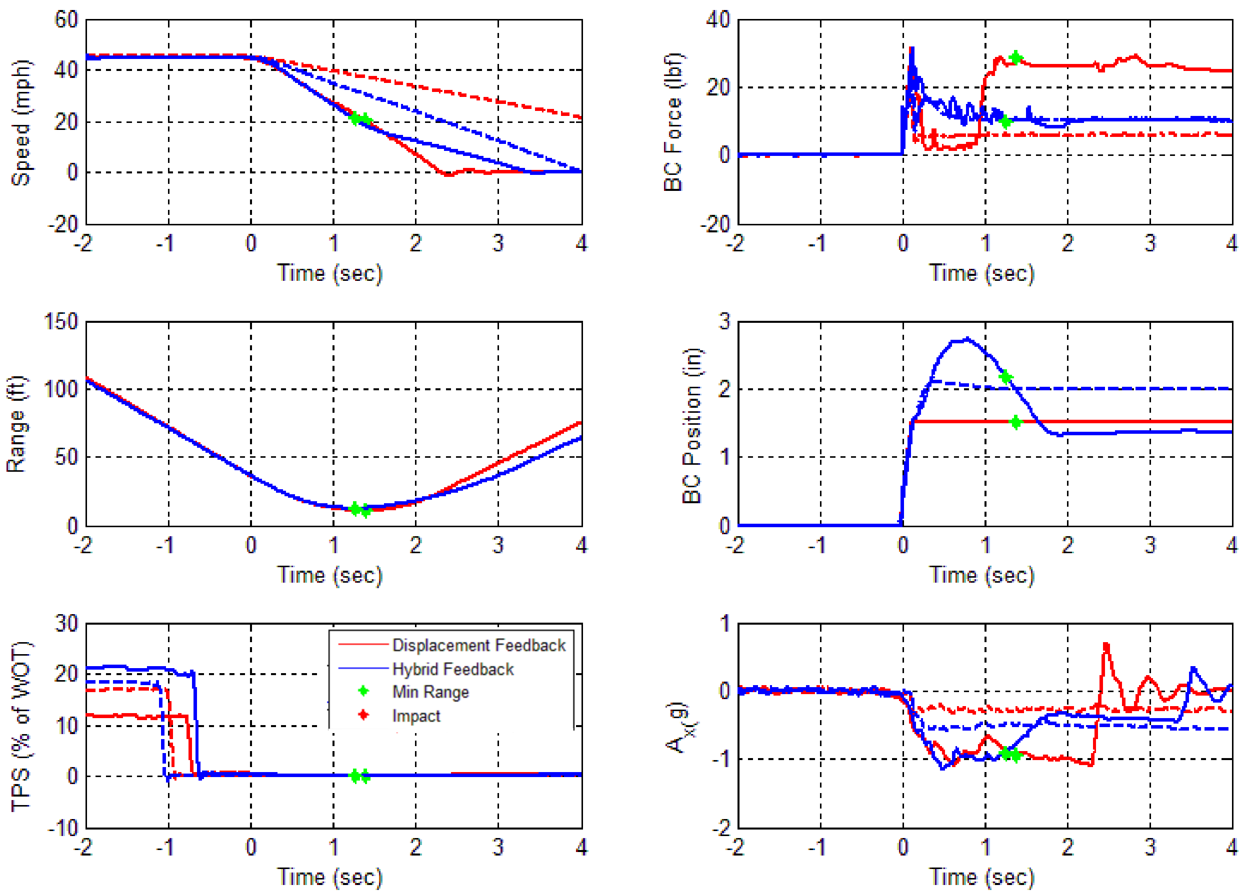

Figure 3-2 Hyundai Genesis brake applications performed with and without a surrogate vehicle. Tests performed with the surrogate were intended to elicit DBS activation (solid lines). Tests performed without the surrogate were not, and were used as baselines for comparison (dashed lines).

Although the decision was not as clear as that for the Jeep Grand Cherokee, NHTSA researchers determined that hybrid feedback would best allow the Hyundai Genesis to demonstrate its DBS braking capability. Data collected from both feedback methods indicate the vehicle's brake pedal physically moves during DBS activation, and NHTSA researchers believe hybrid braking will accommodate this motion to the greatest extent possible. Furthermore, without the use of hybrid braking, brake application force remained at a very low level for much of the braking event, an occurrence that has affected DBS operation with other vehicles.

3.1.3. Acura MDX

Figure 3-3 presents the data used to determine the most appropriate brake control feedback loop for the Acura MDX. For this vehicle,

- The deceleration data produced with a POV clearly indicates hybrid feedback was able to activate DBS, whereas the respective baseline test was not. With displacement feedback, the vehicle's deceleration was greater than that of the baseline, but not nearly to the extent seen with hybrid braking.
- With displacement feedback and the POV, brake pedal force fell below 2.5 lbf (11.1 N) 355 ms after the initial brake application, and remained there for most of the remaining trial (i.e., until the SV-to-POV impact occurred). The trial's peak deceleration of 0.59g did not occur until the time of impact, 1.28 seconds after the brake application was initiated.
- With hybrid feedback and the POV, the controlled reduction of brake pedal force was accompanied by a significant increase in brake pedal position immediately after that needed to produce a deceleration of 0.3g during characterization was achieved (from 1.5 to 2.3 in (38.2 to 58.4 mm), or 53.0 percent). Actuator position and deceleration did not fall back prior to the occurrence of minimum SV-to-POV range.

NHTSA researchers determined that hybrid feedback would best allow the Acura MDX to demonstrate its DBS braking capability. Data collected from both feedback methods indicate the vehicle's brake pedal physically moves during DBS activation, and NHTSA researchers believe hybrid braking will accommodate this motion to the greatest extent possible. Without the use of hybrid braking, brake application force remained at a very low level for much of the braking event, an occurrence that has affected DBS operation with other vehicles. The peak deceleration realized with hybrid braking was 0.82g, 38.4 percent greater than that produced with displacement feedback. Most importantly, use of displacement feedback resulted in an SV-to-POV impact, whereas crash avoidance was realized with the same maneuver and hybrid braking.

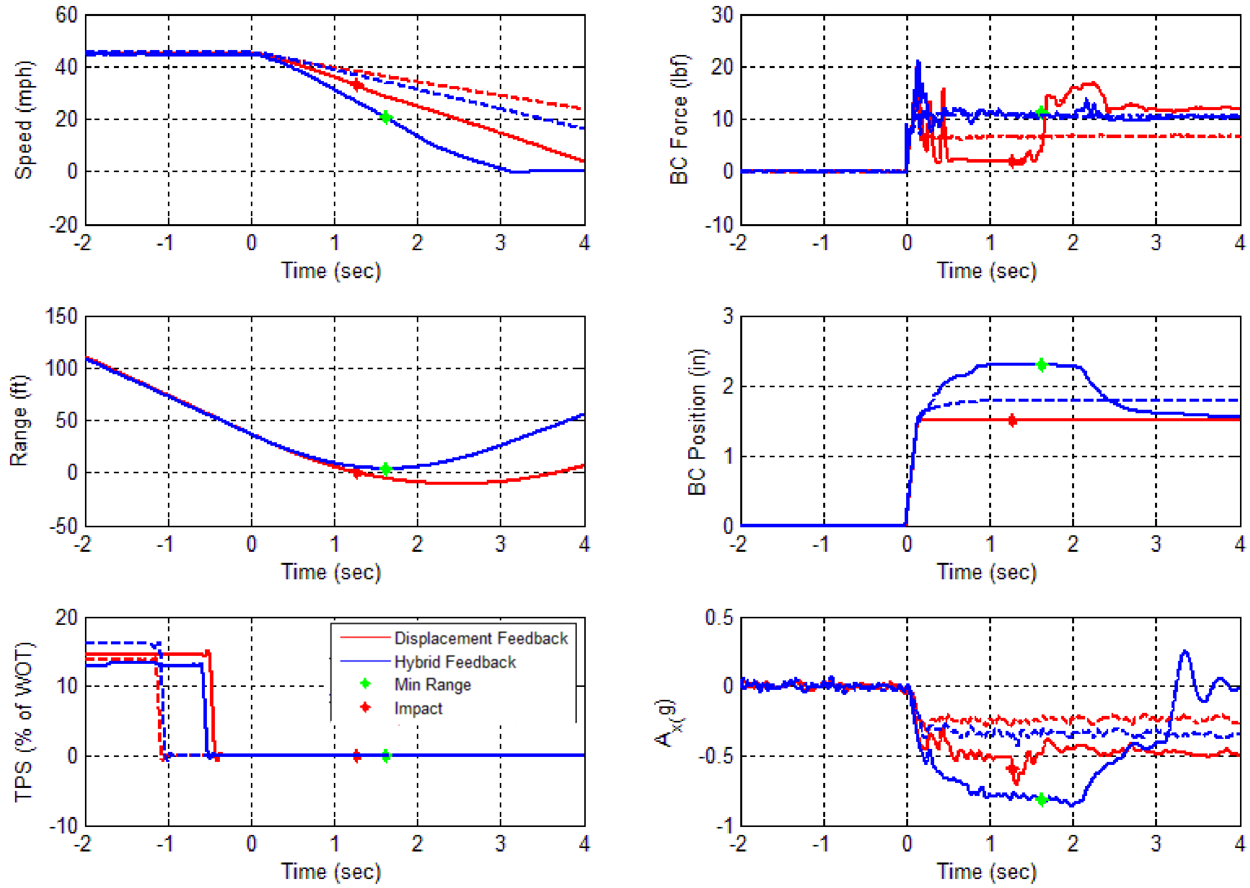

Figure 3-3 Acura MDX brake applications performed with and without a surrogate vehicle. Tests performed with the surrogate were intended to elicit DBS activation (solid lines). Tests performed without the surrogate were not, and were used as baselines for comparison (dashed lines).

3.1.4. BMW i3

The BMW i3 operator's manual provides two descriptions of how the vehicle's "Collision warning with City Braking function" (i.e., the AEB system) can be expected to perform [12]. In the "General information" section of this description, the manual indicates that:

> *"up to approximately 35 mph/60 km/h a braking intervention occurs when appropriate"*

Later in a separate "Braking intervention" section, the manual states that:

> *"The [FCW] warning prompts the driver himself to intervene. During a warning, the maximum braking force is used. A prerequisite for the brake booster is a sufficiently fast and sufficiently strong actuation of the brake pedal. In addition, if there is a risk of collision, the system can assist with a slight braking intervention."*

Since it uses a test maneuver initiated from 45 mph (72 km/h), not having the vehicle's DBS operate at speeds above 35 mph (56 km/h) would prevent the brake control feedback loop selection process described in this report from working with the BMW i3. However, since the language of the manual did not explicitly state DBS (and not just CIB) would operate only at or below 35 mph (56 km/h), the process was attempted. The resulting data are presented in Figure 3-4.

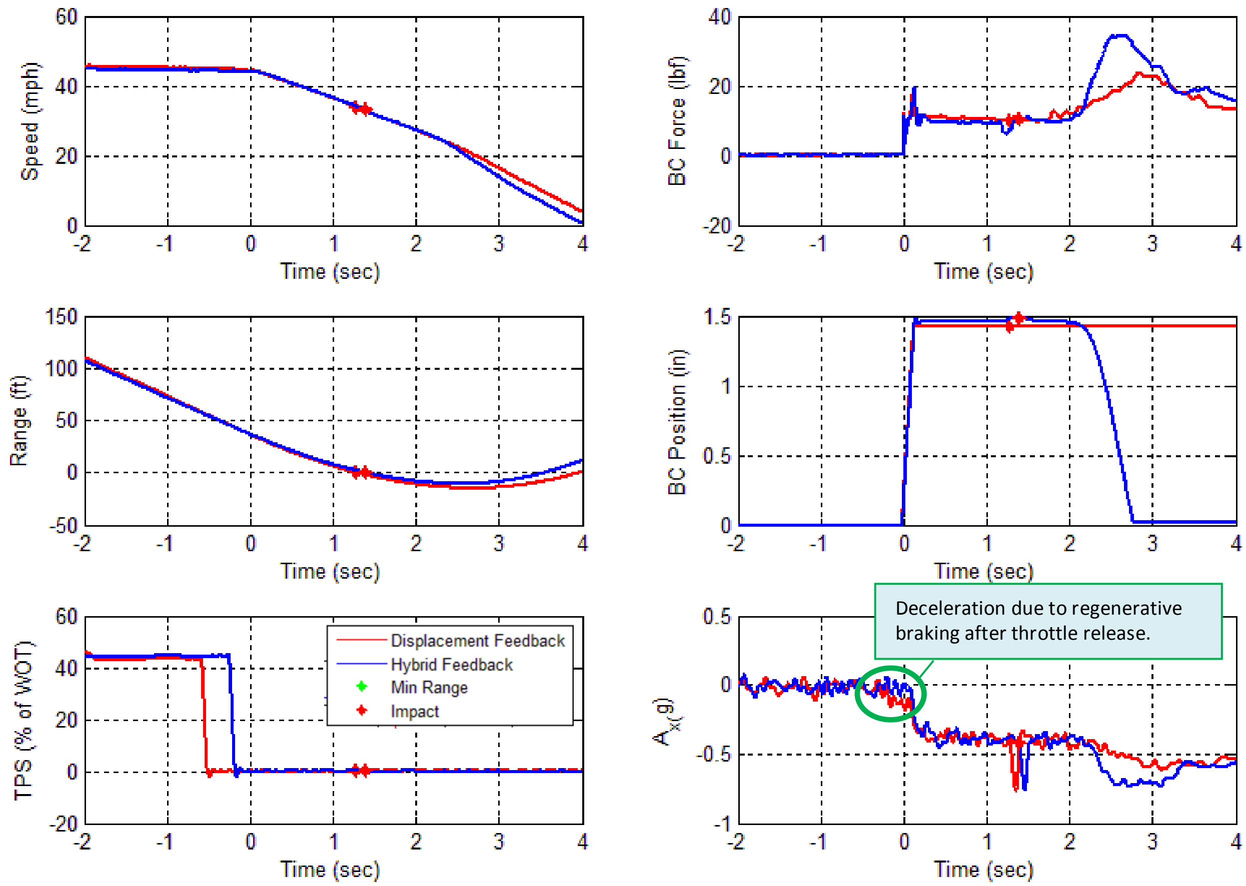

Figure 3-4 BMWi3 brake applications performed during the LVM_45_20 scenario with a surrogate vehicle. Both tests were performed with a surrogate vehicle intended to elicit DBS activation.

From the onset of braking to the end of each test trial, the data produced from the displacement and hybrid-based applications shown in Figure 3-4 were nearly identical. Despite the use of different brake controller logic, the brake forces and positions of each trial were in good agreement and remained quite consistent over time. The contribution of DBS was not apparent for either trial, and they both resulted in an SV-to-POV impact. Based on these results, NHTSA researchers were unable to determine which control method would best allow the BMW i3 to demonstrate its DBS braking capability.

To determine whether performing the control feedback evaluation above 35 mph (56 km/h) prevented the vehicle's DBS from being activated (i.e., the tests were potentially performed above the maximum operational speed), tests performed with the same brake applications and surrogate vehicle were used with the LVS_25_0 test scenario. For this evaluation, two trials with displacement feedback (one baseline, one in the presence of the SSV), and one trial with hybrid feedback were performed. The resulting data are shown in Figure 3-5.

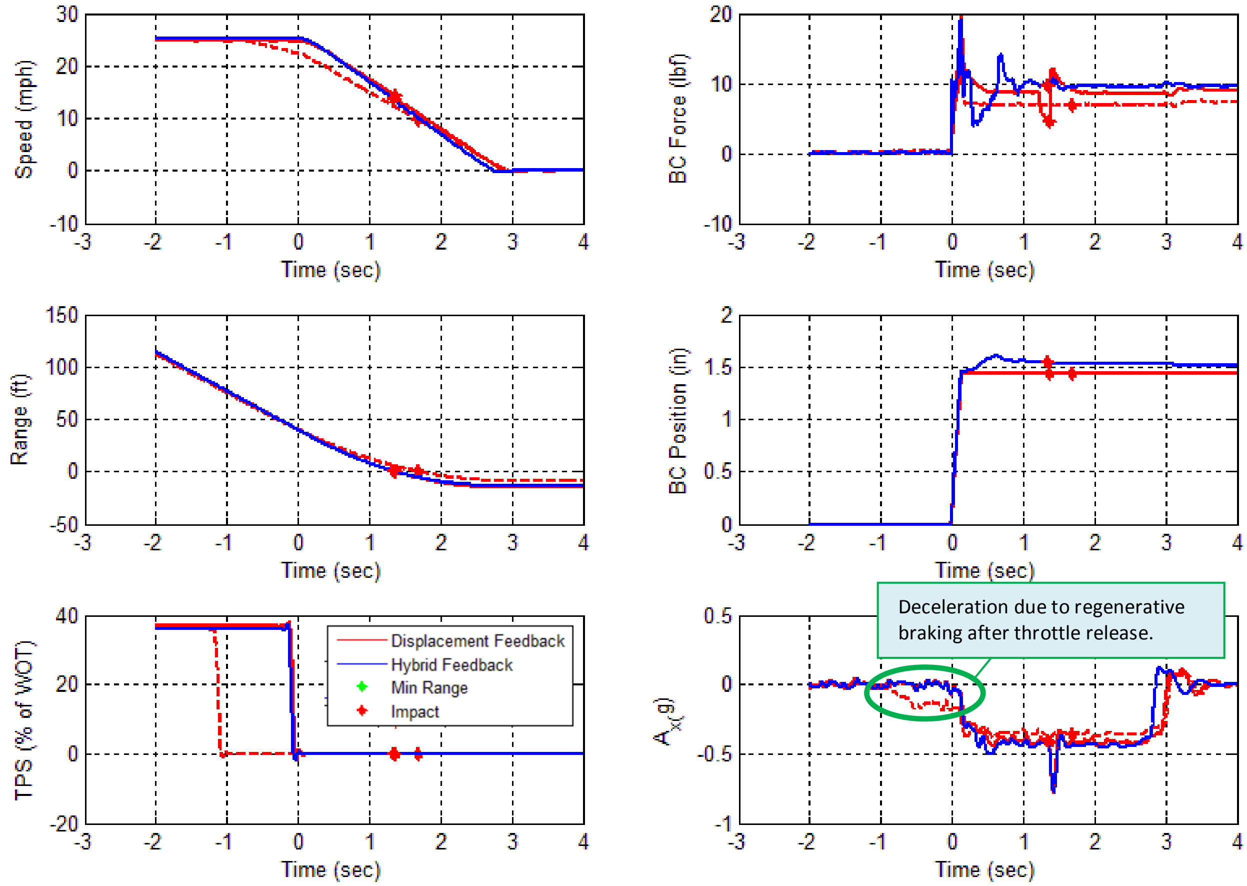

Figure 3-5 BMWi3 brake applications performed with (solid lines) and without (dashed lines) a surrogate vehicle. Tests performed with the surrogate were intended to elicit DBS activation. Tests performed without the surrogate were not, and were used as baselines for comparison. Note the point of impact during the baseline trial is a "virtual" point. The baseline trial was performed as if it was an LVS test, but instead of basing the brake application on the distance to the rear of the SSV, it was based on the distance to a fixed point in the center of the travel lane.

When compared to those performed with displacement feedback, the trial performed with hybrid feedback produced more brake application force disparity and some small differences in brake actuator position. Also, during the test performed with displacement feedback and the SSV, SV brake force fell by 3.9 lbf (17.3 N), or 16.7 percent, over a time 140 ms prior to the SV-to-POV impact. However, the deceleration profile and magnitudes produced with each application method were nearly identical from the onset of braking to the point of SV-to-POV impact. The contribution of DBS was not apparent for either trial.

Comparison of the baseline displacement feedback trial with that using the surrogate vehicle also showed some differences in applied force and deceleration after the initial application (despite the use of identical brake actuator position and timing). However, the deceleration difference from the baseline trial was minor[6], and was not great enough to prevent an SV-to-POV impact.

Based on these results, NHTSA researchers were still unable to determine which control method would best allow the BMW i3 to demonstrate its DBS braking capability. Despite the use of two test scenarios with strong real-world relevance (LVS_25 and LVM_45_20), appropriate application rates (nominally 10 in/s or 254 mm/s), tight test tolerances, and a realistic surrogate vehicle, neither application process was able to realize a significant DBS intervention with this vehicle.

Note: The BMW i3 is equipped with a regenerative brake system that automatically provides a deceleration of approximately 0.2g when the throttle pedal is fully released. During the trials performed with the SSV, the throttle pedal was released just after the vehicle's FCW was presented, or 30 to 50 ms before the brake controller automatically applied the brakes at the pre-programmed SV-to-POV headway. Since no FCW was presented during the baseline trial (no surrogate vehicle was present), the driver released the throttle at a TTC $\approx$ 2.1 seconds (1.07 seconds prior to the brake application) by monitoring an in-vehicle headway display. The difference in throttle release timing accounts for the difference in vehicle speed prior to the brake application. Although regenerative braking was able to reduce vehicle speed by 2.6 mph (4.2 km/h) prior to brake controller activation during the baseline trial, the short period between throttle release and brake application during the SSV-based test did not provide enough time for the effect of regenerative braking to be apparent.

[6] Average deceleration from the onset of the brake application to SV-to-POV impact (1.4 seconds later) was 0.339g vs. 0.332g over the same time with during baseline braking.

3.2. Speed Reductions

Table 3-1 presents the range of speed reductions observed for each vehicle as a function of AEB system and test scenario. Where applicable, an explanation for why some vehicle/scenario combinations were not evaluated is provided. The potential of these speed reductions to satisfy the respective draft ARVs is discussed in Section 3.5.

Table 3-1 SV Speed Reductions Per Scenario (mph).

Vehicle	AEB System	SV Speed Reduction Per Scenario (mph)				
		LVS 25_0	LVM 45_20	LVM 25_10	LVD1 35_35	LVD2 25_25
2014 Acura MDX	CIB	7.5 - 7.9[1]	8.6 - 10.3	7.9 - 15.3	11.0 - 14.0	6.6 - 9.5
2014 Jeep Grand Cherokee	CIB	7.7 - 8.7	9.1 - 12.9	7.9 - 10.5	12.2 - 13.4	12.4 - 12.8
2014 BMW i3	CIB	7.6 - 9.5	Not performed[4]	8.2 - 10.4	8.3 - 11.7	7.5 - 9.0
2015 Hyundai Genesis	CIB	17.4 - 25.5	23.8 - 24.8	14.1 - 15.3	Not performed[5]	Not completed[6]
2014 Acura MDX[2]	DBS	24.3 - 24.9	23.7 - 24.9	14.1 - 15.3	12.9 - 19.5	19.6 - 25.1
2014 Jeep Grand Cherokee[3]	DBS	24.5 - 25.1	24.5 - 25.2	14.2 - 15.1	17.4 - 23.5	24.2 - 25.1
2014 BMW i3[3]	DBS	9.4 - 11.6	Tests not performed[7]			
2015 Hyundai Genesis[2]	DBS	16.3 – 25.2	21.8 - 25.0	13.9 – 15.2	23.7 – 31.3	21.0 – 25.1

[1] The Acura MDX was the first vehicle evaluated after improvements to the SSV load frame had been made. Since the vehicle was unable to satisfy the LVS_25_0 ARV during the first three trials, experimenters decided not to perform the remaining five trials of the eight trial test series.

[2] Brake applications used hybrid feedback

[3] Brake applications used displacement feedback

[4] The BMW i3 CIB has a maximum operational speed of 35 mph (56 km/h), 10 mph (16 km/h) lower than that required by the LVM_45_20 scenario

[5] Radar damage occurred during the CIB LVD2 test series, requiring replacement. Since the Hyundai Genesis appears to be sensitive to impacts with the SSV and provides no indication when minimal-to-no CIB intervention will occur, NHTSA researchers decided not to perform the LVD1 tests, and not to rerun the LVD2 tests with the new equipment.

[6] The forward looking radar was damaged before the LVD2 test series was complete. Only five valid tests were performed, and the test series was not rerun.

[7] Minimal-to-no indication of DBS activation was observed during the brake control feedback loop selection process. So as to avoid unnecessary damage to the test vehicle or equipment and since the vehicle had already been unable to satisfy the LVS ARVs, the remaining DBS tests were not performed.

3.3. Crash Avoidance

Table 3-2 presents a crash avoidance summary for each vehicle as a function of AEB system and test scenario. Where applicable, an explanation for why some vehicle/scenario combinations were not evaluated is provided. The potential of the crash avoidance responses provided in Table 3-2 to satisfy the respective draft ARVs is discussed in Section 3.5.

Table 3-2 Number of Trials Concluding with Crash Avoidance Per Scenario.

Vehicle	AEB System	Number of Trials Concluding with Crash Avoidance Per Scenario				
		LVS 25_0	LVM 45_20	LVM 25_10	LVD1 35_35	LVD2 25_25
2014 Acura MDX	CIB	0/3[1]	0/8	0/8	0/8	0/8
2014 Jeep Grand Cherokee	CIB	0/8	0/8	0/8	0/8	0/8
2014 BMW i3	CIB	0/8	Not performed[4]	0/8	0/8	0/8
2015 Hyundai Genesis	CIB	5/8	8/8	8/8	Not performed[5]	Not completed[6]
2014 Acura MDX[2]	DBS	8/8	8/8	8/8	0/8	7/8
2014 Jeep Grand Cherokee[3]	DBS	8/8	8/8	8/8	7/8	8/8
2014 BMW i3[3]	DBS	0/8	Tests not performed[7]			
2015 Hyundai Genesis[2]	DBS	7/8	7/8	8/8	6/8	6/8

[1] The Acura MDX was the first vehicle evaluated after improvements to the SSV load frame had been made. Since the vehicle was unable to satisfy the LVS_25_0 ARV during the first three trials, experimenters decided not to perform the remaining five trials of the eight trial test series.

[2] Brake applications used hybrid feedback

[3] Brake applications used displacement feedback

[4] The BMW i3 CIB has a maximum operational speed of 35 mph (56 km/h), 10 mph (16 km/h) lower than that required by the LVM_45_20 scenario.

[5] Radar damage occurred during the CIB LVD2 test series, requiring replacement. Since the Hyundai Genesis appears to be sensitive to impacts with the SSV and provides no indication when minimal-to-no CIB intervention will occur, NHTSA researchers decided not to perform the LVD1 tests, and not to rerun the LVD2 tests with the new equipment.

[6] The forward looking radar was damaged before the LVD2 test series was complete. Only five valid tests were performed, and the test series was not rerun.

[7] Minimal-to-no indication of DBS activation was observed during the brake control feedback loop selection process. So as to avoid unnecessary damage to the test vehicle or equipment and since the vehicle had already been unable to satisfy the LVS ARVs, the remaining DBS tests were not performed.

3.4. False Positive Assessment

Table 3-3 presents the range of peak decelerations observed for each vehicle as a function of AEB system and test scenario. Where applicable, an explanation for why some vehicle/scenario combinations were not evaluated is provided. Also included in Table 3.3 are the ARVs for which the peak decelerations are compared against. In the case of CIB, the ARVs are always 0.25g (specified in NHTSA's August 2014 CIB draft test procedure). For DBS, the ARVs are calculated by averaging the eight peak decelerations observed during a series of baseline trials (described in NHTSA's August 2014 DBS draft test procedure). Note that the "STP Avoidance" columns indicate whether the SV was braked to a stop before the front-most part of the vehicle crossed a vertical plane defined by the leading edge of the STP. The potential of the responses provided in Table 3-3 to satisfy the respective draft ARVs is discussed in Section 3.5.

Table 3-3 Peak SV Decelerations and STP Crash Avoidance Summary.

Vehicle	AEB System	Peak SV Deceleration (g)		STP Avoidance (number of trials)	
		STP 45	STP 25	STP 45	STP 25
2014 Acura MDX	CIB	0.14 - 0.23 (vs. 0.25 ARV)	0.09 - 0.25 (vs. 0.25 ARV)	0/8	0/8
2014 Jeep Grand Cherokee	CIB	0.07 - 0.11 (vs. 0.25 ARV	0.03 - 0.06 (vs. 0.25 ARV)	0/8	0/8
2014 BMW i3	CIB	0.07 - 0.08 (vs. 0.25 ARV)	0.04 - 0.07 (vs. 0.25 ARV)	0/8	0/8
2015 Hyundai Genesis	CIB	0.05 - 0.08 (vs. 0.25 ARV)	0.05 - 0.07 (vs. 0.25 ARV)	0/8	0/8
2014 Acura MDX[1]	DBS	0.58 - 0.88 (vs. 0.52 ARV)	0.38 - 0.87 (vs. 0.47 ARV)	0/8	2/8
2014 Jeep Grand Cherokee[2]	DBS	0.42 - 0.54 (vs. 0.52 ARV)	0.36 - 0.40 (vs. 0.49 ARV)	0/8	0/8
2014 BMW i3[2]	DBS	Tests not performed[3]			
2015 Hyundai Genesis[1]	DBS	0.55 - 0.59 (vs. 0.71 ARV)	0.46 - 0.54 (vs. 0.67 ARV)	0/8	0/8

[1] Brake applications used hybrid feedback

[2] Brake applications used displacement feedback

[3] Minimal-to-no indication of DBS activation was observed during the brake control feedback loop selection process so no DBS STP tests were performed with the BMW i3.

3.5. Potential to Satisfy the Draft Assessment Reference Values (ARVs)

The potential of the test vehicles described in this report to satisfy the ARVs defined in the August 2014 CIB and DBS draft test procedure drafts is summarized in Table 3-4. Where applicable, an explanation for why it was not possible to evaluate some vehicle/scenario combinations is provided. Cells highlighted in green indicate the respective ARV was satisfied for at least seven of the eight valid test trials performed. Red cells indicate the vehicle was unable to satisfy the ARV during at least two trials performed within the respective test series. In summary:

- None of the vehicles discussed in this report were able to satisfy all CIB ARVs.
- Only the Jeep Grand Cherokee was able to satisfy each DBS ARV.

The CIB LVD1_35_35 test series was not performed with the Hyundai Genesis, and the CIB LVD2_25_25 series performed with the vehicle was terminated prematurely[7]. Therefore, assessing whether the Genesis was able to satisfy the ARVs during each of the eight respective trials was not possible for these scenarios.

Only LVS 25_0 tests were used to evaluate the BMW i3 DBS system. These tests were unable to satisfy the DBS ARVs. In agreement with the results previously discussed in Section 3.1.4, exploratory tests performed in other DBS test conditions resulted in minimal-to-no indication of DBS activation. So as to avoid unnecessary damage to the test vehicle or equipment and since the vehicle was unable to satisfy the LVS ARVs, the remaining DBS tests were not performed.

[7] Six CIB LVD_25_25 test trials were performed with the Hyundai Genesis, and the last two resulted in SV-to-POV collisions. Speed reductions of 6.8 and 0.1 mph were realized during these trials, resulting in relative impact speeds of 17.8 and 25.0 mph (28.6 and 40.2 km/h), respectively. These impacts are believed to have caused the vehicle's grill to be pushed into its forward-facing radar, damaging the mounting bracket. The damaged bracket was believed to have resulted in a vertical misalignment of the radar, and a situation where the vehicle's AEB system did not operate properly (if at all). Hyundai has indicated that the manner in which the agency performs its CIB tests (approximately five minutes and a new ignition cycle between each trial) did not allow enough time for an alert indicating a system malfunction to the driver to be presented. Since NHTSA researchers could not accurately assess the state (i.e., readiness) of the vehicle's CIB system at the beginning of each trial, and the implication of a non-activation was the potential for SV and/or test equipment damage, the test series was terminated and the vehicle brought to the dealership for repair. Once back from the dealer (grill, radar, and radar bracket replacement), only DBS tests were performed since the maximum SV-to-POV impact speeds were expected to be lower than those potentially realized during comparable CIB tests where no activation occurs. For this reason, CIB LVD_35_35 tests were not performed with the Hyundai Genesis.

Table 3-4 Number of Trials Satisfying the Draft ARVs Per Scenario.

Vehicle	AEB System	LVS 25_0	LVM 45_20	LVM 25_10	LVD1 35_35	LVD2 25_25	STP 45	STP 25
2014 Acura MDX	CIB	0/3[1]	3/8	3/8	8/8	0/8	8/8	7/8
2014 Jeep Grand Cherokee	CIB	0/8	7/8	0/8	8/8	8/8	8/8	8/8
2014 BMW i3	CIB	0/8	Not performed[4]	0/8	1/8	0/8	8/8	8/8
2015 Hyundai Genesis	CIB	8/8	8/8	8/8	Not performed[5]	Not completed[6]	8/8	8/8
2014 Acura MDX[2]	DBS	8/8	8/8	8/8	0/8	7/8	0/8	2/8
2014 Jeep Grand Cherokee[3]	DBS	8/8	8/8	8/8	7/8	8/8	7/8	8/8
2014 BMW i3[3]	DBS	0/8	Tests not performed[7]					
2015 Hyundai Genesis[2]	DBS	7/8	7/8	8/8	6/8	6/8	8/8	8/8

[1] The Acura MDX was the first vehicle evaluated after improvements to the SSV load frame had been made. Since the vehicle was unable to satisfy the LVS_25_0 ARV during the first three trials, experimenters decided not to perform the remaining five trials of the eight trial test series.

[2] Brake applications used hybrid feedback

[3] Brake applications used displacement feedback

[4] The BMW i3 CIB has a maximum operational speed of 35 mph (56 km/h). Evaluation of the LVM_45_20 condition was not possible.

[5] Radar damage occurred during the CIB LVD2 test series, requiring replacement. Since the Hyundai Genesis appears to be sensitive to impacts with the SSV and provides no indication when minimal-to-no CIB intervention will occur, NHTSA researchers decided not to perform the LVD1 tests, and not to rerun the LVD2 tests with the new equipment.

[6] The forward looking radar was damaged before the LVD2 test series was complete. Only five valid tests were performed, and the test series was not rerun.

[7] Minimal-to-no indication of DBS activation was observed during exploratory test trials. So as to avoid unnecessary damage to the test vehicle or equipment and since the vehicle had already been unable to satisfy the LVS ARVs, the remaining DBS tests were not performed.

3.6. Test Repeatability

The CIB and DBS test series were both conducted once a month for four months using a Jeep Grand Cherokee. For these tests, the vehicle was equipped with the same instrumentation package and brake controller configuration (i.e., the equipment was not removed and re-installed each month). The purpose of this research was to determine whether test output, quantified by the measures used to assess the ability to satisfy the draft ARVs, was consistent over time.

3.6.1. Test Conditions

3.6.1.1. Ambient Temperature

Figure 3-6 presents the ambient (atmospheric) temperatures recorded ahead of each individual CIB and DBS test series, respectively. The temperatures ranged from 49 to 80ºF (9 to 27ºC) for CIB and from 49 to 81ºF (9 to 27ºC) for DBS. Temperatures were recorded to potentially explain any differences in braking performance that might arise as testing progressed.

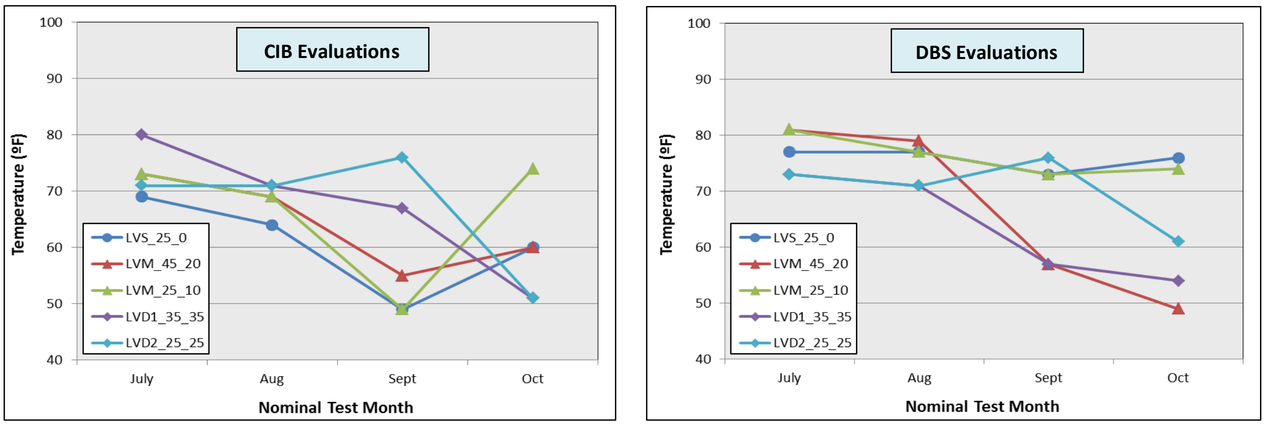

Figure 3-6 Ambient temperatures recorded at test series onset.

3.6.1.2.Surface Friction

Table 3-5 provides the surface friction believed to be most representative of the test surface used during all AEB tests described in this report. The actual test surface was located north of where the measurements were taken, but both surfaces are constructed from concrete and were in close proximity to each other. The peak friction coefficient differences present in each measurement group ranged from 93.8 to 102.4 (with tire rolling), while the skid numbers ranged from 87.3 to 89.1 (with tire skidding).

Table 3-5 TRC Skid Pad S-3 Surface Friction Coefficients

Date	Peak Friction Coefficient	Skid Number
Nominal Value	96.0	89.0
07.02.2014	97.9	89.1
07.15.2014	95.2	n/a
07.28.2014	102.4	87.7
08.11.2014	94.1	89.1
08.28.2014	93.8	n/a
09.15.2014	94.8	87.3
09.29.2014	97.0	n/a
10.13.2014	98.2	89.1
10.27.2014	93.8	n/a

3.6.2. Speed Reductions

Figures 3-7 and 3-8 present the speed reductions observed during the CIB and DBS repeatability evaluations, respectively. Individual graphs are plots of the eight valid trials from that scenario, joined by lines for each nominal test month. In Figure 3-7, the respective CIB ARVs are indicated by a horizontal line (the DBS ARV is crash avoidance in each scenario). Table 3-6 presents the minimum, maximum, mean, and standard deviation for these eight trials and ten series of tests, alongside the ambient temperatures during data collection.

The similarities of the month-to-month stopping performance were examined on a per-maneuver basis using statistics. These findings and the effect of nominal calendar month and temperature are discussed in Sections 3.6.2.1 and 3.6.2.2.

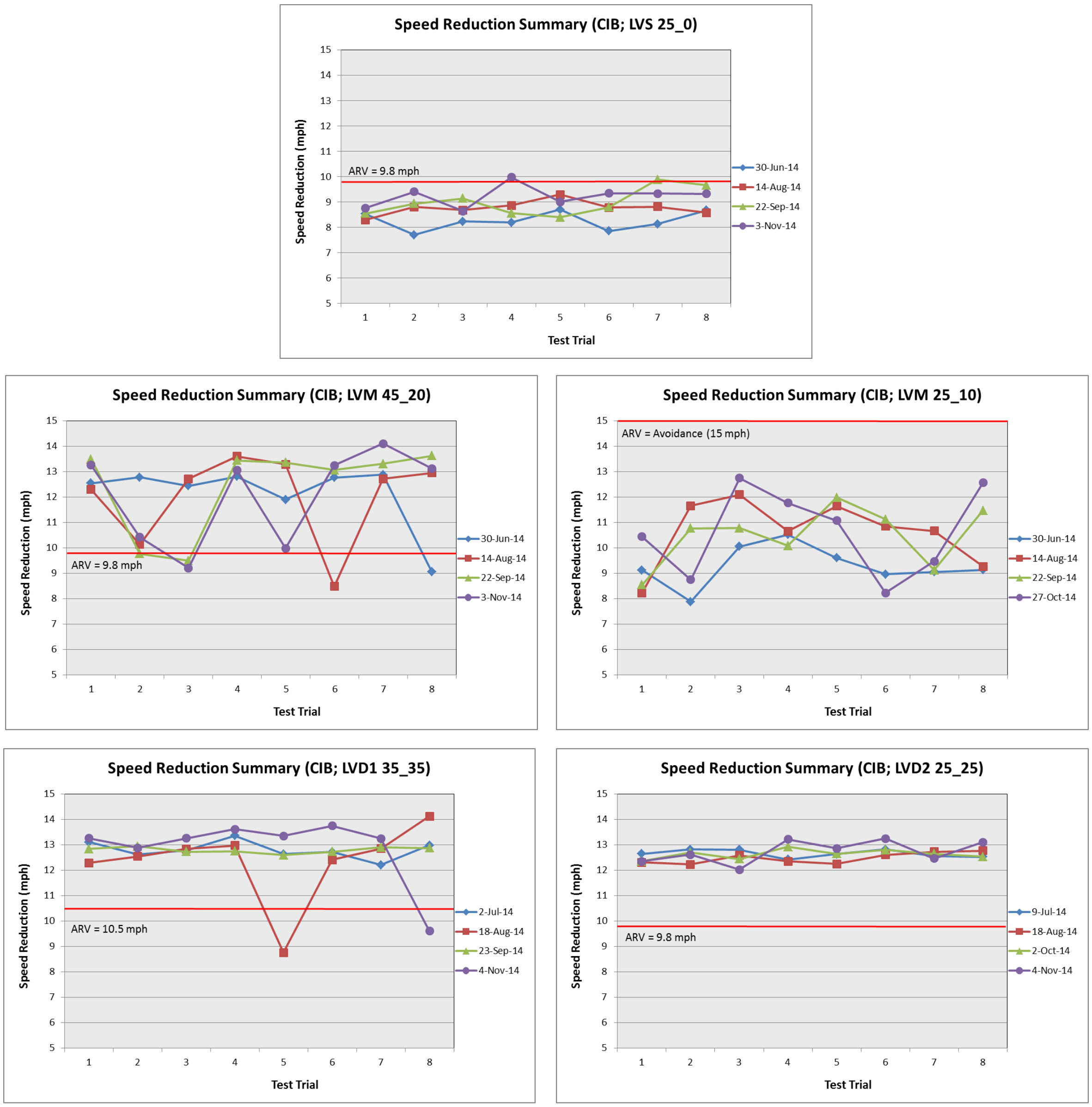

Figure 3-7 Speed reductions observed during each trial/scenario/month combination performed during the CIB repeatability evaluation.

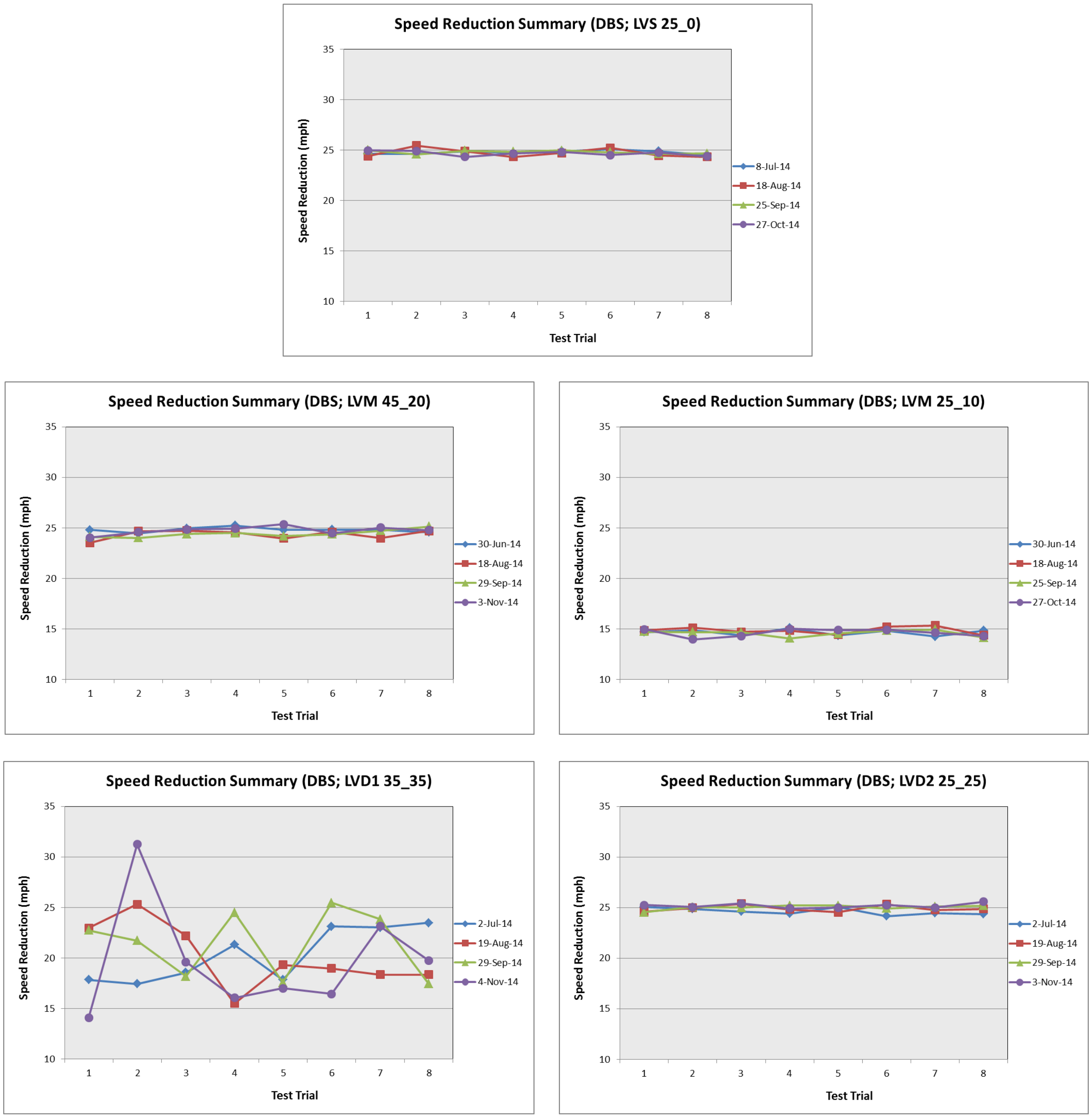

Figure 3-8 Speed reductions observed during each trial/scenario/month combination performed during the DBS repeatability evaluation.

Table 3-6 Monthly Speed Reductions (Jeep Grand Cherokee; Expressed in mph).

Scenario	Measure	CIB				DBS			
		July	Aug	Sept	Oct	July	Aug	Sept	Oct
LVS_25_0	Min	7.7	8.3	8.4	8.6	24.5	24.3	24.6	24.3
	Max	8.7	9.3	9.9	10	25.1	25.4	25	25
	Mean	**8.2**	**8.8**	**9**	**9.2**	**24.8**	**24.7**	**24.8**	**24.7**
	Std Dev	0.37	0.28	0.54	0.42	0.19	0.43	0.16	0.24
LVM_45_20	Min	9.1	8.5	9.5	9.2	24.4	23.5	24	24
	Max	12.9	13.6	13.6	14.1	25.2	24.7	25.1	25.4
	Mean	**12.1**	**12.1**	**12.4**	**12.1**	**24.8**	**24.3**	**24.4**	**24.8**
	Std Dev	1.28	1.68	1.74	1.86	0.24	0.45	0.36	0.39
LVM_25_10	Min	7.9	8.2	8.5	8.2	14.2	14.4	14.1	14
	Max	10.5	12.1	12	12.7	15.1	15.3	14.9	15
	Mean	**9.3**	**10.6**	**10.5**	**10.6**	**14.7**	**14.9**	**14.6**	**14.6**
	Std Dev	0.79	1.3	1.17	1.71	0.3	0.35	0.32	0.39
LVD1_35_35	Min	12.2	8.8	12.6	9.6	17.4	15.5	17.5	14.1
	Max	13.4	14.1	12.9	13.7	23.5	25.3	25.5	31.2
	Mean	**12.8**	**12.3**	**12.8**	**12.9**	**20.1**	**20.1**	**21.4**	**19.7**
	Std Dev	0.35	1.55	0.11	1.34	2.58	3.14	3.26	5.45
LVD2_25_25	Min	12.4	12.2	12.3	12	24.2	24.5	24.5	24.9
	Max	12.8	12.8	12.9	13.2	25.1	25.4	25.2	25.6
	Mean	**12.7**	**12.5**	**12.6**	**12.7**	**24.6**	**24.9**	**25**	**25.2**
	Std Dev	0.15	0.22	0.19	0.45	0.34	0.31	0.22	0.23

3.6.2.1. Month-to-Month Speed Reduction Consistency

Using speed reduction as the dependent variable and month as the independent variable, a single factor analysis was conducted using Proc GLM in SAS. This analysis, summarized in Table 3-7, indicates that for seven of the ten “maneuvers by AEB System” combinations there were no significant differences between mean speed reduction and the month the data were collected (i.e., probability less than 0.05). The DBS LVM_45_20 test condition was marginally significant at 0.0406, while the CIB LVS_25_0 and DBS LVD2_25_25 test conditions were significantly different at 0.0005 and 0.0037, respectively.

Table 3-7 Monthly Speed Reductions And Testing Temperatures With The Jeep Grand Cherokee

AEB System	Maneuver	Pr > F
CIB	**LVS_25_0**	**0.0005**
CIB	LVM_25_10	0.1322
CIB	LVM_45_20	0.9569
CIB	LVD1_35_35	0.7411
CIB	LVD2_25_25	0.3187
DBS	LVS_25_0	0.7844
DBS	LVM_25_10	0.3724
DBS	**LVM_45_20**	**0.0406**
DBS	LVD1_35_35	0.8167
DBS	**LVD2_25_25**	**0.0037**

These three results were then examined using the LSMEANS function in SAS to determine which month-to-month difference was the source of the significance. For the DBS LVM_45_20 test condition, the marginal significance was not directly attributable to any particular month-to-month difference, although the difference between July and August (0.47 mph or 0.76 km/h) was the closest to being significantly different with p > 0.0795, as shown in Table 3-8.

Table 3-8 LSMEANS (Pr>|t|) For The DBS LVM_45_20 Test Condition

Least Squares Means for Effect Month				
	July	Aug	Sept	Oct
July		0.0795	0.1933	0.9913
Aug	0.0795		0.9670	0.1415
Sept	0.1933	0.9670		0.3117
Oct	0.9913	0.1415	0.3117	

For the CIB LVS_25_0 test condition, the significance was attributable to the July-to-September difference (0. 74 mph or 1.2 km/h) and the July-to-October difference (0.97 mph or 1.6 km/h), p > 0.0068 and p > 0.0004 respectively, as shown in Table 3-9. That said, these differences are not believed to be practically significant since the same trend was not present for the other scenarios using data from the same test months. In other words, if the effect of test month was indeed strong, significant differences in mean speed reduction would have been expected for other scenarios, not just the LVS 25_0 condition.

Table 3-9 LSMEANS (Pr>|t|) For The CIB LVS_25_0 Test Condition

Least Squares Means for Effect Month				
	July	Aug	Sept	Oct
July		0.0856	**0.0068**	**0.0004**
Aug	0.0856		0.6963	0.1424
Sept	**0.0068**	0.6963		0.6764
Oct	**0.0004**	0.1424	0.6764	

For the DBS LVD2_25_25 test condition, the significance was attributable to the July-to-September difference (0.40 mph or 0.64 km/h) and July-to-October difference (0.56 mph or 0.90 km/h), $p > 0.0388$ and $p > 0.0023$ respectively, as shown in Table 3-10. However, this outcome is not believed to be practically significant. Not only was the same trend not present for the other scenarios using data from the same test months, but crash avoidance was realized during all DBS LVD2_25_25 test trials. For the LVD2_25_25 maneuver, crash avoidance can only be achieved if the SV comes to a stop before impacting the POV. Therefore, differences in speed reduction can be attributed to only variability in maneuver entrance speed at the time of brake application.

Table 3-10 LSMEANS (Pr>|t|) For The DBS LVD2_25_25 Test Condition

Least Squares Means for Effect Month				
	July	Aug	Sept	Oct
July		0.1949	**0.0388**	**0.0023**
Aug	0.1949		0.8558	0.2358
Sept	**0.0388**	0.8558		0.6672
Oct	**0.0023**	0.2358	0.6672	

3.6.2.2. Effect of Ambient Temperature

Within each test series, the ambient temperatures at test series onset (previously shown in Figure 3-6) were compared to mean speed reduction and standard deviation of speed reduction on a month-to-month basis. Additional comparisons included collapsing across maneuver within each AEB System and finally fully collapsed. Table 3-11 provides the R^2 value associated with those comparisons. R^2 represents the amount of variability the two factors have in common (i.e., how much the change in one factor influences the change in the other). The values on Table 3-11 show that ambient temperature does not have a strong relationship with mean speed reduction or the variability of the speed reductions.

Table 3-11 Effect of Ambient Temperatures At Test Series Onset On Speed Reduction

AEB System	Maneuver	Temp*Mean Speed Reduction (R^2)	Temp*StdDev of Speed Reduction (R^2)
CIB	LVS_25_0	0.4608	0.7164
CIB	LVM_25_10	0.0813	0.0225
CIB	LVM_45_20	0.3472	0.6129
CIB	LVD1_35_35	0.1041	0.1969
CIB	LVD2_25_25	0.5078	0.5975
DBS	LVS_25_0	0.2068	0.3160
DBS	LVM_25_10	0.1270	0.2377
DBS	LVM_45_20	0.0128	0.0832
DBS	LVD1_35_35	0.0415	0.6096
DBS	LVD2_25_25	0.3359	0.0638
CIB	combined	0.0034	0.0032
DBS	combined	0.0257	0.2109
Both	overall	0.0565	0.0805

3.6.3. Ability to Satisfy the Draft ARVs

Table 3-12 presents the ability of the Jeep Grand Cherokee to satisfy the CIB and DBS draft ARVs for each trial/scenario/month. Additionally, this table provides minimum and maximum margins of compliance (MOC) to the draft ARVs. In the case of the CIB LVS_25_0, LVM_45_20, LVD_35_35, and LVD_25_25 scenarios with CIB, MOC was speed-based. For all other tests, MOC was defined by the minimum SV-to-POV range[8]. The results were very consistent, with the ability of the SV to satisfy the draft ARVs during seven of eight trials being scenario-dependent, not dependent on test month.

[8] Minimum SV-to-POV range was selected as the MOC for the scenarios whose ARV is crash avoidance as a way to provide objective data suitable for a repeatability evaluation. This should not be taken to imply that a larger minimum SV-to-POV range is better (i.e., safer) than a smaller one. An excessively large SV-to-POV minimum range implies the vehicle has used more braking than needed to avoid the collision and has the potential for adversely affecting customer acceptance and/or an unnecessary increase in rear-end collisions (i.e., where the SV avoids the POV only to be rear-ended itself).

Table 3-12 Ability To Satisfy NHTSA's Draft ARVs[1] (Jeep Grand Cherokee).

AEB System	Nominal Test Month	LVS_25_0			LVM_45_20			LVM_25_10			LVD1_35_35			LVD2_25_25		
		MOC (mph)		Pass Rate	MOC (mph)		Pass Rate	MOC (ft)		Pass Rate	MOC (mph)		Pass Rate	MOC (mph)		Pass Rate
		Min	Max		Min	Max		Min	Max		Min	Max		Min	Max	
CIB	July	0	0	**0/8**	0	3.1	**7/8**	0	0	**0/8**	1.7	2.9	**8/8**	2.6	3.0	**8/8**
	Aug	0	0	**0/8**	0	3.8	**7/8**	0	0	**0/8**	0	3.6	**7/8**	2.4	3.0	**8/8**
	Sept	0	0.1	**1/8**	0	3.8	**7/8**	0	0	**0/8**	2.1	2.4	**8/8**	2.5	3.1	**8/8**
	Oct	0	0.2	**1/8**	0	4.3	**7/8**	0	0	**0/8**	0	3.2	**7/8**	2.2	3.4	**8/8**

[1] A zero margin of compliance (MOC) indicates the draft ARV was not satisfied during at least one trial in the respective test series.

AEB System	Nominal Test Month	LVS_25_0			LVM_45_20			LVM_25_10			LVD1_35_35			LVD2_25_25		
		MOC (ft)		Pass Rate	MOC (ft)		Pass Rate	MOC (ft)		Pass Rate	MOC (ft)		Pass Rate	MOC (ft)		Pass Rate
		Min	Max		Min	Max		Min	Max		Min	Max		Min	Max	
DBS	July	4.8	9.7	**8/8**	4.2	19.0	**8/8**	6.0	10.4	**8/8**	0	24.6	**7/8**	15.0	18.4	**8/8**
	Aug	7.0	11.5	**8/8**	7.2	17.0	**8/8**	8.0	12.7	**8/8**	0	25.5	**7/8**	11.5	19.3	**8/8**
	Sept	8.0	11.2	**8/8**	6.3	18.5	**8/8**	6.5	11.8	**8/8**	14.9	24.5	**8/8**	13.9	17.2	**8/8**
	Oct	7.4	12.3	**8/8**	5.6	18.3	**8/8**	8.6	12.2	**8/8**	3.5	26.5	**8/8**	19.8	21.1	**8/8**

[1] A zero margin of compliance (MOC) indicates the draft ARV was not satisfied during at least one trial in the respective test series.

3.7. Challenges Encountered During Test Conduct

3.7.1. Simultaneous Brake and Throttle Applications

The brake applications defined in NHTSA's draft DBS test procedure are specified to occur at scenario-specific SV-to-POV headways. In contrast, the Euro NCAP test procedures require the SV brakes be applied at a fixed 1.2 seconds after the SV FCW alert is presented [13].

NHTSA has considered the pros and cons of each application method and believes that the agency's approach provides a better overall opportunity for the SV DBS to demonstrate its braking capability. At low initial maneuver entrance speeds such as 25 mph (40 km/h), NHTSA has observed the SV FCW alert may occur later than it does at 45 mph (72 km/h). For such vehicles, basing brake application timing on when the FCW alert is presented may result in the foundation brakes being applied very late in the pre-crash timeline, which may not allow enough time for DBS to prevent an SV-to-POV impact (NHTSA's draft ARV for each DBS test scenario).

However, while the NHTSA approach can provide more time for DBS operation, it may also result in SV braking being initiated prior to the activation of a late FCW. This can be problematic because the NHTSA draft procedures require the SV driver to maintain vehicle speed with the throttle pedal until the SV FCW is presented, whereas the brake applications are automated independently of FCW activation. Even if the SV driver releases the throttle pedal quickly after the FCW is presented (i.e., less than the 500 ms required by the draft procedure), it is possible the throttle pedal position may not be zero before the brake controller is activated. This can cause the SV brakes and throttle to be applied simultaneously; a condition than not only violates a test validity condition, but also has the potential to suppress DBS activation[9]. NHTSA researchers believe there are two ways to address this condition:

1. **Automate throttle applications using control logic that does not allow for the brakes and throttle to be applied at the same time** (i.e., the throttle would have to be released first, and then the controller would apply force to the brake pedal). The brake controller presently used by NHTSA has the capability to support brake or throttle applications, so this solution would be technically viable. However, the agency is concerned that (1) there are no data to indicate brief periods of simultaneous throttle and brake application have actually suppressed DBS activation during test conduct, (2) the additional complexity will increase the costs needed to perform the tests, and (3) with the exception of throttle release-to-brake application phasing for some vehicles, throttle automation is not required to satisfy the test tolerances specified in the draft DBS test procedure.

[9] This concern is raised for the sake of discussion. NHTSA has not observed this phenomenon during actual test conduct.

2. **Adjust the DBS test procedure to allow for up to 250 ms of simultaneous brake and throttle application overlap (an approach applied to the data discussed in this report)**. This provision is intended to address two situations: (1) the brake application is automatically commanded before the SV's FCW is presented, or (2) the brake application is commanded after the SV's FCW is presented, but before the SV driver has fully released the throttle pedal, as shown in Figure 3-9. In this figure the SV driver released the throttle 255 ms after the FCW alert during Test 87, but the brake controller was activated 15 ms prior to the throttle pedal actually reaching zero. Similarly, the SV driver released the throttle 345 ms after the FCW alert during Test 81, but the brake controller was activated 225 ms prior to the throttle pedal actually reaching zero. During this test, the brake application was (independently) initiated only 120 ms after the FCW was presented, faster than the SV driver was able to respond to it.

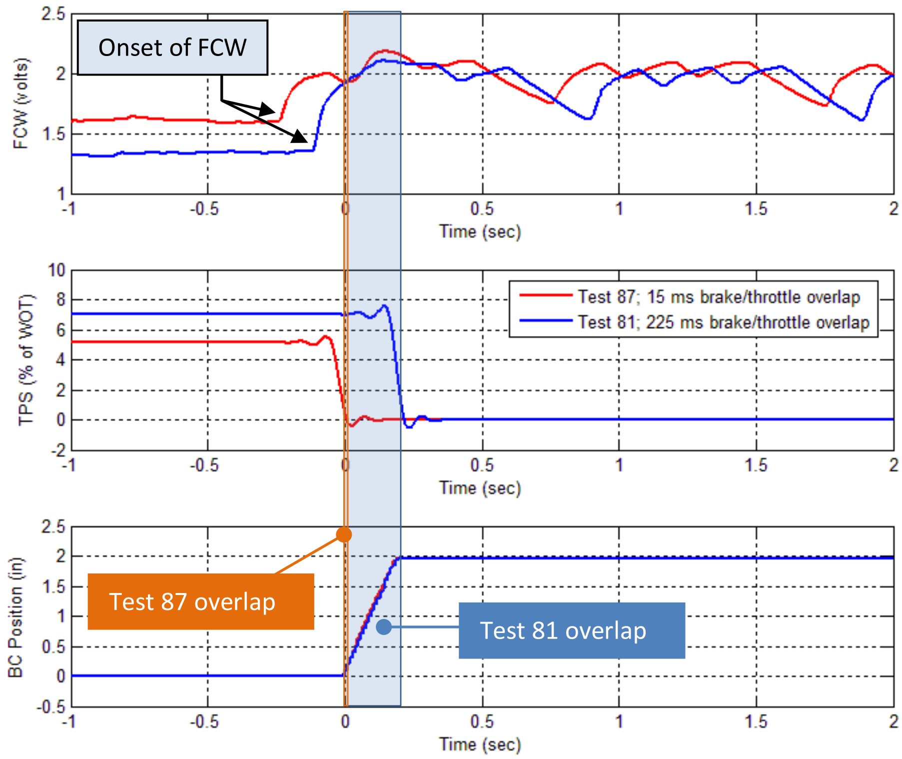

Figure 3-9 LVM_25_10 DBS tests performed with the Jeep Grand Cherokee. The 15 and 225 ms brake/throttle overlap values were the lowest and highest observed during the tests described in this report (i.e., for all vehicles).

The August 2014 CIB and DBS draft test procedures specify that the SV driver must fully release the throttle pedal within 500 ms of the FCW being presented, but prior to the onset of the SV brake applications. The first condition of this requirement was satisfied for all DBS tests during which an FCW was presented. For most combinations of SV and scenario, satisfying the second condition was also possible, however simultaneous brake and throttle applications were observed during tests performed with two of the four vehicles discussed in this report (the Jeep Grand Cherokee and Hyundai Genesis). Table 3-9 presents a summary of these occurrences. In the case of the Jeep Grand Cherokee, results from the four months of repeatability tests are provided. Permitting up to 250 ms of brake and throttle overlap accommodated each occurrence shown in Table 3-13, thereby allowing the trials to be deemed valid and the corresponding data appropriate for inclusion in the discussion of test results.

Note: If brake/throttle overlap is present, the provision allowing it to be present for ≤ 250 ms may reduce the time available for the SV driver to release the throttle pedal after being presented with the FCW alert. For example, if the SV FCW alert occurred at the same instant the brake controller initiated SV braking, the driver would have only up to 250 ms to fully release the throttle pedal, not the 500 ms specified in the August 2014 draft DBS test procedure.

Table 3-13 SV Brake / Throttle Application Overlap Duration Ranges (ms)

Vehicle	Test Month	DBS Scenario				
		LVS_25_0	LVM_45_20	LVM_25_10	LVD1_35_35	LVD2_25_25
2014 Acura MDX	n/a					
Jeep Grand Cherokee	July	15 – 185	None	15 – 225	None	None
	August	15 – 110	None	20 – 145	170	None
	September	25 – 105	None	15 – 135	None	None
	October	15 – 80	None	115 – 215	None	None
2014 BMW i3	n/a					
Hyundai Genesis	October	None	None	50 – 190	None	15 – 110

3.7.2. Brake Characterization Output

The brake characterization process described in the agency's draft DBS test procedure is intended to provide a simple, practical, and objective way to determine the application magnitudes used during system evaluations. To begin characterization, the brake controller slowly applies the SV brake with a pedal velocity of 1 in/s (25 mm/s) from a speed of 45 mph (72 km/h). Linear regressions are applied to the deceleration data from 0.25 to 0.55g to determine the brake pedal displacement and application force needed to achieve 0.3g. Characterization results for the vehicles discussed in this report are shown in Table 3-14.

The characterization process is straight-forward and the per-vehicle output is very repeatable. However, NHTSA has received feedback from some vehicle manufacturers that the DBS brake application magnitudes should be based on those capable of achieving 0.4g during characterization, not 0.3g (to reduce the potential for unintended DBS activations from occurring during real-world driving). The agency's response has been twofold: (1) that 0.3g is conservative but consistent with the findings of a NHTSA event data recorder (EDR) analysis of rear end crash data [1], and (2) when the 0.3g-based application magnitudes output from characterization are actually used during DBS evaluation (i.e., used in conjunction with brake pedal application rates ten times faster than used for characterization), the decelerations typically exceed 0.3g[10].

Table 3-14 SV Brake Characterization Results

Vehicle		Displacement @ 0.3g		Force @ 0.3g	
		(in)	(mm)	(lbf)	(N)
2014 Acura MDX		1.5	38.2	12.9	57.5
2014 Jeep Grand Cherokee	06.25.14	2.0	49.9	13.5	60.1
	08.14.14	1.9	47.2	11.1	49.5
	09.24.14	1.8	45.3	9.5	42.4
	10.22.14	1.8	45.8	8.6	38.2
2014 BMW i3		1.4	36.3	24.2	107.8
2015 Hyundai Genesis		1.5	38.7	11.4	50.7

Tables 3-15 and 3-16 present deceleration data collected during baseline stops performed from 25 and 45 mph (40 and 72 km/h), respectively. No surrogate vehicle was present in the forward path of the SV for these tests, so there were no DBS activations. Unless indicated, eight stops were performed for each brake controller mode. The mean values presented in columns three and four are effective decelerations, calculated from the point of the brake application to either (1) a distance either 40.3 ft (12.3 m) away from it[11] or (2) from the onset of the brake application to the instant when the SV speed reached 20 mph (32 km/h)[12]. Since these calculations include brake application and SV brake system response times, these values would nominally be expected to be ≤0.3g. The peak values presented in columns five through seven summarize the peak decelerations observed during the same interval used to calculate the mean values, and typically occurred just after the desired brake application magnitude was first achieved (i.e., due to response overshoot).

In Tables 3-15 and 3-16, the brake controller mode used to evaluate each vehicle's respective DBS is highlighted in bold. In summary,

- From 25 mph (40 km/h), these applications produced peak decelerations from 0.35g (Acura MDX) to 0.57g (Hyundai Genesis) with hybrid feedback, and from 0.36 to 0.40g with displacement feedback (Jeep Grand Cherokee).

[10] The extent to which these differences exist appears to depend on the interaction of vehicle, brake application method, and test speed.

[11] For DBS tests performed in the LVS_25_0 scenario, the SV brakes are applied at TTC = 1.1s. If the SV does not stop within 40.3 ft (12.3 m) from this point, an SV-to-POV impact will occur.

[12] For DBS tests performed in the LVM_45_20 scenario, the SV brakes are applied at TTC = 1.0s. If the SV does not reduce its speed below 20 mph (32 km/h) before reaching the POV, an SV-to-POV impact will occur.

- From 45 mph (72 km/h), these applications produced peak decelerations from 0.37g (Acura MDX) to 0.59g (Hyundai Genesis) with hybrid feedback, and from 0.40 to 0.44g with displacement feedback (Jeep Grand Cherokee).
- In the case of the Acura MDX, hybrid feedback produced peak decelerations less than 0.4g during seven of eight baseline trials performed from 25 mph (40 km/h), and during one of the eight baseline trials performed from 45 mph (72 km/h). For the Jeep Grand Cherokee, displacement feedback produced peak decelerations less than 0.4g during five of eight baseline trials performed from 25 mph (40 km/h).

Table 3-15 SV Baseline Braking Data; 25 mph (40 km/h) Initial Speed

Vehicle	Brake Controller Feedback Mode	Baseline Longitudinal Deceleration (g)				
		Mean[1]		Peak		
		Min	Max	Min	Max	Mean
Acura MDX	Displacement	0.24	0.26	0.30	0.33	0.31
	Hybrid	**0.29**	**0.34**	**0.35**	**0.41**	**0.38**
Jeep Grand Cherokee	**Displacement**	**0.29**	**0.32**	**0.36**	**0.40**	**0.39**
	Hybrid	0.34[2]		0.41[2]		
Hyundai Genesis	Displacement	0.24[2]		0.40[2]		
	Hybrid	**0.40**	**0.46**	**0.51**	**0.57**	**0.54**

[1] Calculated from the onset of the brake application to distance 40 ft (12.3 m) away (nominal TTC = 1.1 s).
[2] Only one 25 mph (40 km/h) baseline trial was performed in this test condition.

Table 3-16 SV Baseline Braking Data; 45 mph (72 km/h) Initial Speed

Vehicle	Brake Controller Feedback Mode	Baseline Longitudinal Deceleration (g)				
		Mean[1]		Peak		
		Min	Max	Min	Max	Mean
Acura MDX	Displacement	0.27	0.29	0.32	0.39	0.35
	Hybrid	**0.33**	**0.41**	**0.37**	**0.48**	**0.42**
Jeep Grand Cherokee	**Displacement**	**0.35**	**0.36**	**0.40**	**0.44**	**0.42**
	Hybrid	0.40[2]		0.47[2]		
Hyundai Genesis	Displacement	0.27[2]		0.34[2]		
	Hybrid	**0.45**	**0.49**	**0.55**	**0.59**	**0.57**

[1] Calculated from the onset of the brake application to the instant when the SV speed reached 20 mph (32 km/h).
[2] Only one 45 mph (72 km/h) baseline trial was performed in this test condition.

The baseline tests summarized in Tables 3-15 and 3-16 demonstrate the combination of (1) the characterization process described in the August 2014 DBS test procedure and (2) the control feedback selection process described in Section 2.3.1 of this report output brake application magnitudes capable of producing average decelerations of ≥0.29g and peak values ≥0.35g. Should a more consistent identification of the brake application magnitudes needed to achieve a specific mean deceleration (whether it be 0.3g, 0.4g, or otherwise) be required, additional and potentially iterative steps will need to be added to the characterization process. Using the output from the existing characterization as a starting point, it is envisioned the revised process could involve the following steps:

1. Identify the brake application magnitudes from the existing characterization process.
2. Perform baseline stops (no surrogate vehicle in the forward path of the SV) from 25, 35, and 45 mph (40.2, 56.3, and 72.4 km/h) using the application magnitudes from Step 1.
3. For each test speed, calculate the average deceleration from the onset of the brake application to a time 250 ms before the SV speed reaches zero.
4. If the mean deceleration calculated in Step 3 is lower than desired, calculate the necessary increase brake displacement magnitude (displacement feedback) or application force (hybrid feedback) using the following equation:

$$BA_{desired} = \frac{(a_{x,desired})(BA_{initial})}{(a_{x,initial})} \qquad where,$$

$BA_{desired}$ = desired brake application magnitude (displacement or force)

$BA_{initial}$ = initial brake application magnitude from Step 1 or 3

$a_{x,desired}$ = desired deceleration magnitude

$a_{x,initial}$ = initial deceleration magnitude from Step 1 or previous iteration of Step 4

5. Repeat Steps 2 through 4 until the mean decelerations are within ±10 percent of the desired level for each SV test speed.
6. Once the correct input magnitudes have been determined, the LVS, LVM, LVD, and STP DBS evaluations may be performed.

Note: At the time this report was published, NHTSA had not validated the extent to which this revised process could improve the consistency of the vehicle-to-vehicle baseline decelerations, or assessed what effect the additional steps could have on test burden.

3.7.3. Maintaining a Constant Force Fallback Rate

Both brake controller feedback modes discussed in this report use displacement feedback to bring the SV brake pedal to the position determined from the characterization process. By using displacement feedback, the desired application rate of 10 in/s (254 mm/s) can be directly specified and is accurately controlled, a feature to help ensure DBS activation can be consistently activated.

To achieve the commanded application rate as quickly as possible, the brake controller uses a brief period of high application force to (1) accelerate the SV brake pedal from rest, and (2) establish the commanded SV pedal position determined from characterization. The magnitude of the peak force associated with the later typically exceeds the fallback force value used during hybrid-based applications, and the extent to which they differ is vehicle-dependent. To help control the manner in which pedal force transitions from the period of high initial force to that determined from characterization, NHTSA's hybrid applications specify a commanded fallback force rate of 56 lbf/s (250 N/s).

3.7.3.1. Fallback Rate Background

If the commanded fallback force rate (i.e., the rate of force reduction) is too high, the brake controller may reduce pedal displacement in an attempt to achieve it. NHTSA is concerned that if this occurs, the SV's DBS may interpret the simultaneous reduction of brake force and displacement as the driver releasing the brakes, an indication the supplementary braking provided by DBS is not (or is no longer) necessary. Should DBS be switched off, NHTSA would not be able to evaluate its performance.

If the commanded fallback force rate is too slow, brake pedal displacement may be excessive. Once the brief period of high force needed to accelerate the brake pedal to the commanded position has passed, NHTSA researchers have observed that brake pedal force has a tendency to fall since maintaining a given pedal position often requires less force than rapidly establishing it. If the commanded fallback force rate is too slow, a significant increase in pedal position may be required to achieve it. This is because accurately controlling fallback rate requires the SV brake pedal to be pushed against the brake controller actuator with forces high enough that they can be reduced in a controlled manner. In other words, pedal position must be increased to offset the effect of force overshoot decay.

When NHTSA developed its hybrid feedback specifications, a fallback rate of 56 lbf/s (250 N/s) was found to best balance the ability of the brake controller to control fallback rate without excessive pedal displacement.

3.7.3.2. Ability to Satisfy Commanded Fallback Rate

NHTSA's ability to accurately control the fallback force rate was monitored during the 2014 DBS tests. For vehicles where DBS activation does not result in the SV brake pedal falling towards the floor, or causes it to push back up against the driver's foot, the brake controller's ability to accurately control the fallback force rate appears to be quite good, as indicated by the Jeep Grand Cherokee force data previously shown in Figure 3-1. However, other factors within the brake feedback selection process described in Section 2.3.1 resulted in that vehicle being evaluated with displacement feedback.

For the vehicles evaluated with hybrid braking (the Acura MDX and Hyundai Genesis), achieving a consistent fallback rate close to that commanded was not possible. Specifically, the linearity of the fallback force was affected by the brake controller's limited ability to compensate for brake pedal movement during DBS operation while simultaneously attempting to achieve the commanded fallback rate or maintaining a constant application force.

3.7.4. Additional Brake Application Tolerance Specifications

The brake application rates used for characterization (1 ± 0.5 in/s or 25 ± 12.7 mm/s) and DBS testing (10 ± 1 in/s or 254 ± 25 mm/s) were specified in the August 2014 draft DBS test procedure. To help insure additional brake application parameters are input as intended, and that they can be practically executed, NHTSA developed the following tolerances:

- The initial brake pedal position determined from the characterization process must be realized at the end of the 10 in/s (254 mm/s) application ramp.
- For tests performed with displacement feedback,
  - A pedal position overshoot of up to 20 percent beyond the commanded value is allowed during tests performed with displacement feedback, provided it lasts no longer than 100 ms.
  - From 100 ms after completion of the 10 in/s (254 mm/s) application ramp to the end of the valid test interval, brake pedal position must be within ± 10 percent of the position magnitude determined from the characterization process.
- For tests performed with hybrid feedback,
  - Application force must be ≥ 2.5 lbf (11.1 N) while the force fallback rate is being commanded.
  - A commanded fallback rate of 56 lbf/s (250 N/s) is recommended. Adjustment of this rate is permitted if it does not allow the minimum application force during fallback to remain ≥ 2.5 lbf (11.1 N).
  - From completion of the commanded force fallback to the end of the valid test interval, the average fallback force must be within ± 10 percent of the force magnitude determined from the characterization process.

3.7.4.1. Ability to Satisfy the New Tolerance Specifications

Satisfying the new initial brake pedal position specification is not believed to be problematic. For nearly every DBS evaluation performed by NHTSA, some amount of position overshoot at the completion of the initial application ramp has been realized. This provision simply ensures the proper position magnitude has been programmed into the brake controller.

Satisfying the additional displacement feedback initial brake pedal position specifications is also not believed to be problematic. This provision simply helps to ensure appropriate brake controller tuning has been performed prior to test conduct (i.e., that the proportional-integral-derivative (PID) controller is properly configured).

The third new group of specifications is intended to provide a practical way to ensure hybrid applications are acceptably input. The primary goal of the hybrid application method is to prevent brake pedal force from reaching zero during DBS operation. Beyond that, the inputs must be applied as consistently as possible, at a magnitude determined from characterization. Unfortunately, the tests performed with the Acura MDX and Hyundai Genesis revealed significant brake pedal movement can occur during DBS operation, and that the force feedback mode used by NHTSA's brake controller was unable to fully compensate for it. Figure 3-10 provides an example of this phenomenon for four DBS scenarios performed with the Hyundai Genesis. The commanded fallback rates and forces were 56 lbf/s and 11.4 lbf (250 N/s and 50.7 N, respectively.

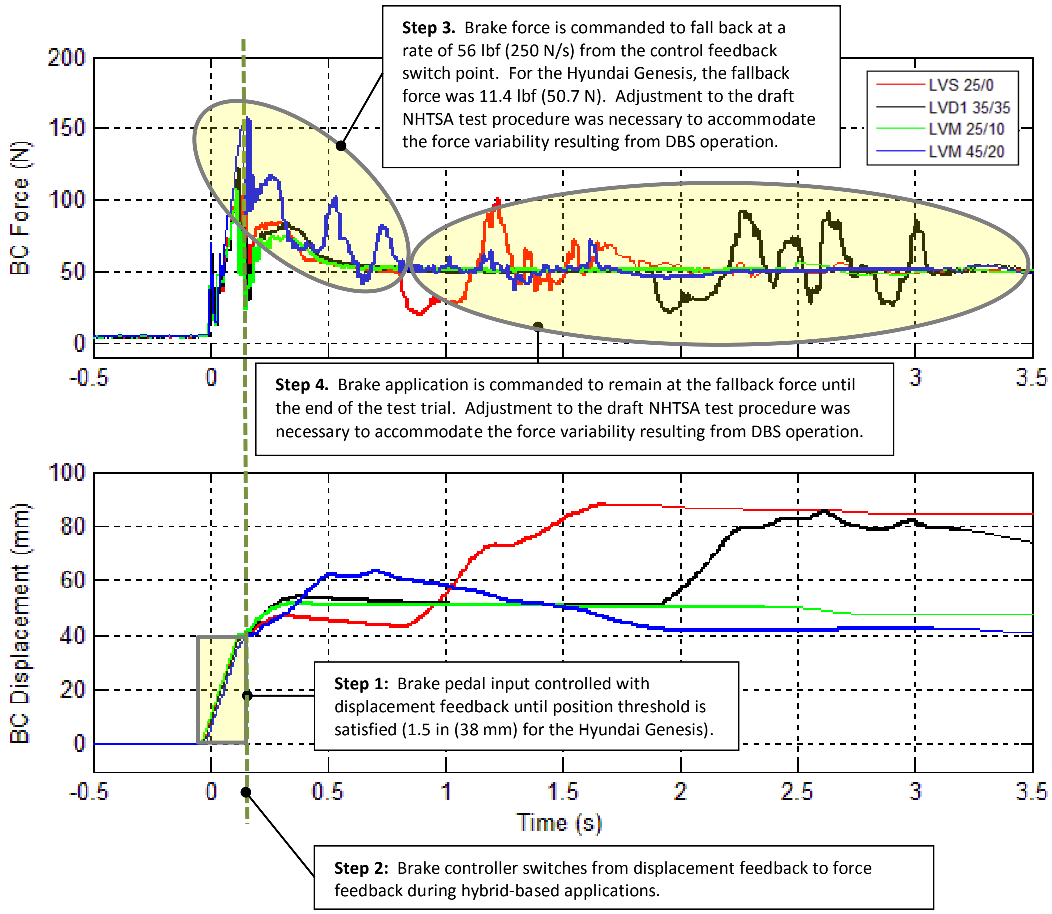

Figure 3-10 Hybrid feedback tests performed with the Hyundai Genesis. The input force disparity, which varied among the different scenarios, is believed to be the result of the brake controller being unable to respond to rapid changes in brake pedal position resulting from DBS intervention.

NHTSA believes the most appropriate way to consider how well the desired force is maintained during hybrid braking is to consider the *average* value from completion of the commanded force fallback to the end of the test trial's valid interval. The flexibility of this method provides the brake controller with time to respond to rapid changes in pedal position, while still ensuring the overall input magnitude is close to that actually commanded.

3.7.4.2. Comments Regarding the Euro NCAP AEB Brake Applications

The brake applications specified in the Euro NCAP AEB test procedure are similar to those defined by the hybrid brake applications described in NHTSA's August 2014 draft DBS procedure. Both methods switch feedback modes from displacement to force feedback during the application; however the Euro NCAP process includes a provision that allows one of two switch points to be used. In the first method, which is conceptually identical to that used by NHTSA, the switch occurs after a desired brake pedal displacement threshold has been satisfied. In the second method, the switch occurs after the *application force threshold* determined from characterization has been realized. Within a given test trial, the switching method used by the brake controller is automatically based on which threshold is satisfied first.

To determine whether switching feedback modes at the application force threshold from characterization would reduce the brake force variability observed during the NHTSA hybrid tests, two LVS tests were performed with the Hyundai Genesis. The resulting data, shown in Figure 3-12, did not indicate this approach would result in a meaningful reduction of brake force input variability for the Hyundai Genesis. Rather, NHTSA has concerns this method could adversely affect the ability of the DBS to be activated for some vehicles since the initial application rate of this trial was 3.7 in/s (93 mm/s)[13], much slower than that specified in the NHTSA hybrid method (10 ± 1 in/s or 254 ± 25 mm/s)[14].

Whether this observation is a vehicle-specific anomaly or would occur during evaluation of other vehicles is unknown. In the case of the Hyundai Genesis, accelerating the pedal from rest caused a brief spike in applied force before the brake pedal displacement threshold was satisfied. For the two trials shown in Figure 3-11, the magnitudes of these spikes (18.1 and 17.0 lbf (80.5 and 75.4 N) for the Euro NCAP and NHTSA hybrid applications, respectively) were greater than the application force magnitudes output from characterization[15], thus satisfying the second Euro NCAP application mode switch condition. From that point, the brake controller attempted to maintain the force feedback-based value of 11.4 lbf (50.7 N). However, due to the rapid decay of the initial spike in applied force and the brake pedal movement that

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[13] 3.7 in/s (93 mm/s) is the slope of a best fit line applied to the brake pedal position data from 25 to 75 percent of the commanded position value determined from characterization.

[14] NHTSA's June 2012 draft DBS test procedure specified an application rate of 7 ± 1 in/s (178 ± 25 mm/s) be used to evaluate system performance. However, feedback provided in response to a July 3, 2012 Request for Comment describing the agency's CIB/DBS research efforts indicated this was too slow, and that it could potentially lead to DBS false positives during non-critical brake applications in the real-world (i.e., during driving situations where a rear-end crash may not have been imminent). For this reason, the application speed was increased to 10 ± 1 in/s (254 ± 25 mm/s), a magnitude recommended by multiple vehicle manufacturers [14].

[15] The application force capable of producing a deceleration of 0.3g during characterization, the value used in NHTSA's draft DBS test procedure, was 11.4 lbf (50.7 N). A force of 14.5 lbf (64.6 N), the value used in the Euro NCAP AEB test procedure, produced a deceleration of 0.4g.

occurs during DBS operation, the brake controller was unable to maintain a consistent application force until nearly 2.5 seconds after initiation of the braking event (in agreement with the settling time observed during the NHTSA hybrid-based test, but approximately 1 second after the SV stopped).

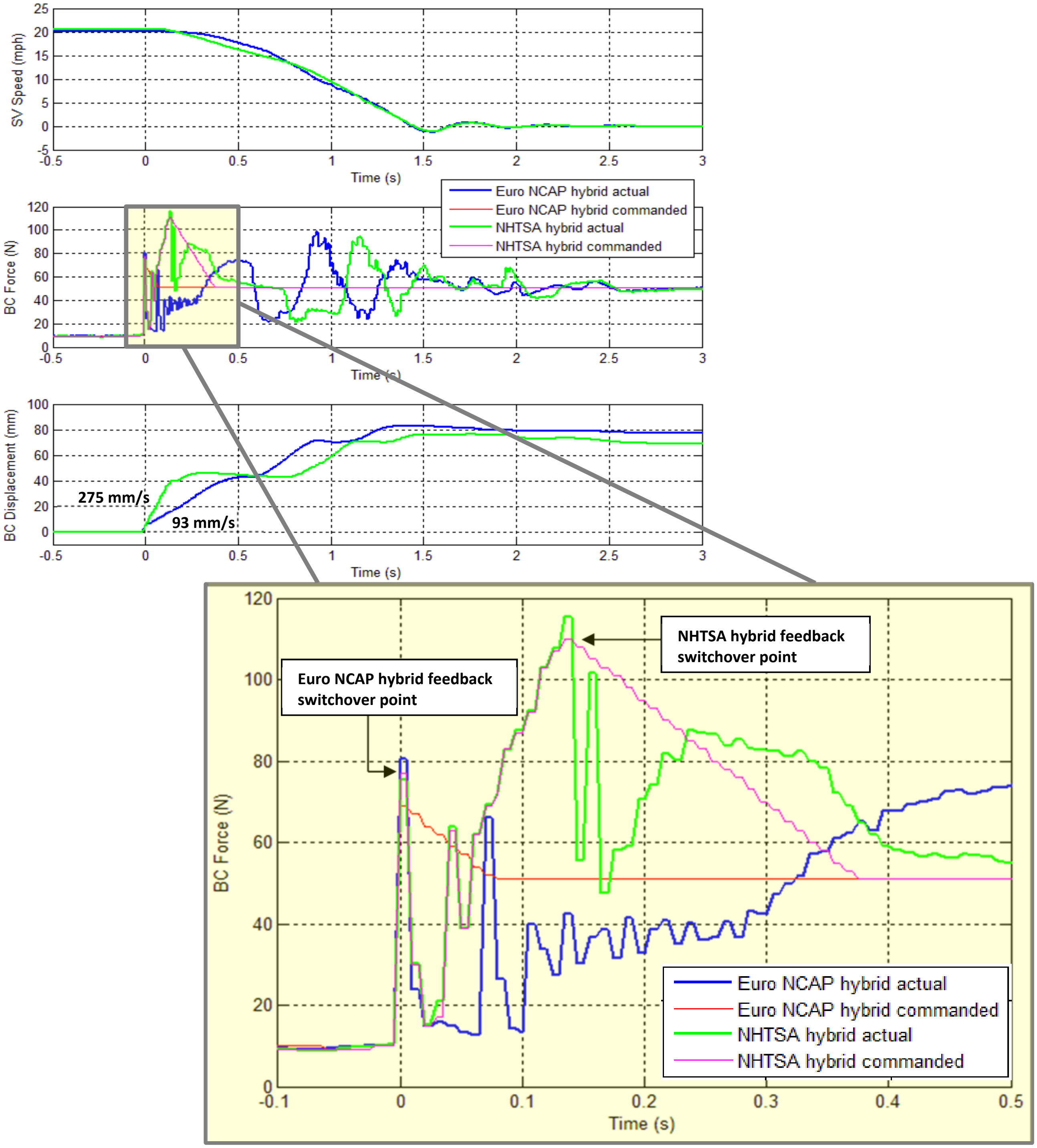

Figure 3-11 Comparison of the NHTSA and Euro NCAP hybrid brake applications. Both trials were performed from 20 mph (32 km/h) with a Hyundai Genesis and the LVS test scenario. Crash avoidance was realized with both trials; however, the initial brake application rate was 66 percent slower during with the Euro NCAP-based trial.

4.0 CONCLUDING REMARKS

NHTSA's 2014 light vehicle AEB test program evaluated the ability of four light vehicles to be tested with the agency's August 2014 draft CIB and DBS test procedures. The vehicles were equipped with AEB systems inclusive of a 77 GHz LRR and/or a mono-camera. Additionally, test output repeatability and future refinements to the DBS test procedure were discussed.

4.1. AEB Test Results

The maneuvers were successfully validated and the performance of the vehicles compared to a common set of ARVs. In summary:

- None of the vehicles discussed in this report were able to satisfy all CIB ARVs if their performance was considered against a "seven of eight" evaluation criteria
- Only the Jeep Grand Cherokee was able to satisfy each DBS ARV.
- CIB false positives were observed with the Acura MDX during 1 of 8 STP tests performed from 25 mph (40 km/h).
- DBS false positives were observed during 6 of 8 STP tests performed from 25 mph (40 km/h) with the Acura MDX. From 45 mph (72 km/h), DBS false positives occurred during each of the eight tests performed with the Acura MDX and during 1 of 8 STP tests performed with the Jeep Grand Cherokee. The AEB systems of these vehicles were both based on a single LRR only.

The CIB and DBS test series were both conducted once a month for four months using a Jeep Grand Cherokee. For these tests, the vehicle was equipped with the same instrumentation package and brake controller configuration (i.e., the equipment was not removed and re-installed each month).

- Statistically significant differences where present in month-to-month speed reductions for the LVS_25_0 tests performed with CIB and the LVD2_25_25 tests performed with DBS. However, these differences were small (< 1.0 mph or 1.6 km/h), not believed to be practically significant, and did not affect whether the vehicle satisfied the ARVs during at least seven of eight trials for each test condition.
- Ambient temperatures within a range of 49 to 81ºF (9.4 to 27.2ºC) were not found to have a meaningful effect on mean speed reduction or speed reduction variability.

4.2. Comments Regarding DBS Test Conduct

The DBS tests described in this report were based on NHTSA's August 2014 draft procedures, but included some minor differences to address unique situations that occurred during test conduct. These differences were intended to provide clarification, not to affect (increase) test severity.

A brake controller feedback selection process was used to determine whether a vehicle's DBS performance should be evaluated with displacement or hybrid feedback. This process considered the relationship of brake pedal displacement, application force, and deceleration during DBS activation.

A 250 ms throttle and brake application overlap was allowed to address the situation where the SV's FCW alert occurs late in the pre-crash timeline. Without this provision it was not possible to satisfy all DBS validity requirements for some vehicles, specifically those pertaining to throttle release-to-brake application timing.

Tolerances for the brake applications used during DBS evaluations were applied to ensure the brake pedal positions, forces, and rates described in the draft DBS test procedure were properly commanded, and that they could be practically achieved with the agency's brake controller.

A method to more accurately determine brake pedal displacement and application force needed to achieve a nominal deceleration magnitude with the vehicle's foundation brakes was discussed. However, at the time this report was published, NHTSA had not validated effectiveness of this method, or quantified how test burden will be affected by the additional steps it would require.

5.0 REFERENCES

1. "*Automatic Emergency Braking System Research Report*," Docket NHTSA-2012-0057-0037

2. "*Crash Imminent Brake System Performance Evaluation - Working Draft, August 2014*," Docket NHTSA-2012-0057-0038

3. "*Dynamic Brake Support Performance Evaluation - Working Draft, August 2014*," Docket NHTSA-2012-0057-0038

4. Request for Comment in the Federal Register seeking responses to the public release of its CIB/DBS research efforts (80 FR 4630, January 28, 2015); Docket NHTSA-2015-0006-0001

5. "*Forward-Looking Advanced Braking Technologies Research Report*," Docket NHTSA-2012-0057-0001

6. "*Crash Imminent Brake System Performance Evaluation, June 2012 Working Draft*," Docket NHTSA-2012-0057-0001

7. "*Dynamic Brake Support Performance Evaluation, June 2012 Working Draft*," Docket NHTSA-2012-0057-0001

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

9. "*NHTSA's Strikeable Surrogate Vehicle Preliminary Design Overview*," Docket NHTSA-2012-0057-0032

10. "*Revised Specifications to a Report Titled NHTSA's Strikeable Surrogate Vehicle (SSV) Design Overview*," Docket NHTSA-2012-0057-0039

11. "*Radar Measurements of NHTSA's Surrogate Vehicle SS-V*," Docket NHTSA-2012-0057-0034

12. "BMW i3 Owner's manual," part number 01 40 2 955 749 ue

13. Euro NCAP protocol website (http://www.euroncap.com/technical/protocols.aspx)

14. Request for Comment in the Federal Register seeking responses to the public release of its CIB/DBS research efforts (77 FR 39561, July 3, 2012); Docket NHTSA-2012-0057-0002

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