Forward-Looking Advanced Braking Technologies Research Report

NHTSA
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Executive Summary

While improvements to the structural design of vehicles continue to enhance their safety, technologies, such as forward-looking advanced braking technologies, will likely represent the next wave of significant advances in vehicle safety. The National Highway Traffic Safety Administration identifies and evaluates those technologies that it believes have the potential for measurable vehicle safety improvements and that are beginning to be included in new light vehicles[1]. The agency takes particular interest in technologies with the potential to avoid or address crash types that represent a significant percentage of annual vehicle crashes.

Forward-looking advanced braking technologies, in particular Dynamic Brake Support (DBS) and Crash Imminent Braking (CIB), are designed to address the most common type of two-vehicle collisions: rear-end collisions.

Approximately, two years ago, NHTSA began a thorough examination of the current state of the development, functionality, and deployment of DBS and CIB. The agency surveyed the literature, both scientific and manufacturer generated, met with various parties including manufacturers and suppliers, and conducted a series of vehicle tests to gain a better understanding of the capabilities of then-current systems and their ability to address the problem of rear-end crashes.

As a result of these efforts, the agency believes DBS and CIB have the potential to enhance the safety of light vehicles. Based on the performance we observed on the test track, NHTSA preliminarily estimates the number of equivalent lives saved by a combination of forward collision warning (FCW), DBS, and CIB systems to be over 1,000 annually. In an effort to enhance our understanding of these systems, we have identified information gaps that merit further research and exploration. This includes continued efforts regarding refined effectiveness estimates, test operation (including how to ensure repeatability using a target or surrogate vehicle), refinement of performance criteria, and exploring the need for an approach and criteria for “false positive” tests to minimize unintended negative consequences. This report details our findings with respect to CIB and DBS and summarizes our observations to date about these promising technologies.

[1] Light vehicles are passenger cars, multipurpose passenger vehicles (MPVs), trucks, or buses with a gross vehicle weight rating (GVWR) of 4,536 kg (10,000 lb) or less.

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I. Introduction

There are presently three forward-looking advanced crash avoidance technologies available to address rear-end crashes involving light vehicles in the United States: Forward Collision Warning (FCW), Dynamic Brake Support (DBS), and Crash Imminent Braking (CIB).

These technologies, listed in order of increasing vehicle system assistance/intervention may be generally defined as follows:

Forward Collision Warning (FCW): a system that uses information from forward-looking sensors, usually a camera or radar, to determine whether or not a crash is likely or unavoidable and, in such cases, *warns* the driver so the driver can brake and/or steer to avoid or minimize the impact of the crash.

Dynamic Brake Support (DBS): a system that uses information from forward-looking sensors about driving situations in which a crash is likely or unavoidable to *supplement automatically* the output of the brakes when the DBS system senses that the force being applied by the driver to the brake pedal is insufficient to avoid the crash.

Crash Imminent Braking (CIB): a system that uses information from forward-looking sensors to *automatically apply* the brakes in driving situations in which a crash is likely or unavoidable and the driver makes no attempt to avoid the crash.

This report focuses on the recent research and analysis of then-current production DBS and CIB systems conducted by the National Highway Traffic Safety Administration (NHTSA). Typically, vehicles that are equipped with DBS and/or CIB are also equipped with FCW and utilize the forward-looking sensors used for FCW. Information provided by the FCW system's front-facing sensors, combined with measurement of the driver's brake application, serve as the basis for the DBS and CIB systems' intervention. The total amount of braking that may result from the operation of DBS and CIB[2] systems varies, ranging from very mild up to the vehicle's maximum braking capacity in accordance with varying strategies deployed by the manufacturers.

Although crash avoidance sensor technologies and their implementation have made significant advances in recent years, at this time only a limited number of vehicle makes and models are equipped with FCW, DBS, or CIB.

Several studies sponsored by the agency and others have suggested that these forward-looking advanced braking technologies may provide substantial benefits. Recent agency-sponsored research that estimated significant potential benefits include the following reports: Evaluation of

[2] The magnitude of the intervention in first generation CIB systems was approximately 0.5-0.6g of deceleration. Second and third generation systems, now finding their way into production, can apply up to the maximum braking capability of the vehicle (e.g., approximately 1g on a dry, high-coefficient surface). Typically, these later generation systems offer two intervention stages. During the first deceleration, magnitudes similar to those produced with first generation systems are initiated. However, when the collision is deemed absolutely unavoidable (i.e., the vehicle is a matter of feet from the object it is about to strike), a second more substantial CIB intervention occurs. For some vehicles, the second stage can maximize deceleration by applying full braking and activating the vehicle's antilock braking system (ABS) if necessary.

an Automotive Rear-end Collision Avoidance System [DOT HS 810 569], Integrated Vehicle-Based Safety Systems (IVBSS) Light Vehicle Field Operational Test Independent Evaluation [DOT HS 811 516], Advanced Crash Avoidance Technologies (ACAT) Program – Final Report of the Honda-DRI Team, Volume I: Executive Summary and Technical Report [DOT HS 811 454A], and Advanced Crash Avoidance Technologies (ACAT) Program – Toyota Final Report [Forthcoming].

Although several studies show potential benefits, the estimated effectiveness of the technologies varies from study to study. Further, these studies used prototype systems whose performance may vary from actual production systems. Furthermore, the target population (those crashes that would be favorably affected by the installation and operation of these technologies) is not always well-defined and also varies considerably between studies. As a result, in 2010 NHTSA began to thoroughly examine the state of forward-looking advanced braking technologies, analyzing their performance and identifying areas of concern or uncertainty in an effort to better understand the potential benefits of these systems. This report is a summary of these efforts.

The agency estimates the current market penetration for any type of forward-looking advanced braking technology to be less than one percent of new light vehicles. As a result, there is very little real world crash or naturalistic data that can serve as the basis for assessing the effectiveness of these technologies in the field.

Based on our efforts to date, the agency believes that DBS and CIB systems appear to have the capability to provide safety benefits (to varying degrees depending on which vehicle make and model is considered). However, there remains work to be done. This includes continued efforts regarding refined effectiveness estimates, test operation (including how to ensure repeatability using a target or surrogate vehicle), refinement of performance criteria, and exploring the need for an approach and criteria for "false positive" tests to minimize unintended negative consequences. This report details our findings with respect to CIB and DBS and summarizes our observations to date about these promising technologies.

II. Review of Literature and Current Activities

The agency has reviewed and documented activities by others, including vehicle manufacturers, automotive component/system suppliers, consumer groups, academia, insurance industry organizations from both the U.S. and Great Britain, and industry-government collaborations. The agency also corresponded and met with vehicle manufacturers, suppliers, and other organizations to obtain information relating to forward-looking advanced braking technologies. Examples of these activities include:

- A review of research conducted by other entities including:
  - The work of the Crash Avoidance Metrics Partnership (CAMP)[3] CIB Consortium.
  - NHTSA's Advanced Crash Avoidance Technologies (ACAT) programs, specifically the work of Honda Research and Development Company, Ltd. and Dynamic Research, Inc. on Advanced Collision Mitigation Braking (A-CMBS), and the work of Toyota Motor Corporation on a Pre-Collision Safety System. Both of these projects developed a Safety Impact Methodology (SIM) tool and estimated safety benefits for pre-production prototype systems.[4]
  - European Advanced Forward Looking Safety Systems Working Group (vFSS), which is working to assemble performance-based test protocols with a focus on evaluation of target systems.
  - German Motoring Club, ADAC, which is developing a comparative test of advanced emergency braking systems.
  - European ASSESS, Assessment of Integrated Vehicle Safety Systems for improved vehicle safety. The main objective of ASSESS is to develop harmonized assessment procedures and related tools for integrated safety systems.

- A review of various publicly-available sources of forward-looking advanced braking technologies was performed. (See Appendix A: "Rear-End Crash Avoidance Technology Literature Review" at the end of this report.) Many of these reports included benefits assessments with varying degrees of uncertainty. The earliest benefits assessment projections merely talked about the potential of FCW systems, as DBS and CIB systems were not yet implemented. Later studies, which included idealized operational algorithms and modeling, were more theoretical in nature. Finally, as prototype systems were developed and these technologies began to be produced, they were studied both on the track and in real-world testing (a process that continues with this effort). These studies based on test data offer benefit assessments with ever improving estimates. Because forward-looking advanced braking technologies are still in the early stages of their deployment and use in vehicles, further research is needed to improve benefits estimates. Most of the research reports applied to the United States, but a few applied to Germany or the European Union and are included for reference in Appendix A.

- A review of regulation and guideline documents under development in other areas of the world including a proposed European regulation that would require automatic emergency braking systems (AEBS) on heavy vehicles[5]; a draft of ISO 22839 that relates to Forward

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[3] CAMP is a NHTSA-sponsored effort by Continental, Delphi Corporation, Ford Motor Company, General Motors Corporation and Mercedes-Benz to define minimum performance measures and objective tests for crash imminent braking systems and to assess the harm reduction potential of various system configurations and performance capabilities.

[4] The ACAT program had two objectives. The first was to develop a formalized Safety Impact Methodology (SIM) tool to estimate the ability of advanced technology applications in full vehicle systems to address specific motor vehicle crashes. The second objective of the program was to demonstrate how the results of objective tests can be used by the SIM to forecast the safety benefit of a real system.

[5] United Nations Economic Council for Europe (UN ECE) Working Party on Brakes and Running Gear (GRRF). 2011. Proposal for a Regulation on Advanced Emergency Braking Systems (AEBS). Geneva, Author. <http://www.unece.org/fileadmin/DAM/trans/doc/2011/wp29grrf/ECE-TRANS-WP29-GRRF-2011-15e.pdf>

Vehicle Collision Mitigation Systems (FVCMS)[6]; and guidelines of the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) for collision mitigation braking systems[7].

- The review of and comment from vehicle manufacturers on the preliminary and revised CIB and DBS test protocols developed by the agency to evaluate the performance capabilities of these systems, as well as comments from vehicle manufacturers who executed testing in accordance with the test protocols.

III. Target Population

A. Initial Determination of Target Population

The agency carefully considered and conducted research to allow it to define the population of crashes on which it would expect forward-looking advanced braking technologies to have a positive impact. Determining the target population is extremely important for estimating the effectiveness of forward-looking advanced braking technologies.

Approximately 1.7 million rear-end collisions involving a passenger vehicle with frontal damage occur annually. Although these crashes are generally not severe, they involve five million persons, injuring 700,000 and killing 1,000 on average annually. Almost three-quarters (73%) of the collisions result in no injuries (property damage only).[8]

To identify possible crash types that should not be included in the target population, the agency conducted an in-depth review of 29 cases from 2003 through 2009 that were found in the agency's National Automotive Sampling System Crashworthiness Data System (NASS-CDS).[9] The cases selected involved one or more fatalities resulting from a rear-end crash. For each of these crashes, the scene diagram, vehicle and crash scene photographs, crash summary, injury patterns, vehicle crash performance, and overall crash outcomes (i.e. involvement of other occupants in the vehicle or occupants in another vehicle involved in the crash) were examined and analyzed.

[6] International Organization for Standardization (ISO). Intelligent Transport System – Forward Vehicle Collision Mitigation Systems – Operation, Performance, and Verification Requirements. Draft ISO / NP 22839 2011. Geneva, Author. <http://www.iso.org>

[7] Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The Guideline for the AEBS (Advanced Emergency Braking System). Translated into English by the JASIC. Japan, Author.

[8] The figures in this paragraph reflect weighted cases from the file obtained by combining the 2006-2008 FARS with the non-fatal cases in the 2006-2008 GES and imputing unknown values.

[9] NASS-CDS has detailed data on a representative, random sample of thousands of minor, serious, and fatal crashes. Field research teams across the U.S. study about 5,000 crashes a year involving passenger cars, light trucks, vans, and sport utility vehicles. Crash investigators obtain data from crash sites, studying evidence such as skid marks, fluid spills, broken glass, and bent guard rails. They locate the vehicles involved, photograph them, measure the crash damage, and identify interior locations that were struck by the occupants. These researchers interview crash victims and review medical records to determine the nature and severity of injuries.

The crashes were grouped according to similarities and the frequency with which similar crashes occurred. There were ten crashes that occurred at high impact speed (estimated to be greater than 80 km/h [50 mph]). The amount of rear-end crush in the lead vehicle that occurred in these crashes exceeded the amount of crush allowed in FMVSS No. 301, *Fuel system integrity* crash tests. In these cases, all of the fatalities occurred in the lead vehicle. In three of the cases a post-crash fire occurred.

Ten cases involved impact with a tractor-trailer. In all of these cases the driver in the subject vehicle (the following vehicle) sustained fatal injuries. In four of these ten cases the driver was under the influence of alcohol. In five cases, a second event was most harmful, which means the rear-end crash preceded and likely caused a second more harmful event resulting in fatal injuries to an involved occupant. For example, a fatality might have resulted from a rollover or from a head-on crash with a vehicle in an opposing lane that occurred after the rear-end impact. There were two cases involving an older vehicle (at least 20 years old). In both of these crashes unbelted occupants in the following vehicle sustained the fatal injuries, and the following vehicles were not equipped with frontal air bags. These crashes were likely survivable if the occupants had been restrained. Two fatal cases were classified as “other” and did not fit the categories just discussed. In one case the lead vehicle cut in front of the following vehicle which resulted in the lead vehicle rolling over. In the other case, NASS-CDS did not provide enough information to make an assessment.

It is highly unlikely, based upon the performance of currently available CIB and DBS systems, that either technology would have been effective in fatal crashes involving either high impact speed or impact with a larger truck or trailer because, given the impact speed involved in these crashes, the technology would not have decreased the impact speed enough to prevent the fatality. Accordingly, as a result of the case review, it was determined that cases with a relative impact speed greater than 80 km/h (50 mph) in which a fatality or fatalities occur in the lead vehicle and cases in which a fatality or fatalities occur in the following vehicle after an impact with a large truck or trailer should be excluded from the target population. However, because CIB and DBS will likely be effective in crashes where the second event is the most harmful event by reducing the severity or preventing the second event from occurring, it was determined that these types of crashes should remain in the target population.

To further understand the crashes targeted by CIB and DBS systems, the agency considered the balance of coverage (i.e., operating conditions where system-induced braking would be expected to intervene) and suppression algorithms (i.e., conditions in which system-induced braking would, by design, not be expected despite the potential for a rear-end crash) with input from vehicle manufacturers and system suppliers who had production systems deployed or prototypes used in agency-sponsored research activities. Based on the agency’s understanding and incorporating the above NASS-CDS case reviews, we defined the following initial target population for current production systems. In cases where one system addresses a particular crash scenario (such as impacts into a stopped lead vehicle) and another does not, we included the crash scenario in the definition below. Thus the agency’s initial target population reflects the widest collection of crash scenarios potentially addressed by one or more CIB or DBS system currently in production.

The combined CIB and DBS target population consisted of crashes in which the front of a passenger vehicle (the subject vehicle), which was going straight in a travel lane in a controlled fashion at a speed of 9 mph or higher, strikes a motor vehicle (the lead vehicle or principal other vehicle) that was stopped or going straight in the same lane and direction as the subject vehicle, and the subject vehicle driver did not steer to try to avoid the crash. As mentioned above, the following were excluded from the target population: crashes with a fatality in the lead vehicle and crashes into a large truck or trailer with a fatality in the subject vehicle. These exclusions were based on an engineering judgment that the system would not affect the outcome of such crashes.

Applying these limitations to information in police reports resulted in an estimate of 940,000 crashes per year in which a CIB/DBS system could have possibly reduced or mitigated the effects of the crashes involved. This identified target population is roughly evenly split between crashes in which the subject vehicle driver did not brake prior to impact (430,000 crashes) and those in which the driver did (500,000 crashes).[10]

B. Further Refinement of Target Population

Using the basic criteria established to identify the target population, a second group of cases was identified and reviewed to better understand rear-end crashes and to see if there were any other types of crashes that should be excluded from the target population as initially defined. This second group of rear-end crash cases was found in the National Motor Vehicle Crash Causation Study (NMVCCS)[11] from 2005 through 2008 and included various types of rear-end crashes, not just those involving a fatality. The cases were examined in detail to determine whether forward-looking advanced braking technologies would be expected to have had an impact on these crashes. Factors considered that might have affected the ability of an advanced forward-looking braking technology's ability to intervene included roadway conditions, time available for a system to react, the curvature of the road involved, situations in which one vehicle cuts into the lane of a following vehicle, situations in which a driver steers the vehicle such that a system would assume the driver is an engaged driver and therefore would not activate, and any other factors reflected in information available for a crash that indicated CIB/DBS would not be effective.

Based on the review of these cases, CIB or DBS would not have been effective in a number of rear-end crash cases because the lead vehicle cut into the lane of the following vehicle, and the system would not have had time to detect and react to the crash threat. After excluding these cases in which CIB or DBS would not have had an effect, 94% of the weighted cases in which some braking occurred and 99% of the weighted cases in which no braking occurred remained relevant to the technology.

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[10] Figures do not sum to the total presented due to rounding.

[11] NMVCCS utilizes the infrastructure of the National Automotive Sampling System (NASS) program to collect data throughout the United States. The goal of the project is to produce annual data files with approximately 4800 cases. The NMVCCS includes on-scene data collection, which is not part of the NASS-CDS data collection process. Data gathered in this project is useful in identifying what crash avoidance technologies are needed in the driving environment, for drivers and passengers, and in vehicles and how they should be designed.

To verify if it was appropriate to exclude cases in which the driver tried to avoid the crash by steering, thereby suppressing the CIB/DBS systems, 40 cases were coded to indicate that the driver steered before impact were reviewed. These cases were cases in which some braking was applied and therefore DBS might have been of benefit. Based on this analysis it was determined that 19 percent of the weighted cases would have benefited from DBS technology. This was because it appeared the steering was applied so late in the event that the technology would have activated prior to the avoidance maneuver.

Applying these adjustments[12] to the initial assessment of 940,000 targeted crashes reduces this figure by 30,000 to an estimated 910,000 targeted crashes, which equals roughly half (54%) of the safety problem (1.7 million rear-end collisions on average annually). These crashes involve an estimated 2,700,000 persons per year, and a total annual cost of $47 billion.

Other entities[13] have estimated a wide range of target populations. NHTSA's target population falls roughly in the middle of these other estimates. The target population identified by the agency reflects the coverage of current production systems as implemented in vehicles today, while those derived by others often reflect prototype or hypothetical future systems. A number of study authors[14] feel that future systems will be able to address a much wider set of crashes, including head-on collisions and crashes into pedestrians, bicyclists, animals, and inanimate objects. Only a very few systems have begun to address these types of crashes. The agency believes that false-positive activations (braking in the absence of a threat) and resulting consumer acceptance issues may be hindering the development of systems to address these types of crashes. Other differences in target populations arise from the treatment of (other) suppression algorithms, with some studies effectively ignoring suppression algorithms required by vehicle manufacturers. For example, some systems will not apply automatic braking if the driver uses steering or throttle inputs higher than the vehicle's suppression threshold, effectively yielding to the driver's commands even if the sensors detect an impending collision. Some studies include such crash scenarios in their target populations, even though the system will not activate braking.

The assumptions we used in determining the target population include:

- Current CIB and DBS production systems target only crashes in which the front of a passenger vehicle strikes a motor vehicle (the lead vehicle or principal other vehicle) that was stopped or going straight in the same lane and direction as the subject vehicle. Current systems do not activate braking for impending head-on collisions, nor for collisions into bicyclists, animals, or inanimate objects. Although some newer systems automatically brake in response to an imminent collision with a pedestrian, the capability still remains very limited. Therefore, systems included in the target population did not include any potential benefits from avoiding or mitigating crashes with pedestrians.

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[12] The adjustment factors were computed and applied for each countermeasure separately (CIB versus DBS). Aggregated adjustment figures (such as the 4% reduction in the police-reported target population) appear here for a simpler exposition.

[13] Van Auken et al. (2011), Carpenter et al. (2011), Georgi et al. (2009), Jermakian (2010), Kusano and Gabler (2010), and Insurance Institute for Highway Safety (2010).

[14] Van Auken et al. (2011), Georgi et al. (2009), Jermakian (2010), and Insurance Institute for Highway Safety (2010).

- At the time the analyses were performed, CIB and DBS systems did not provide automatic or supplemental braking at speeds less than 9 mph or if the driver executed a steering avoidance maneuver prior to the time at which a system would otherwise brake.
- Current CIB and DBS systems are ineffective in crashes with a fatality in the lead vehicle and for crashes into a large truck or trailer with a fatality in the subject vehicle.

A list of sources used in addressing the question of target population may be found in Appendix B to this notice.

IV. Test Protocols

Test protocols must provide the agency with a detailed way to objectively evaluate CIB and DBS system performance. The test protocols must be repeatable and reproducible. The test protocols discussed in this document were developed in two stages. The "preliminary test protocols" were developed using available knowledge of CIB and DBS system design and operational characteristics. Data produced from use of the preliminary protocols, in conjunction with discussions pertaining to them, were used to refine and streamline the protocols in a number of important ways. These modifications are provided in Section C. Test Protocol Refinement below and are referred to as "revised test protocols" throughout this report.

A. Preliminary Test Protocols

In order to objectively assess the CIB and DBS system performance, the agency derived its protocols from those already used to evaluate FCW performance in the New Car Assessment Program (NCAP). Like those used for the FCW NCAP evaluations, the preliminary CIB and DBS test protocols used two of the three maneuvers intended to represent situations in which a subject vehicle (SV) was about to collide with another vehicle directly in front of it in one of two scenarios: 1) when the lead vehicle, or principal other vehicle (POV), was stationary or 2) when the POV was moving at a constant speed slower than the SV.[15, 16] While FCW is typically a passive technology used only to issue an alert before some predetermined time-to-collision (TTC) threshold is exceeded (i.e., while the driver still has an opportunity to avoid the crash by using steering, braking, or a combination thereof), CIB and DBS endeavor to actively reduce pre-impact vehicle speed. Therefore, to best evaluate CIB and DBS, some changes were made to the FCW NCAP test protocols. The test matrix specified within the preliminary CIB and DBS test protocols is shown in Table 1.

[15] The test maneuvers represent two of the most common types light-vehicle crashes involving two vehicles: lead vehicle stopped and lead vehicle decelerating. There are approximately 792,000 crashes annually in which the lead vehicle is stopped (20.46% of all two-vehicle, light-vehicle crashes). This is the most common type of two-vehicle, light-vehicle crash. There are also 347,000 crashes annually in which the lead vehicle is decelerating (8.96% of all two-vehicle, light-vehicle crashes). This is the third most common type of two-vehicle light-vehicle crash. (See Table 11, Pre-Crash Scenarios of Two-Vehicle Light-Vehicle Crashes, in the NHTSA Report, "Pre-Crash Scenario Typology for Crash Avoidance Research," DOT HS 810 767 April 2007.)

[16] The FCW NCAP also evaluated a third scenario where the POV was decelerating in front of the SV. Scenarios in which the POV was decelerating are considered to be similar to the scenario (2) in which the POV is moving at a constant speed slower than the SV and were not evaluated as separate maneuvers during this CIB and DBS research program.

Table 1. Test Matrix Specified Within the Preliminary CIB and DBS Test Protocols

<table>
<tr><th rowspan="3">Pre-Crash Scenario</th><th rowspan="3">Test Speeds</th><th colspan="4">Brake Pedal Inputs (Applied with a Programmable Brake Controller)</th></tr>
<tr><th rowspan="2">CIB</th><th colspan="3">DBS</th></tr>
<tr><th>Timing (Time-to-Collision)</th><th>Magnitude</th><th>Nominal Rate</th></tr>
<tr><td rowspan="2">Stopped POV</td><td>SV: 45 mph
POV: 0 mph</td><td>None</td><td rowspan="2">• TTC = 2.1 sec
• TTC = 1.1 sec</td><td rowspan="4">• Constant brake pedal position
• 50% of input needed for ABS
• 75% of input needed for ABS
• 100% of input needed for ABS</td><td rowspan="4">12.6 in/s</td></tr>
<tr><td>SV: 25 mph
POV: 0 mph</td><td>None</td></tr>
<tr><td rowspan="2">Slower POV</td><td>SV: 45 mph
POV: 20 mph</td><td>None</td><td rowspan="2">• TTC = 2.0 sec
• TTC = 1.0 sec</td></tr>
<tr><td>SV: 25 mph
POV: 10 mph</td><td>None</td></tr>
</table>

Key differences from the FCW NCAP test include:

- Use of a surrogate POV. The FCW NCAP test protocols allow for the use of an actual mid-sized passenger vehicle for the POV or target equipment that has a physical- and radar-profile representative of a mid-sized car. During conduct of FCW NCAP tests, there is little risk for an SV-to-POV collision. Therefore, to date, an actual vehicle has been used as the POV. Conversely, there is potential for a CIB and DBS test trial to conclude with an SV-to-POV collision. Therefore, to ensure the preliminary tests could be performed safely, the POV was a realistic-looking surrogate. It was an inflatable "balloon" car designed to appear as a "real" car to the SV's CIB and DBS forward-looking sensors, while being able to be repeatedly hit without risk of injury to the SV driver or damage to either the SV or POV.[17]

- Use of multiple speed ranges per test condition. The crash data indicates many rear-end collisions occur at low speed. Also, CIB and DBS system functionality and effectiveness can depend on the speed of the vehicles involved. Therefore, in addition to the moderate SV and POV speed combinations used in the FCW NCAP test protocol (i.e., tests where the SV was 45 mph), lower speed combinations were also used (i.e., tests where the SV was 25 mph).

- During each maneuver executed under the FCW NCAP the driver is prohibited from physically applying the service brakes and the FCW must activate no later than a specified point in time prior to a collision defined as "time-to-collision" or "TTC." Brake applications occurred at one of two TTCs during DBS evaluations. For each driving

[17] Research conducted on behalf of the agency utilized a balloon car that simulates a Volkswagen Golf. Agency research indicates that there are approximately 24 variations of balloon cars in the world. The agency's VRTC will also be using a foam car in future research.

scenario, the (single) TTC alert magnitudes specified in the FCW NCAP performance requirements are intended to provide a reasonable amount of time for the driver to be able to detect, comprehend, and respond to an FCW alert. Using a programmable brake controller (i.e., braking robot) during the DBS tests, the SV brakes were applied at the same TTCs specified in the FCW NCAP performance requirements. Given that driver reaction time from onset of an FCW alert to the onset of a brake application can be taken to be approximately one second, a second set of brake application TTCs one second shorter than those specified in the FCW NCAP performance requirement were also used.

- Multiple brake application magnitudes were used during DBS evaluations. An analysis of Event Data Recorder (EDR) information found that 66 percent of drivers involved in rear-end collisions applied some, albeit insufficient, braking prior to the crash.[18] As a result, three brake application magnitudes were used to evaluate the contribution of DBS realized during moderate, hard, and maximum brake inputs (corresponding to 50, 75, and 100 percent of the brake pedal displacement[19] necessary to activate the test vehicle's antilock brake systems, respectively).
- The number of repeated test trials per condition was nominally increased from seven (7) used in the FCW NCAP to ten (10) to provide a good balance of sample size and test burden.

B. Test Track Evaluations

Using the preliminary test protocols, the agency performed test track evaluations of vehicles representative of the limited number of makes and models in the U.S. presently equipped with CIB and/or DBS. These evaluations took place at NHTSA's Vehicle Research and Test Center (VRTC) in East Liberty, Ohio. Production vehicles used for this research included a 2010 Mercedes E350, a 2010 Toyota Prius, and a 2010 Ford Taurus. To increase the sample population, development vehicles utilizing algorithms similar to those of production vehicles were also used. These vehicles included a 2004 BMW 530d, an older development vehicle equipped with a supplier's more contemporary algorithm, and a 2011 Audi A8. While each of these vehicles was equipped with DBS, only the Mercedes E350, Toyota Prius, and Audi A8 were also equipped with CIB.

Analysis of the test results focused on the ability of a vehicle's CIB and DBS system to prevent or mitigate the effects of rear-end crashes in the two scenarios. Overall summaries of these test results are provided in Tables 2-5.

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[18] This analysis examined 136 weighted cases from event data recorder (EDR) data.
[19] The downward position of the vehicle's brake pedal resulting from an application of force to the pedal face, measured from an "at rest" position where no force is applied.

1. Impact Speed Reductions Attributable to CIB

For the CIB evaluations, no brake application was input by the SV driver during the test runs. Therefore, the speed reductions shown in Table 2 are entirely due to the automatic braking provided by the system. Note that although the preliminary CIB tests were performed with three CIB-equipped vehicles, only two provided system operation in the stopped lead vehicle scenario (the Mercedes E350 and the Toyota Prius). The CIB system installed on the Audi A8 that was tested by the agency did not respond to non-moving objects, such as a stopped vehicle in the path of the subject vehicle; therefore, the stopped lead vehicle scenario was not performed with the Audi A8.

Table 2. Overall Range of Average SV-to-POV Impact Speed Reductions Attributable to CIB

SV: 45 mph **POV: 0 mph**	**SV: 25 mph** **POV: 0 mph**	**SV: 45 mph** **POV: 20 mph**	**SV: 25 mph** **POV: 10 mph**
3 mph[1]	3 – 10 mph[1]	7 – 15 mph	7 – 13 mph

[1]Based on data from two vehicles.

2. Impact Speed Reductions Attributable to DBS

Unlike the CIB evaluations, DBS tests included multiple brake applications per test condition. Since the braking performance contribution from DBS was evaluated at each of three different brake application inputs (100, 75, and 50 percent of the brake pedal displacement necessary to activate the test vehicle's antilock brake system), there are three data sets summarized in Tables 3, 4, and 5 (i.e., one for each magnitude of braking applied). When considering the speed reductions attributed to CIB shown in Table 2, the reductions are referenced to the initial speed of the SV. However, when considering DBS data, the reductions are referenced to results from "baseline" tests (i.e., tests whose braking was affected not by DBS, but only by how far the brake pedal was pushed). The values shown in Tables 3-5 present the impact speed reductions beyond those realized by baseline braking, not the speed at which the SV impacts the POV. Although both the DBS-based and baseline tests were performed with a programmable brake controller, baseline tests were performed without a POV. The absence of a POV prevented activation of DBS during baseline test runs since no threat would be apparent to the SV's forward-looking sensors, thereby allowing the vehicle's foundation braking to be objectively quantified.

For many tests summarized in Tables 3-5, the baseline braking was capable of preventing an impact with the surrogate POV. In these cases, the contribution of additional braking from a DBS intervention was not relevant (if it was present at all). Therefore, as presented in these tables, a "0 mph" impact speed reduction does not necessarily imply poor DBS performance. Rather, this result simply means the combination of test scenario conditions and brake application magnitude did not require a DBS intervention.

3. Impact Speed Reductions Attributable to DBS with 100% Brake Application

Table 3 presents a summary of results from preliminary DBS tests performed with brake pedal displacement capable of activating the vehicles' respective ABS systems with baseline braking alone. With the exception of most 45 mph stopped lead vehicle tests performed with braking initiated at TTC = 1.1 seconds, no crashes occurred. In the condition where crashes were observed, there was no statistically significant difference in impact speed for two of the four vehicles evaluated (Toyota Prius and the BMW 530d development vehicle). For the remaining two vehicles, DBS was able to reduce the average impact speed by 4.1 to 11.2 mph (for the Mercedes E350 and Audi A8, respectively).

Table 3. Overall Range of Average SV-to-POV Impact Speed Reductions Attributable to DBS
(Brake Application = 100% of the brake pedal displacement necessary to activate ABS)

SV: 45 mph POV: 0 mph		**SV: 25 mph POV: 0 mph**		**SV: 45 mph POV: 20 mph**		**SV: 25 mph POV: 10 mph**	
TTC = 2.1s	**TTC = 1.1s**	**TTC = 2.1s**	**TTC = 1.1s**	**TTC = 2.0s**	**TTC = 1.0s**	**TTC = 2.0s**	**TTC = 1.0s**
0 mph[1]	0 – 11 mph[1, 2, 3]	0 mph[1]	0 mph[1]	0 mph	0 mph	0 mph	0 mph

[1]Based on data from four vehicles.

[2]Difference attributable to automatic pre-braking that occurred before the brake pedal application during tests performed with the Audi A8.

[3]Not significantly different from no-DBS baseline test runs for 2 of 4 vehicles.

4. Impact Speed Reductions Attributable to DBS with 75% Brake Application

When the brake application magnitude was reduced from 100 to 75 percent of the displacement needed to activate ABS, more SV-to-POV crashes occurred in some, but not all, test conditions. In agreement with the 100 percent brake application tests, none of the 75 percent brake application tests performed with the longer TTC (i.e., 2.0 or 2.1, depending on whether the test used a slower moving or stopped POV, respectively) resulted in a crash, including those performed with baseline braking. This was also true for all slower moving tests performed with the Mercedes E350 and Audi A8 (i.e., using both combinations vehicle speeds), and for all other vehicles during slower moving tests performed with nominal SV/POV speeds of 25/10 mph. Table 4 summarizes the results from preliminary DBS tests performed with 75 percent of the displacement needed to activate ABS.

Table 4. Overall Range of Average SV-to-POV Impact Speed Reductions Attributable to DBS
(Brake Application = 75% of the brake pedal displacement necessary to activate ABS)

SV: 45 mph POV: 0 mph		SV: 25 mph POV: 0 mph		SV: 45 mph POV: 20 mph		SV: 25 mph POV: 10 mph	
TTC = 2.1s	**TTC = 1.1s**	**TTC = 2.1s**	**TTC = 1.1s**	**TTC = 2.0s**	**TTC = 1.0s**	**TTC = 2.0s**	**TTC = 1.0s**
0 mph[1]	8 – 10 mph[1]	0 mph[1]	0 – 2 mph[1, 2]	0 mph	0 – 9 mph[2]	0 mph	0 mph

[1]Based on data from four vehicles.

[2]Not significantly different from no-DBS baseline test runs for 1 of 4 vehicles.

In the case of the slower moving lead vehicle tests with a SV speed of 45 mph and a POV speed of 20 mph performed with the Toyota Prius, BMW 530d development vehicle, and Ford Taurus, in which braking was nominally initiated at TTC = 1.0 seconds, some or all of the baseline trials concluded in a crash with the POV, but crashes were avoided during each DBS test trial. For these vehicles, the average impact speed reductions ranged from 2.0 to 8.2 mph.

For the stopped POV tests performed with braking nominally initiated at TTC = 1.1 seconds and a nominal initial SV speed of 25 mph, three of the four vehicles avoided SV-to-POV impacts during each baseline and DBS test performed. In the case of the Toyota Prius, every baseline trial concluded in a crash with the POV, as did some of the DBS test trials. For the tests where a crash did occur with DBS, the average impact speed reduction was 1.9 mph (not a statistically significant results at $\alpha = 0.05$, with the cavaeat that the small sample population makes an assessment of statistical significance not practically meaningful).

For the stopped POV tests performed with braking nominally initiated at TTC = 1.1 seconds and a nominal initial SV speed of 45 mph, SV-to-POV impacts occurred during each baseline and DBS test performed for each vehicle. For this condition, DBS reduced the average impact speed by 7.6 to 9.9 mph.

5. Impact Speed Reductions Attributable to DBS with 50% Brake Application

When the brake application magnitude was reduced from 75 to 50 percent of the displacement needed to activate ABS, the number of SV-to-POV crashes increased significantly from that realized during higher brake magnitudes. In agreement with the results from the 100 and 75 percent brake application tests, no slower moving POV tests performed with 50 percent braking nominally initiated at TTC = 2.0 seconds and a nominal initial SV speed of 25 mph resulted in a crash, even if it was performed with baseline braking. This continued to be the case for the Mercedes E350 when braking was nominally initiated at TTC = 1.0 seconds. For the BMW 530d developmental vehicle and the Audi A8, some or all of the baseline trials concluded in a crash with the POV, but crashes were avoided during each DBS test trial. For these vehicles, the average impact speed reductions ranged from 5.7 to 7.8 mph. In the case of the Toyota Prius and Ford Taurus, all baseline trials concluded in a crash with the POV, as did some of the DBS test trials. For these vehicles, when a crash did occur with DBS, the average impact speed reduction was 0 mph (not a statistically significant results at $\alpha = 0.05$) to 1.5 mph in this test condition.

Table 5 summarizes the results from preliminary DBS tests performed with 50 percent of the displacement needed to activate ABS.

In the case of the slower moving lead vehicle tests with a SV speed of 45 mph and a POV speed of 20 mph performed and with braking nominally initiated at TTC = 2.0 seconds, no baseline or DBS test trial resulted in a SV-to-POV crash for the Mercedes E350 or Ford Taurus. In the case of the Toyota Prius, some or all of the baseline trials concluded in a crash with the POV, but crashes were avoided during each DBS test trial and an average impact speed reduction of 6.2 mph was realized. For the BMW 530d developmental vehicle, crashes occurred during all test trials, and an average impact speed reduction of 8.8 mph was realized during each DBS test trial (although it was not a statistically significant result at $\alpha = 0.05$).

Reducing the time braking was nominally initiated to TTC = 1.0 seconds during the higher speed slower moving POV tests increased the number of crashes realized for each vehicle. For the Mercedes E350 and the Audi A8, some or all of the baseline trials concluded in a crash with the POV, but crashes were avoided during each DBS test trial. For these vehicles, an average impact speed reduction of 14.3 to 14.4 mph was realized. With the Toyota Prius, every baseline trial concluded in a crash with the POV, as did some of the DBS test trials. For the tests where a crash did occur with DBS, the average impact speed reduction was 15.0 mph. In the case of the BMW 530d development vehicle and Ford Taurus, SV-to-POV impacts occurred during each baseline and DBS test. For these vehicles, the average impact speed reductions ranged from 0.8 mph (not a statistically significant result at $\alpha = 0.05$) to 4.7 mph.

During stopped POV tests performed with a nominal SV speed of 25 mph in which braking was nominally initiated to TTC = 2.1 seconds, the Mercedes E350 was able to avoid the POV during all baseline and DBS test trials. With the Audi A8, every baseline trial concluded in a crash with the POV, as did some of the DBS test trials. For the tests where a crash did occur with DBS, the average impact speed reduction was 4.0 mph for this vehicle. In the case of the Toyota Prius and BMW 530d development vehicle, SV-to-POV impacts occurred during all test trials in this condition, and the small differences in impact speed (less than 1.0 mph) were not statistically significant at $\alpha = 0.05$.

When the TTC from which braking was nominally initiated during the slower stopped POV tests was reduced to 1.1 seconds, every baseline trial performed with the Mercedes E350 and Toyota Prius concluded in a crash with the POV, as did some of the respective DBS test trials. For the tests where a crash did occur with DBS, the average impact speed reduction was 1.3 to 1.7 mph (not a statistically significant result at $\alpha = 0.05$). For the BMW 530d development vehicle and Audi A8, SV-to-POV impacts occurred during all test trials in this condition, and impact speed reductions ranged from 0.6 mph (not a statistically significant result at $\alpha = 0.05$) to 2.4 mph.

The most extreme test condition specified in the preliminary DBS test protocol was the test scenario with a nominal SV speed of 45 mph, a POV speed of 0 mph, and the brake application magnitude of 50 percent. With one vehicle exception, every baseline and DBS test trial performed in this condition resulted in a SV-to-POV impact. The sole exception was for the Mercedes E350 with braking initiated at TTC = 2.1 seconds; although every baseline trial produced a crash, some tests performed with DBS did not. In that particular test condition, the impact speed reduction was 8.4 mph for the Mercedes E350. For the other vehicles, impact speed reductions were from 0 to 4.2 mph when braking was initiated at TTC = 2.1 seconds. When the braking was initiated at TTC = 1.1 seconds, the impact speed reductions were from 0 mph (not a statistically significant result at $\alpha = 0.05$) to 5.3 mph.

Table 5. Overall Range of Average SV-to-POV Impact Speed Reductions Attributable to DBS
(Brake Application = 50% of the brake pedal displacement necessary to activate ABS)

SV: 45 mph POV: 0 mph		SV: 25 mph POV: 0 mph		SV: 45 mph POV: 20 mph		SV: 25 mph POV: 10 mph	
TTC = 2.1s	**TTC = 1.1s**	**TTC = 2.1s**	**TTC = 1.1s**	**TTC = 2.0s**	**TTC = 1.0s**	**TTC = 2.0s**	**TTC = 1.0s**
0 – 8 mph[1]	0 – 5 mph[2]	1 – 4 mph[2]	1 – 2 mph[2]	0 – 9 mph[2]	1 – 15 mph[3]	0 mph	0 – 8 mph[3]

[1]Based on data from four vehicles; not significantly different from no-DBS baseline test runs for 2 of 4 vehicles.
[2]Not significantly different from no-DBS baseline test runs for 2 of 5 vehicles.
[3]Not significantly different from no-DBS baseline test runs for 1 of 5 vehicles.

6. Frequency of CIB Non-Activations or Late Activations

In addition to impact speed reduction, the SV's ability to repeatably activate CIB and DBS was of interest. A summary of test results indicating how often the CIB system failed to activate in the presence of a crash threat is provided in Table 6. Unfortunately, a similar summary is not available for the DBS test runs. Identifying CIB activations during review of the test data is a straight-forward process because the SV is responsible for producing all braking during a given trial, an action that can be objectively detected by analyzing brake line pressure data. Detecting DBS non-activations in this way is not possible, because some braking (and therefore brake line pressure) is provided by the brake pedal application itself, which precedes activation of DBS. Although differences in SV deceleration can be used to provide indications of DBS vs. no-DBS activities, NHTSA does not believe these data provide enough resolution to conclusively distinguish baseline test runs from DBS-based tests where only a mild intervention may have been present.

A late activation was identified by an observed change in brake line pressure at a time-to-collision too short to effectively decelerate the vehicle. A late activation resulted not only in a crash with the surrogate vehicle, but also in a speed reduction less than observed during other trials performed with same vehicle in the same test series. Possible reasons for CIB non-activations are discussed later in this document.

Table 6. CIB Non-Activation / Very Late Activation Summary

Vehicle	SV: 45 mph POV: 0 mph		SV: 25 mph POV: 0 mph		SV: 45 mph POV: 20 mph		SV: 45 mph POV: 20 mph	
	# of test runs	**percent**	**# of test runs**	**percent**	**# of test runs**	**percent**	**# of test runs**	**percent**
Mercedes E350	2 of 8	25.0	1 of 14	7.1	0 of 10	0	0 of 5	0
Toyota Prius	3 of 7	42.9	0 of 10	0	0 of 10	0	2 of 7	28.6
Audi A8 (non-U.S. model)	No Stopped Lead Vehicle operation				0 of 7	0	0 of 5	0

C. Test Protocol Refinement

The agency revised the February 2011 preliminary test protocols based on our research findings and input from manufacturers who witnessed tests of their vehicle or systems and enhanced the agency's understanding of test protocols they were using. The outcome of these evaluations was more refined and detailed specifications, protocols, and test choreography. Of particular significance was (1) the removal of the most extreme stopped lead vehicle condition (SV speed = 45 mph), (2) refined brake application instructions for performing DBS tests, and (3) inclusion of performance measures. The revised June 2012 CIB and DBS test protocols are available in the Forward Looking Advanced Braking Technologies docket NHTSA-2012-0057 at www.regulations.gov.[20]

1. Removal of the 45 mph Stopped Lead Vehicle Test Condition

Removal of the high speed tests in the stopped lead vehicle test conditions was necessary to reduce the potential for test vehicles being damaged during performance evaluations. Specifically, NHTSA is concerned that high-speed collisions with even the "softest" known surrogate vehicles are capable of inducing CIB and DBS sensor misalignment—damage that has the potential to confound the outcome of subsequent test trials.

Based on the test results previously shown in Table 5, average speed reduction attributable to CIB intervention during stopped lead vehicle tests performed from 45 mph was only 3 mph. This outcome was realized with the respective systems operating as designed. Should CIB activation not occur, the surrogate vehicle impact would nominally be expected to occur at 45 mph. From a testing perspective, a 45 mph impact speed is believed to be unreasonably high, due to the risk of damaging the subject vehicle. In contrast, the nominal speed differentials of the other three test conditions, 15-25 mph, are reasonable.

[20] The revised June 2012 CIB and DBS test protocols, which are available in Docket NHTSA-2012-0057, are the same as the test protocols that were used by the agency for testing in October 2011.

2. Refined Brake Application Instructions for Performing DBS Tests

Unlike the test protocol used to evaluate CIB, NHTSA's revised DBS test protocol includes significant changes from the preliminary version. The revised brake application timing and a new method to calculate the magnitude of brake application are the most important changes.

In the case of DBS evaluations, the revised test protocol specifies only the shorter of the TTCs that were preliminarily specified per scenario. This is because baseline braking alone was frequently able to prevent crashes with the surrogate vehicle when applied at the longer TTC, thereby making evaluation of DBS crash avoidance performance non-relevant.

The revised DBS test protocol specifies the use of one (rather than three) brake application that produces a deceleration of 0.3g during foundation brake system characterization, a process described in the DBS test protocol. The 0.3g deceleration magnitude specified in the June 2012 DBS test protocol was chosen based on consideration of EDR data (which indicates the average deceleration realized before a rear-end collision occurs is approximately 0.32-0.38g if the driver of the striking vehicle actually applies the brakes, on dry pavement) and the minimum deceleration necessary to active DBS for some production vehicles (0.3g). Use of this deceleration magnitude is also intended to eliminate the possibility of avoiding a collision with the SV using foundation brakes alone; some form of supplemental braking is required to avoid the collision (as shown in Table 7).

Brake characterization refinement was necessary for two reasons. First, relating the brake application magnitude used during DBS evaluations to that capable of producing maximum deceleration was not found to be as universally applicable across the entire light vehicle fleet as anticipated. Specifically, the amount of brake pedal travel at 50 and 75 percent of that needed to activate ABS (the method used to objectively quantify the occurrence of maximum braking) can vary significantly, as can the respective deceleration levels at these application magnitudes. Use of the brake application magnitudes needed to achieve a fixed deceleration of 0.3g is believed to provide a more consistent way to normalize the brake inputs used for DBS performance evaluation. Secondly, some baseline tests were able to avoid collisions with the surrogate vehicle; even those performed with the shorter TTC (i.e., 1.1 and 1.0 seconds) and brake pedal travel inputs at 50 and 75 percent of that needed to realize maximum braking. Recognizing this could compromise the ability to distinguish a vehicle equipped with DBS versus one with very strong foundation brakes and no DBS, a different approach was deemed necessary.

3. Inclusion of Performance Measures

Based on the agency's test track evaluations and feedback received, the CIB and DBS test scenarios have been revised and performance measures are being considered as presented in Table 7. For both technologies, the performance measures should be satisfied during each of the eight repeated runs per test condition.[21]

[21] The preliminary test protocol required ten (10) repeated runs per test condition. The revised protocol has reduced the test burden slightly; eight (8) repeated runs per test condition are now specified.

Table 7. CIB and DBS Performance Measures Under Consideration

Pre-Crash Scenario	SV Speed Reduction at Impact or Crash Avoidance (No impact)					
	CIB			DBS		
	SV: 25 mph POV: 0 mph	SV: 25 mph POV: 10 mph	SV: 45 mph POV: 20 mph	SV: 25 mph POV: 0 mph (Brake apply at TTC = 1.1s)	SV: 25 mph POV: 10 mph (Brake apply at TTC = 1.0s)	SV: 45 mph POV: 20 mph (Brake apply at TTC = 1.0s)
Stopped POV	≥ 9.8 mph (15.8 km/h)	--	--	No SV-to-POV impact	--	--
Slower POV	--	No SV-to-POV impact	≥ 9.8 mph (15.8 km/h)	--	No SV-to-POV impact	No SV-to-POV impact

The performance measures provided in Table 7 consider the current state of technology, and the capabilities of current CIB and DBS-equipped vehicles. As a point of reference, the CIB performance measures under consideration can be achieved with an effective test vehicle deceleration of 0.6g (5.9 m/s^2) from a pre-CIB activation TTC of 0.6 seconds. The DBS performance measures under consideration can be achieved in the following ways:

1. When the SV test speed is 25 mph (40.2 km/h), the POV = 0 mph, and TTC = 1.1 seconds, crash avoidance requires an effective deceleration of approximately 0.52g (5.1 m/s^2).
2. When the SV test speed is 25 mph (40.2 km/h), the POV = 10 mph (16.1 km/h), and TTC = 1.0 seconds, crash avoidance requires an effective deceleration of approximately 0.34g (3.4 m/s^2).
3. When the SV test speed is 45 mph (72.4 km/h), the POV = 20 mph (32.2 km/h), and TTC = 1.0 seconds, crash avoidance requires an effective deceleration of approximately 0.57g (5.9 m/s^2).

   Note that in each of these specifications, the term "effective deceleration" is provided for informative purposes only. The effective deceleration interval is calculated using a simple step input, in which the effective deceleration is realized from the onset of the brake application to the time of minimum SV-to-POV range (zero if an impact occurs).

To date, only a limited number of tests have been performed by the agency using the revised test protocols. In the case of the CIB test protocols, the basic test conduct was largely unchanged between the preliminary and revised test protocols. Therefore, and with two exceptions, existing data was used to predict whether the previously evaluated vehicles would be capable of satisfying the performance measures shown in Table 7. The two exceptions were a 2010 Subaru Outback (a non-production development vehicle leased by NHTSA to increase the limited sample size of its test fleet) and a 2012 Volvo S60.[22] These vehicles were evaluated after completion of the preliminary test trials using procedures nominally equivalent to those specified

[22] The test track evaluation of these vehicles occurred after the benefit assessment was performed, and were therefore no included in the related calculations.

in the revised test protocols, albeit with a different number of repeated trials per test condition. The outcome of the combined analysis is presented in Table 8.

Table 8. Ability to Satisfy the CIB Performance Measures under Consideration

Vehicle	SV: 25 mph POV: 0 mph		SV: 25 mph POV: 10 mph		SV: 45 mph POV: 20 mph	
	# of test runs	percent	# of test runs	percent	# of test runs	percent
Mercedes E350	9 of 13	69%	3 of 5	60%	10 of 10	100%
Toyota Prius	0 of 10	0%	0 of 5	0%	0 of 10	0%
Audi A8 (non-U.S. model)	No Stopped Lead Vehicle operation		0 of 5	0%	6 of 7	86%
Subaru Outback (non-U.S. model)	10 of 10	100%	5 of 5	100%	6 of 6	100%
Volvo S60	5 of 5	100%	5 of 5	100%	5 of 5	100%

Unlike the test protocols used to evaluate CIB, NHTSA's revised DBS test protocol includes significant changes from the preliminary version, with the method used to calculate the magnitude of brake application being the most important change.

Although the brake application magnitude specified in the revised DBS test protocol differed explicitly from those of the preliminary protocol, speed reductions produced during preliminary tests performed with the smallest inputs provide a reasonable approximation of how the vehicles would have performed had the revised inputs been used. Results of this analysis are provided in Table 9. Note that in the case of the Volvo S60, the latest DBS protocol was performed with fewer test trials per condition than ultimately specified in the revised protocol (five trials rather than eight).

Table 9. Estimated Ability to Satisfy the DBS Performance Measures under Consideration

Vehicle	SV: 25 mph POV: 0 mph		SV: 25 mph POV: 10 mph		SV: 45 mph POV: 20 mph	
	# of test runs	percent	# of test runs	percent	# of test runs	percent
Mercedes E350	1 of 10	10%	9 of 9	100%	11 of 11	100%
Toyota Prius	0 of 5	0%	0 of 4	0%	4 of 4	100%
BMW 530d (development vehicle)	0 of 1	0%	1 of 1	100%	0 of 1	0%
Ford Taurus	No Stopped Lead Vehicle operation		1 of 2	50%	0 of 5	0%
Audi A8 (non-U.S. model)	0 of 5	0%	5 of 5	100%	4 of 4	100%
Subaru Outback (non-U.S. model)	5 of 5	100%	5 of 5	100%	10 of 10	100%
Volvo S60	5 of 5	100%	5 of 5	100%	7 of 9	78%

The number of valid samples per cell varied in Tables 8 and 9. In some cases, only a few test runs were performed due to limited test vehicle availability. In other cases, some of the test runs performed did not satisfy a validity requirement (e.g., vehicle speed measured within ±1.0 mph of the desired initial value) and were not considered for subsequent analysis. In some instances, extra test runs (i.e., beyond a nominal specification) were performed because the in-vehicle experimenter believed some tests within a given series may have been non-valid, only to later find they were acceptable.

V. Preliminary Benefits Estimates Based On Three Research Vehicles

This section will discuss the results of the agency's benefits estimates based upon the speed reduction of vehicles equipped with DBS and CIB measured using the preliminary February 2011 test protocols discussed earlier.[23]

[23] Based on the test track runs performed at VRTC, for the Mercedes DBS system, we assumed that 7% - 27% of drivers who did not apply the vehicle's brakes in a targeted crash would apply the brakes in response to the FCW alert within 1.2 seconds. Likewise, for the Toyota DBS system, we assumed that 30% - 43% would respond to the FCW alert. However, we note that the FCW alert data for the Audi were not available for the benefit estimate. In addition, as inferred in the target population discussion, we assumed that CIB and DBS systems do not avoid or mitigate any crashes outside of the target population identified previously. Further, for the DBS baseline brake

In addition to the speed reductions from vehicle tests using the preliminary test protocols, the ranges of benefits estimates by the agency were also based on assumptions that included the following:

- All light vehicles would be equipped with FCW[24], DBS, and CIB. These DBS and CIB systems would perform at levels equivalent to the performance of the three best performing vehicles in the agency's test track evaluation of vehicles.
- FCW would prevent 15 percent[25] of all injuries in the target population.[26]
- No passenger vehicles currently in use are equipped with FCW, DBS, and/or CIB. [27]
- Passenger car test track results for CIB/DBS systems would apply to all new light vehicles.
- SV performance in a decelerating POV scenario is similar to its performance during POV moving at a constant speed slower than the SV.

Based upon the speed reduction from vehicle testing in the scenarios discussed earlier, the injury reduction was estimated using the delta-v reduction and the corresponding reduction in injury risk.[28] Injury risk versus delta-v curves that have been previously used by the agency for its Tire Pressure Monitoring rulemaking, were utilized. NASS-CDS police reported estimates of tow away crashes were adjusted to reflect all police reported crashes.

Using these assumptions and applying them to the target population identified, the agency found that CIB alone on all light vehicles would prevent 13,000 - 28,000 minor injuries (Abbreviated Injury Scale (AIS) level 1 & 2), 500 – 700 (AIS 3 – 5) serious injuries and save 38 – 63 lives annually. DBS alone would prevent 53,000 – 94,000 minor injuries (AIS 1 & 2), 1,000 – 1,700 (AIS 3 – 5) serious injuries, and save 3 – 19 lives annually.

FCW, CIB, and DBS combined would prevent 94,000 – 145,000 minor injuries (AIS 1 & 2), 2,000 – 3,000 (AIS 3 – 5) serious injuries, and save 78 – 108 lives annually, as shown in Table 10.

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performance, we assume that on average drivers brake at 0.275g, based on EDR data. Additionally, we assumed that the systems never brake in the absence of a threat for the crashes in the target population.

[24] The agency believes that manufacturers will not install DBS and CIB without FCW and for the purpose of estimating benefits will assume FCW will provide a warning prior to any automatic brake intervention.

[25] For additional discussion on the 15% effectiveness, see the Final decision notice to upgrade NCAP. 73 FR 40016 (July 11, 2008).

[26] Najm, W. G., Stearns, M. D., Howarth, H., Koopmann, J., and Hitz, J., "*Evaluation of an Automotive Rear-End Collision Avoidance System*". U.S. Department of Transportation, National Highway Traffic Safety Administration, DOT HS 810 569, March 2006.

[27] We assumed that no passenger vehicles currently in use are equipped with these technologies since the current market penetration is only about 1%.

[28] The delta-v is defined as a change in velocity of a vehicle in front to rear end crashes. The final speed after impact is assumed to be the same for the subject vehicle and the other vehicle. The reduction in delta-v was calculated from the delta-v's with and without the technologies.

Table 10. Preliminary Effectiveness Estimates for Three FCW/CIB/DBS Systems

Injuries and lives saved, FCW+CIB+DBS				Overall % effective[29]
Minor injuries	Serious injuries	Fatal	Equivalent Lives	
94,000 – 145,000	1,900 – 2,800	78 – 108	1,000 – 1,400	29% - 41%

VI. Observations

As indicated earlier in this document, NHTSA has made significant strides in its understanding of the current state of forward-looking advanced braking technologies. However, there is more it must learn. What follows are observations on the key areas in which the agency needs additional information or in which its knowledge needs further refinement.

A. Test Protocols

Test protocols are by their very nature complex and detailed. Based on the agency's test track evaluation experience, the agency believes the June 2012 revised test protocols represent a solid start toward test protocols that can be used to assess CIB and DBS system performance on the test track. However, questions remain that need to be addressed and refinements that will likely need to be made.

1. Reasonableness, Repeatability and Reproducibility

Only a limited number of vehicles have been evaluated with the test protocols. For this reason, the agency does not know whether the test protocols will be reasonable, repeatable and reproducible for all current and future production vehicles. For example, from a reasonability standpoint, the tolerances in the protocols (i.e., maintaining the SV and POV test speeds within 1 mph or specified speeds, the longitudinal centering of the SV to the POV within 1 foot, or the yaw rate within 1 deg/sec) may be too narrow or more details may be needed in the instructions. From a repeatability and reproducibility standpoint, NHTSA does not yet understand how testing at different test tracks and locations with the same vehicle or how the use of different test targets (surrogate vehicles) would impact the agency's test results.

2. Brake Application Methodology

The revised DBS test protocol includes the provision for a vehicle to be evaluated with brake applications based on either constant pedal position (i.e., application force is modulated) or constant application force (i.e., pedal position is modulated). Each option can be executed accurately and repeatably with a programmable brake controller.

[29] The overall percent effectiveness is based on Equivalent Lives.

However, an unforeseen consequence of accurate pedal control, particularly when constant pedal position is used, is that it can potentially affect DBS system operation. There are two reasons for this effect. First, some DBS systems determine if or how the driver has applied the brakes by monitoring brake pressure at certain places within the system. Second, in some contemporary implementations, DBS activation causes a small increase in pedal travel toward the floor caused by the system hydraulics. If the driver pushes the brake pedal down, the system expects the brake pressure to increase. However, if the pedal is pushed down and the pedal position is held constant while DBS is in operation (one of the two application options in the DBS protocol), the pedal movement expected from DBS cannot occur, and the brake pressure monitored within the system is reduced. Despite the fact that pedal displacement remains constant, the DBS system interprets the reduction in system pressure to be an indication that the driver has partially released his/her brake application. On the test track, the agency found that this misinterpretation can turn off the supplemental braking provided by DBS, causing the system output to revert back to the foundation brakes (i.e., baseline braking).

Whether this issue presents a real-world safety concern is unknown. Additionally, since the agency has only evaluated a small population of vehicles equipped with DBS, NHTSA cannot yet determine the implications for its ability to evaluate DBS system performance on the test track for contemporary or future vehicles, including those equipped with brake-by-wire systems.

3. Surrogate Vehicles and Tow Apparatus

NHTSA recognizes surrogate vehicles (i.e., strikeable artificial vehicles) are necessary to safely perform CIB and DBS tests. NHTSA believes an acceptable surrogate vehicle should be "realistic" to systems using Radar, camera, LIDAR[30], and/or infrared sensors to assess the potential threat of a rear-end collision. The surrogate vehicle should be able to withstand repeated impacts from CIB or DBS-equipped test vehicles with little to no hysteresis[31] over time. A test vehicle should not incur damage resulting from repeated impacts with the surrogate vehicle. Construction of surrogate vehicles should be consistent. The agency will continue to follow developments related to surrogate vehicles.

The agency is also interested in the two apparatus required to move the surrogate vehicle during the moving POV test scenarios. The apparatus must not be identified by the forward-looking sensors during the execution of tests. The apparatus must be able to meet the test specifications and tolerances (e.g., test speed, lateral movement restrictions, and yaw rates). Like the surrogate vehicle, the two apparatus must be able to withstand repeated impacts from the CIB- or DBS-equipped test vehicles.

[30] Light Detection and Ranging (LIDAR) sensors transmit coherent infra-red light pulses and can be used to determine a vehicle's closing speed on a lead vehicle or object by measuring the time of flight for the pulses reflected from an object in front of the subject vehicle.
[31] Here hysteresis refers to the time required after an impact for the surrogate vehicle, if deformed by the impact, to return to its original shape.

4. False Positives/Non-activations

The agency is analyzing the issue of CIB and DBS false positive activations, as they may have an adverse effect on safety and on consumer acceptance of these technologies. The current test protocols define a false positive activation as a condition where the technology automatically applies the vehicles brakes in response to a perceived, but not genuine, threat of a rear-end crash.

Using a test matrix consisting of five vehicles and eight scenarios, the agency has performed tests to evaluate CIB false positives on a test track. The agency was able to repeatably observe false positive CIB activations for some vehicles in specific test conditions, such as driving over a 1-inch thick steel plate commonly used as a temporary road repair. Ultimately, this study concluded false positive propensity was a vehicle-dependent phenomenon with an unknown risk to real-world safety.

B. Evaluation Criteria

1. Speed Reduction

In the test protocols, NHTSA specified speed reduction magnitudes it believes are realistic and attainable. The test protocols require the speed reductions to be satisfied for eight of eight test trials. The tests as drafted would be performed in the idealized confines of test tracks, with nearly ideal environmental conditions, and with minimal throttle and steering inputs. NHTSA's tests indicate it may be possible for vehicles currently equipped with CIB and DBS to satisfy the revised test protocols. NHTSA believes the performance measures under consideration are appropriate, however it will continue to assess the performance measures in the test protocols for other factors that the agency may not be aware of at this time.

C. Costs

The agency is continuing its efforts to understand the costs of CIB and DBS systems. That is why it is proceeding with a cost tear-down study. The agency hopes to learn the end cost to the consumer as a function of sensing technology (e.g., RADAR, camera(s), LIDAR, infrared, etc., or any combination thereof) and system configuration (CIB, DBS, CIB and DBS). The agency will also be carefully monitoring the status of CIB and DBS in the marketplace for indications that the prevalence of these technologies is such that costs should decline as economies of scale take hold.

D. Benefits

To determine preliminary benefit estimates, NHTSA made a number of assumptions, the validity of which it will need to continue to test.

The agency needs a better understanding of certain measures relating to forward looking advanced braking technologies so that it can better assess the impact of these technologies. The measures of interest are:

- Speed reductions that occur as a result of forward looking advanced crash braking technologies in various crash modes, such as lead vehicle stopped, moving at a slower speed, or decelerating.
- The average deceleration of a vehicle when a driver applies the brakes without any forward-looking advanced braking technologies.
- The typical FCW alert time prior to an anticipated crash at various speeds and in various crash modes.
- The percentage of drivers that respond to a FCW alert in various crash modes.
- The typical driver reaction time in various crash modes when the driver hears a FCW alert.
- The average decelerations of a vehicle when a CIB or DBS system is activated at various speeds and in various modes.

The agency is continuing to pursue information on these issues.

E. System Suppression

The agency is aware that at least some forward looking advanced braking systems include algorithms that suppress the activation of the system if certain conditions occur. These conditions may include:

- a minimum level of steering or movement of the accelerator pedal;
- one or more of the vehicle occupants unbelted;
- upper and lower velocity limits; and
- restrictions in the differences in speed between the subject vehicle and principal other vehicle.

In addition to algorithms that may suppress forward-looking advanced braking systems, the agency is interested in better understanding how environmental conditions, such as darkness or weather conditions like rain and fog, can render a system ineffective and what modifications are expected to improve system performance in these conditions over time.

Both suppression algorithms and other conditions that can render a system ineffective can have a significant impact on system performance, execution of test protocols, and the benefits that can be expected to be derived from systems.

F. Real-World/Field Data

As indicated elsewhere in this report, the small number of vehicles on the road equipped with any form of forward-looking advanced braking technology makes obtaining real-world data very difficult. The agency is exploring ways of getting data from other sources including through agreements with telematics services.

VII. Conclusions

Based on NHTSA's efforts to date, the agency believes that CIB and DBS systems may provide safety benefits (to varying degrees depending on which vehicle make and model is considered). Furthermore, the agency's efforts described above have significantly enhanced NHTSA's knowledge of forward-looking advanced braking technologies and the state of their development. However, the agency wants to further enhance its knowledge so that it will be in a position to assure that American consumers get the full benefit of these technologies. Specifically, there is much uncertainty with respect to how test track performance relates to real-world performance and the performance criteria that should be used to assess these systems.

NHTSA is continuing its research into various matters relating to CIB and DBS technologies. This work will include a tear-down study to further refine the agency's understanding of system costs, evaluation of additional vehicles with CIB and/or DBS that are available, further research on surrogate vehicles and the associated tow apparatus that can be used in the testing of CIB and DBS systems, further evaluation of the application of automatic brake controllers in DBS system testing, and an examination of system non-activation and false-positive conditions.

Appendix A: Rear-End Crash Avoidance Technology Literature Review

No.	Source	Reference
1	NHTSA	Knipling, R. R., Mironer, M., Hendricks, D. L., Tijerina, L., Everson, J., Allen, J. C., and Wilson, C. 1993. Assessment of IVHS Countermeasures for Collision Avoidance: Rear-End Crashes. Report no. DOT HS 807 995. Washington, DC: National Highway Traffic Safety Administration.
2	NHTSA	National Highway Traffic Safety Administration Benefits Working Group. 1996. Preliminary Assessment of Crash Avoidance Systems Benefits. Washington, DC: U.S. Department of Transportation.
3	Bosch	Bosch. 2005. Predictive Safety Systems - From Convenience towards Collision Avoidance and Collision Mitigation. Presentation, ADAS, Nivelies, Belgium.
4	DRI/Honda CMBS	Sugimoto, Y. and Sauer, C. 2005. Effectiveness Estimation Method for Advanced Driver Assistance System and its Application to Collision Mitigation Brake System. Paper no. 05-0148. Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles (CD-ROM). Washington, DC: National Highway Traffic Safety Administration.
5	NHTSA ACAS FOT	Najm, W. G., Stearns, M. D., Howarth, H., Koopmann, J., and Hitz, J. 2006. Evaluation of an Automotive Rear-end Collision Avoidance System. Report no. DOT HS 810 569. Washington, DC: National Highway Traffic Safety Administration.
6	Volvo	Coelingh, E., Jakobsson, L., Lind, H., and Lindman, M. 2007. Collision Warning With Auto Brake – a Real-life Safety Perspective. Paper no. 07-0450. Proceedings of the 20th International Technical Conference on the Enhanced Safety of Vehicles (CD-ROM). Washington, DC: National Highway Traffic Safety Administration.
7	IIHS	Farmer, C.M. 2008. Crash Avoidance Potential of Five Vehicle Technologies. Arlington, VA: Insurance Institute for Highway Safety.
8	Mercedes-Benz	Schittenhelm, H. 2008. Design of Effective Collision Mitigation Systems and Prediction of their Statistical Efficiency to Avoid or Mitigate Real World Accidents. Paper no. F2008-08-109. FISITA 2008 World Automotive Congress.
9	Bosch	Georgi, A., Zimmermann, M., Lich, T., Blank, L., Kickler, N., Marchthaler, R. 2009. New Approach of Accident Benefit Analysis for Rear End Collision Avoidance and Mitigation Systems. Paper no. 09-0281. Proceedings of the 21th International Technical Conference on the Enhanced Safety of Vehicles (CD-ROM). Washington, DC: National Highway Traffic Safety Administration.
10	GDV	Kuehn, M., Hummel, T., Bende, J. 2009. Benefit Estimation of Advanced Driver Assistance Systems for Cars Derived from Real-life Accidents. Paper no. 09-0317. Proceedings of the 21th International Technical Conference on the Enhanced Safety of Vehicles (CD-ROM). Washington, DC: National Highway Traffic Safety Administration.
11	IIHS	Jermakian, J. S. 2010. Crash Avoidance Potential of Four Passenger Vehicle Technologies. Arlington, VA: Insurance Institute for Highway Safety.
12	NHTSA IVBSS FOT	Nodine, E., Lam, A., Stevens, S., Razo, M. and Najm, W. 2011. Integrated Vehicle-Based Safety Systems (IVBSS) Light Vehicle Field Operational Test Independent Evaluation. Report no. DOT HS 811 516. Washington, DC: National Highway Traffic Safety Administration.

No.	Source	Reference
13	VTTI-Toyota (PCS)	Kusano, K. D. and Hampton, C. G. 2010. Potential Occupant Injury Reduction in Pre-Crash System Equipped Vehicles in the Striking Vehicle of Rear-end Crashes. AAAM Annual Conference.
14	DRI/Honda A-CMBS ACAT	Van Auken, R. M, Zellner, J. W., Chiang, D. P., Kelly, J., Silberling, J. Y., Dai, R., Broen, P. C., Kirsch, A. M., and Sugimoto, Y. 2011. Advanced Crash Avoidance Technologies (ACAT) Program – Final Report of the Honda-DRI Team, Volume I: Executive Summary and Technical Report. Report no. DOT HS 811 454A. Washington, DC: National Highway Traffic Safety Administration.
15	Toyota ACAT	Not yet published.
16	CAMP CIB	Carpenter, M. G., Feldmann, M., Fornari, T. M., Moury, M. T., Walker, C. D., Zwicky, T. D., and Kiger, S. M. 2011. Objective Tests for Imminent Crash Automatic Braking Systems Final Report. Report no. DOT HS 811 521. Washington, DC: National Highway Traffic Safety Administration.
17	EU	Wilmink, I., Janssen, W., Jonkers, E., Malone, K., van Noort, M., Klunder, G., Rämä, P., Sihvola, N., Kulmala, R., Schirokoff, A., Lind, G., Benz, T., Peters, H. and Schönebeck, S. 2008. Impact Assessment of Intelligent Vehicle Safety Systems. eIMPACT Deliverable D4. Version 2.0.
18	EU	COWI. 2006. Cost-benefit Assessment and Prioritisation of Vehicle Safety Technologies Final Report. Contract TREN/A1/56-2004. European Commission, Brussels.
19	Honda CMBS	http://www.ertico.com/honda-receives-euro-ncap-advanced-award-for-safety-innovation/

Appendix B: References Used in Developing Target Population Estimates

Van Auken, R. M, Zellner, J. W., Chiang, D. P., Kelly, J., Silberling, J. Y., Dai, R., Broen, P. C., Kirsch, A. M., and Sugimoto, Y. (2011). Advanced Crash Avoidance Technologies (ACAT) Program – Final Report of the Honda-DRI Team, Volume I: Executive Summary and Technical Report. Report no. DOT HS 811 454A. Washington, DC: National Highway Traffic Safety Administration.

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Delphi. (October 21, 2009). The Case for Preventing Vehicle Crashes, Saving Lives, and Reducing Injuries - Active Safety Systems . NHTSA / Delphi / Volvo / TASI Meeting. Washington, DC.

Eugensson, A., Axelsson, J.-O., and Broberg, T. (November 24, 2009). Volvo Cars Active Safety Demo. P-NCAP at CERAM.

Georgi, A., Brunner, H., and Scheunert, D. (2006). GIDAS German In-Depth Accident Study. FISITA 2004. Barcelona, Spain. www.gidas.org.

Georgi, A., Zimmermann, M., Lich, T., Blank, L., Kickler, N., and Marchthaler, R. (2009). New Approach of Accident Benefit Analysis for Rear End Collision Avoidance and Mitigation Systems. Paper Number 09-0281. The 21st International Technical Conference on the Enhanced Safety of Vehicles. Stuttgart, Germany.

Jermakian, J. (2010). Crash Avoidance Potential of Four Passenger Vehicle Technologies, R1130. Arlington, VA: The Insurance Institute for Highway Safety.

Kusano, K., & Gabler, H. C. (2010). Target Population for Injury Reduction from Pre-Crash Systems, 2010-01-0463. Washington DC: SAE International.

Mandel, D. (2010). Drawing the Line on Vehicle Technology. www.autoweek.com.

Insurance Institute for Highway Safety (2010). Status Report: Future Vehicles, Vol. 45, No. 5, pp. 1-7.