U.S. Department of Transportation
National Highway Traffic Safety Administration

NHTSA
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DOT HS 811 521 September 2011

Objective Tests for Automatic Crash Imminent Braking (CIB) Systems

Final Report
Volume 1 of 2

CAMP

Crash Imminent Braking Consortium

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Mercedes-Benz

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 811 521		

4. Title and Subtitle Objective Tests for Imminent Crash Automatic Braking Systems Final Report Volume 1 of 2	5. Report Date September 2011 6. Performing Organization Code
7. Authors Carpenter, Michael G., Feldmann, Michael, Fornari, Thomas M., Moury, M. Todd, Walker, Christopher D., Zwicky, Timothy D., Kiger, Steven M.	8. Performing Organization Report No.
9. Performing Organization Name and Address Crash Avoidance Metrics Partnership on behalf of the Crash Imminent Braking Consortium 39255 Country Club Drive, Suite B-40 Farmington Hills, MI 48331	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTNH22-05-H-01277
12. Sponsoring Agency Name and Address U.S. Department of Transportation National Highway Traffic Safety Administration 1200 New Jersey Avenue, SE Washington, DC 20590	13. Type of Report and Period Covered Final Report September 2007 – August 2010 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report documents the work completed by the Crash Avoidance Metrics Partnership (CAMP) Crash Imminent Braking (CIB) Consortium during the project titled "Objective Tests for Imminent Crash Automatic Braking Systems." Participating companies in the CIB Consortium were Continental, Delphi Corporation, Ford Motor Company, General Motors, and Mercedes-Benz. The purpose of this project was to attempt to define minimum performance requirements and objective tests for crash imminent braking systems and to assess the potential benefits of various system configurations and performance capabilities.

17. Key Word	18. Distribution Statement
	Document is available to the public from the National Technical Information Service www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	150	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorize

Executive Summary

This report documents the work completed by the Crash Avoidance Metrics Partnership (CAMP) Crash Imminent Braking (CIB) Consortium during the project titled "Objective Tests for Imminent Crash Automatic Braking Systems." Participating companies in the CIB Consortium were Continental, Delphi Corporation, Ford Motor Company, General Motors, and Mercedes-Benz. The purpose of this project was to attempt to define minimum performance requirements and objective tests for crash imminent braking systems and to assess the potential benefits of various system configurations and performance capabilities. The project was sponsored by the National Highway Traffic Safety Administration (NHTSA).

This document is a required deliverable under NHTSA Cooperative Agreement No. DTNH22-05-H-01277, Project Order 0002. The material which follows presents a detailed description of the work and analyses conducted during this project.

The first phase of the project involved target crash scenario selection and development of preliminary functional requirements. This phase provided the foundation for the remainder of the CIB Project by delivering two important initial requirements. First, the priority crash scenarios provided the basis from which objective test methods and benefits estimation methods were developed in the project. Second, the preliminary functional requirements provided the starting point for defining the CIB system combinations that the project team would need to build into test vehicles for evaluating, developing and validating the proposed objective test methods.

The second phase of the project involved specifying and building the test systems to be used throughout the remainder of the project. As part of this work, a survey document was distributed to key, automotive, forward-looking sensor suppliers requesting assessment of the potential performance capabilities of their technologies relative to the priority crash modes identified in the first phase. Completed surveys were compiled and analyzed with viable brake actuator options added by the CIB Consortium Participants to form a list of potential CIB system candidates.

The data and information gathered in the project were used to develop preliminary functional requirements which described an initial set of CIB system and component capabilities required for the project test vehicles. This information was combined to develop an overall set of initial minimum performance specifications for the project test vehicles based upon both the priority crash scenarios and the available sensing and braking technologies. An important aspect of this work was determining candidate CIB systems to be used for developing test methods based upon the developed CIB performance specifications.

A technology selection methodology was used to rank and select the systems to be built into the Performance Improvement Prototype (PIP) vehicles. This process involved defining the criteria and weighting factors for system ranking, performing computer simulations to generate data for evaluating the candidate systems, conducting the ranking process using a Pugh analysis technique to select appropriate systems to build, and obtaining agreement with NHTSA on the selected systems.

During the final step of the project's second phase, source organizations were selected for building the PIP vehicles and the target systems needed for testing. This task involved identifying the basic test types needed and defining requirements for test vehicles, target systems, system hardware, and data acquisition and ground truth measurements. System suppliers were also selected and the test systems were fabricated. Finally, based upon results from initial testing, the test systems were modified as needed to support the project requirements.

The third phase of the project involved the development, demonstration, and validation of the objective tests for evaluating CIB systems. The initial work in this phase focused on the development of test methods based on the priority crash scenarios established early in the project. This work began with development of a list of proposed verification test methods for each of the established crash scenarios and operational scenarios. The test methods were then evaluated with representative baseline systems and were then further evaluated and refined using the PIP vehicles. This work also included the development of tools for processing data collected during the Real-World Operational Assessment Data (ROAD) Trip conducted during the third phase.

This third phase of the project also focused on the final development, validation, and finalization of test methods based on the prioritized crash scenarios established early in the project. A limited set of system settings were used in this test validation work. These selected system values represented a range of potential settings in future production systems that were chosen to ensure that the test methods were capable of detecting different system performance characteristics. The objective was to "Test the Tests" with a range of system settings and measure the sensitivity of the test methodology to these settings.

A ROAD Trip was executed during this third project phase. This activity involved the collection of six weeks of operational data intended to represent a real-world user profile (e.g., the breakdown of road types traveled represented those of a typical driver). The data analysis from this trip identified potential driving conditions under which the various CIB system configurations tested were prone to false activations. This data was then used to identify test methods for assessing CIB system "sensor specific" operational performance.

The fourth and final phase of the project involved finalizing the CIB performance specifications and development of the benefits estimation methodology. For the functional test method minimum performance metrics, three measures are presented as both a means for establishing minimum performance values and as a means for differentiating between CIB systems. These measures include the ability of a CIB system to respond to the three functional test scenarios, the percentage of tests in which CIB system activation occurred in each of these test scenarios, and the average speed reduction achieved by the CIB system in each of these test scenarios. The performance metrics presented for the operational test scenarios represent a minimum set of real-world conditions for which any given CIB system could reasonably be expected to execute some level of automatic braking.

The proposed benefits estimation methodology was developed in the fourth phase by NHTSA and the Volpe National Transportation Systems Center (Volpe). This effort is expected to be documented separately in a report to NHTSA from the Volpe Center. This methodology attempts to link measured CIB system performance to existing United States field crash data. CIB Consortium participation within this process consisted of providing feedback on the information supplied by Volpe and sample test data for Volpe to use in exercising the concept methodology. Information was exchanged between the NHTSA, Volpe, and the CIB Consortium through regularly scheduled Benefits Estimation Working Group meetings. This group consisted of NHTSA/Volpe representatives, the CIB Technical Management Team (TMT), and additional technical experts from various CIB partner companies. These technical experts provided knowledge in the following areas: crash databases, crash injury risk estimation, statistics, and vehicle safety system benefits analyses.

Review of the proposed methodology by the Benefits Estimation Working Group suggested that the general concept and framework appear logical. However, the complexities of and the limitations within the available real-world data necessary to populate the model resulted in inherent uncertainties in the benefits estimations. Therefore, the comments and feedback from the CIB Consortium were provided to form recommendations for further improvements to the proposed benefits estimation methodology and to identify additional work needed to develop or gather additional data which could further improve the confidence in the CIB benefits estimates.

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List of Acronyms

AAAM	Association for the Advancement of Automotive Medicine
ABS	Antilock Braking System
AIS	Abbreviated Injury Scale
ARS	Advanced Restraint System
C2C	Car-to-Car
C2I	Car-to-Infrastructure
CAMP	Crash Avoidance Metrics Partnership
CDS	Crashworthiness Data System
CAN	Controller Area Network
CIB	Crash Imminent Braking
DGPS	Differential Global Positioning System
EDR	Electronic Data Recorder
EHB	Electro-Hydraulic Braking
EMB	Electro-Magnetic Braking
F-B	Front- to-Back
F-F	Front-to-Front
FARS	Fatality Analysis Reporting System
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
FOT	Field Operational Test
FoV	Field of View
FYL	Functional Years Lost
GES	General Estimates System
GHz	Gigahertz
GIDAS	German In-Depth Accident Study
GPS	Global Positioning System
HMI	Human-Machine Interface

KE	Kinetic Energy
LCD	Liquid Crystal Display
LD	Lateral Direction
LIDAR	Light Detection and Ranging
LTAP	Left Turn Across Path
LTIP	Left Turn Into Path
LVD	Lead Vehicle Decelerating
LVM	Lead Vehicle Moving
LVS	Lead Vehicle Stopped
MAIS	Maximum Abbreviated Injury Scale
NASS	National Automotive Sampling System
NBSM	Never-Before-Seen-Moving
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
OD	Opposite Direction
OEM	Original Equipment Manufacturer
PBA	Panic Brake Assist
PCDS	Pedestrian Crash Data System
P-CP	Pedestrian – Crossing Path
P-IP	Pedestrian – In Path
PIP	Performance Improvement Prototype
PVC	Polyvinyl Chloride
RCS	Radar Cross Section
ROAD	Real-World Operational Assessment Data
RTIP	Right Turn Into Path
RWUP	Real-World User Profile
SCP	Straight Crossing Path
SIM	Simulated
TMT	Technical Management Team

TRK	Track
TTC	Time to Collision
UMTRI	University of Michigan Transportation Research Institute
UTC	Coordinated Universal Time
V-O	Vehicle-to-Object
V-P	Vehicle-to-Pedestrian
VRTC	Vehicle Research and Test Center
V-V	Vehicle-to-Vehicle

1 Introduction

The Crash Imminent Braking (CIB) Project is being conducted by the Crash Avoidance Metrics Partnership (CAMP) CIB Consortium, which consists of Continental, Delphi Corporation, Ford Motor Company, General Motors and Mercedes-Benz. The project is sponsored by the National Highway Traffic Safety Administration (NHTSA) through NHTSA Cooperative Agreement No. DTNH22-05-H-01277, Project Order 0002. From inception to completion, the project ran 36 months from September 2007 through August 2010.

The purpose of the project was to develop and validate performance requirements and objective test procedures for CIB systems and to assess the harm reduction potential of various system configurations with differing CIB performance capabilities. Vehicle-based, pre-crash safety systems activate prior to impact when a crash is predicted to be unavoidable based on environmental data provided by vehicle sensors. CIB systems with adjustable characteristics were integrated into test vehicles in order to develop minimum performance requirements and further characterize the vehicle system CIB performance sensitivity to the pre-crash sensor specifications. These results were augmented with the final tests exercised on a limited number of system configurations. Data obtained during testing was used to provide preliminary estimates of potential harm reduction benefits of the prototype systems evaluated.

The first phase of the project focused on the identification of target (or priority) crash scenarios and the development of preliminary functional requirements for pre-crash sensing and braking systems.

The second phase of the project involved conducting a survey of automotive technology suppliers to identify forward-looking sensors and systems that could potentially be used in future CIB systems. In addition, the initial minimum performance specifications for the project prototype CIB systems were determined and candidate CIB systems were identified. These specifications were intended as the initial set of development system performance parameters which could be revised based upon vehicle testing, outcome of the harm reduction analysis and technology performance during later project tasks. Next, preliminary evaluations and ranking of technology candidates were conducted in order to select CIB systems to build into the CIB Performance Improvement Prototype (PIP) development vehicles. The end of the second phase of the project focused on sourcing and building the selected CIB system combinations into the PIP vehicles and developing test target systems for evaluating these systems.

The third phase of the project involved developing objective test procedures and evaluating their capability to differentiate the relative performance and potential benefits of the selected systems. These test procedures assess both desired activations as well as false positive/negative (i.e., false alarm/miss) tests for each crash and operational scenario included in the performance specifications. During this phase, additional development and confirmation of test methods was conducted, the test methods were verified to be capable of differentiating the relative performance of the selected systems, and the validated test methods were finalized. Real-world data was also gathered for the purposes of developing operational assessment tests to evaluate CIB system robustness against false activations.

The fourth and final phase of the project involved finalization of the CIB performance specifications and development of the benefits estimation methodology. For the functional test method minimum performance metrics, three measures are presented as both a means for establishing minimum performance values and as a means for differentiating between CIB systems. These measures include the ability of a CIB system to respond to the three functional test scenarios, the percentage of tests in which CIB system activation occurred in each of these test scenarios, and the average speed reduction achieved by the CIB system in each of these test scenarios. The performance metrics presented for the operational test scenarios represent a minimum set of real-world conditions for which any given CIB system could reasonably be expected to execute some level of automatic braking.

The proposed benefits estimation methodology was developed in the fourth phase. This included summarizing the achieved impact velocity reductions, and estimating the reductions in harm associated with these reduced impact velocities. This work focused on developing and finalizing a methodology for estimating the potential benefits of CIB systems. The proposed benefits estimation methodology was developed by NHTSA and the Volpe National Transportation Systems Center (Volpe) and is expected to be documented separately in a report to NHTSA. This methodology attempts to link measured CIB system performance to existing United States field crash data. CIB Consortium participation within this process consisted of providing feedback on the information supplied by Volpe and sample test data for Volpe to use in exercising the concept methodology. The comments and feedback from the CIB consortium were documented to provide recommendations for further improvements to the proposed benefits estimation methodology, and to identify additional work needed to develop or gather additional data which could further improve the confidence in the CIB benefits estimates.

2 Identification of Target Crash Scenarios and Preliminary Functional Requirements

This section of the report describes the identification and prioritization of the crash scenarios that were deemed to be most applicable to Crash Imminent Braking systems from the crash database analysis by NHTSA, Volpe and the CIB Technical Management Team (TMT). These crash scenarios provide the basis for the establishment of preliminary functional requirements and served as input for developing the test procedures. The results of the priority crash scenario research were also used later in the project by Volpe in their development of proposed benefits estimation methods. That process is further discussed in Section 5 and is expected to be documented separately in a report to NHTSA from the Volpe Center.

2.1 Identification of Crash Field Databases

The analysis of U.S. national vehicle crash data was separated into two phases. This work was conducted jointly by the CIB TMT and Volpe. First, a top-down analysis of the National Automotive Sampling System (NASS) databases, including the Crashworthiness Data System (CDS), General Estimates System (GES), and Fatality Analysis Reporting System (FARS) databases, was conducted. This work was summarized in Eigen and Najm (2009a). In this project, "top-down" analysis refers to the statistical analysis of available crash data to define the scope of the overall crash problem to be addressed by this project. This step allowed the identification of priority crash scenarios for additional analysis.

Each of the selected crash databases contained different levels of crash event details and statistical information. FARS and NASS-GES, for example, contained very little detailed data of the individual events that would be needed to develop a test method that would simulate these events. The NASS-GES database contained the largest number of cases and was useful for determining national trends and statistics for prioritization of crash types. Analysis of the FARS database ensured that prioritization of crash modes paid particular attention to fatal crashes. NASS-CDS, on the other hand, contained many fewer cases than GES since it only includes crashes involving towed vehicles. However, this crash database contained more detail for each of the cases entered. NASS-CDS data, therefore, provided the initial information for the second analysis step, referred to as the "bottom-up" analysis. This work was summarized in Eigen and Najm (2009b).

The bottom-up analysis consisted of a detailed review of the individual crash cases to identify the events leading up to the crash scenarios selected for study. The NASS-CDS database alone still contained insufficient data for many of the cases to complete a thorough bottom-up analysis. Therefore, these studies were supplemented with Electronic Data Recorder (EDR) information, German In-Depth Accident Study (GIDAS) data and Field Operational Test (FOT) data, as appropriate and publicly available. Additionally, during the top-down analysis, a relatively high percentage of cases involving pedestrians were noted. Since the aforementioned databases contained little detail for assessing the applicability of CIB systems to these pedestrian cases, additional case review studies were conducted using the Pedestrian Crash Data Study (PCDS) database.

Figure 1 provides a visual representation of the process flow used within this analysis and the steps used for the top-down and bottom-up phases. Next, the processes used within each of these steps will be described in further detail.

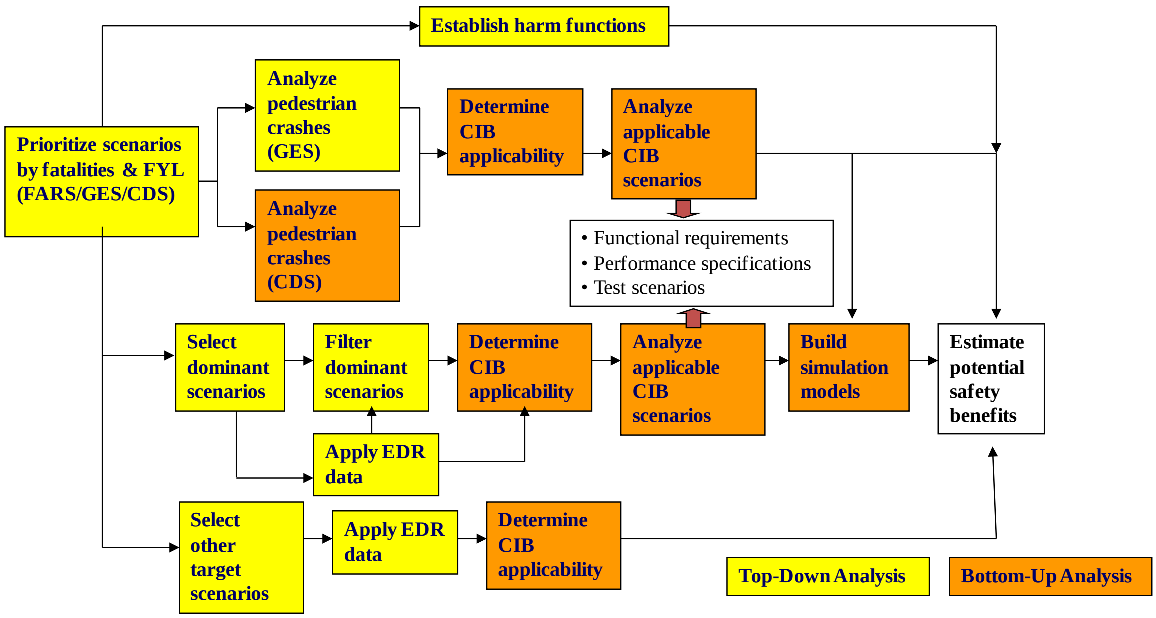


Figure 1: Analysis of Crash Data

2.2 Analyze Crash Types and Crash Time Sequence of Events

Figure 2 shows the basic process used during the top-down analysis to derive the priority crash events used throughout the CIB Project.

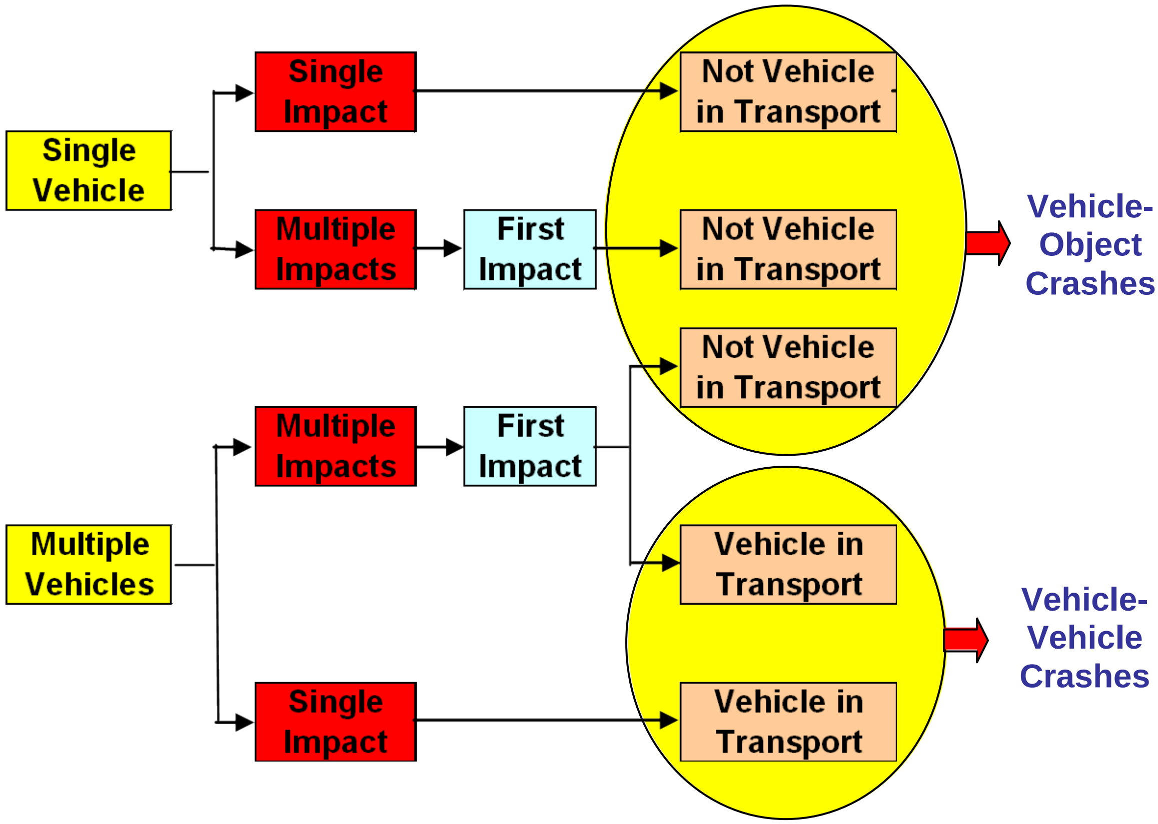


Figure 2: Crash Analysis Breakdown

As shown in Figure 2, the crash data was first sorted into single vehicle and multiple vehicle partitions. Each of these sets was then divided into single impact or multiple impact categories. For multiple impact conditions, cases were analyzed based upon the first impact of the crash sequence. The first impact in a multiple impact scenario provides the best detection opportunity for the forward-looking sensors included with CIB systems. Additionally, since CIB systems mitigate the severity of crashes by reducing the initial impact speed, any reduction of impact speed associated with the first impact should likewise reduce the severity, or potentially the likelihood, of subsequent impacts in a crash sequence. Lastly, a determination of the impacted object was made. If the object was a vehicle in transport, the crash was categorized as a vehicle-to-vehicle impact. All other impacts with objects that were not vehicles in transport were categorized as vehicle-to-object crashes.

From the FARS database, vehicle-to-object and vehicle-to-vehicle crashes were analyzed based upon light vehicles newer than 1998 model year involving frontal damage during the first impact and included all persons involved in the crash.

For NASS-CDS and GES databases, vehicle-to-vehicle and vehicle-to-object crashes were ranked based upon Functional Years Lost (FYL) for light vehicles newer than 1998 model year involving frontal damage during the first impact and included all persons involved. The FYL measure is computed based on the Maximum Abbreviated Injury

Scale values of 2 and higher of any persons involved in the crash (i.e., AIS2+ injuries). The Abbreviated Injury Scale (AIS) is a classification system for assessing impact injury severity developed and published by the Association for the Advancement of Automotive Medicine (AAAM) and is used for coding single injuries, assessing multiple injuries or assessing cumulative effects of more than one injury. The term MAIS refers to the maximum single AIS for a person with one or more injuries. Scale values represent the following:

- AIS 0 is uninjured
- AIS 1 is minor
- AIS 2 is moderate
- AIS 3 is serious
- AIS 4 is severe
- AIS 5 is critical
- AIS 6 is maximum/fatal

Priority crash modes were determined, which are summarized in Tables 1 and 2. Table 1 summarizes the vehicle-to-object and vehicle-to-pedestrian crash priorities from the FARS, CDS, and GES data. Table 2 summarizes the vehicle-to-vehicle crash priorities from the same databases. Table 1 and Table 2 highlight the crash types providing the highest percentage of fatalities for the FARS data or functional years lost for the GES and CDS data. The results are presented side-by-side from the three data sources to demonstrate that the priorities derived from each database are generally the same across these sources although the order may be slightly different.

Table 1: Results Summary of Vehicle-to-Object and Vehicle-to-Pedestrian Crashes – FARS, CDS, GES

FARS (by Specific Obstacle)			GES (by Pre-Crash Scenario / Object Combination)			CDS (by Pre-Crash Scenario / Object Combination)		
Pre-Crash Scenario	**Total Fatalities**	**% of Total Fatalities**	**Pre-Crash Scenario**	**FYL**	**% FYL**	**Pre-Crash Scenario**	**FYL**	**% FYL**
Pedestrian	7,204	26.5%	**Pedestrian – Person**	81,193	22.7%	**Road Departure – Ground**	170,186	17.8%
Tree	3,183	14%	**Road Departure – Ground**	45,285	12.7%	**Road Departure – Pole**	168,399	17.6%
Guardrail Face	1,629	6%	**Road Departure – Structure**	36,285	11.9%	**Road Departure – Structure**	160,876	16.8%
Ditch	1,387	5.1%	**Cyclist – Person**	31,209	10.1%	**Road Departure – Tree**	140,062	14.6%
			Road Departure – Tree	20,545	8.7%			
			Road Departure – Pole	20,174	5.7%			

CDS: Crashworthiness Data System
FARS: Fatality Analysis Reporting System
FYL**:** Functional Years Lost
GES: General Estimates System

Table 2: Results Summary of Vehicle-to-Vehicle Crashes

FARS (by Impact Type)			GES (by Pre-Crash Scenario / Impact Type Combination)			CDS (by Pre-Crash Scenario / Impact Type Combination)		
Pre-Crash Scenario	**Total Fatalities**	**% of Total Fatalities**	**Pre-Crash Scenario**	**FYL**	**% FYL**	**Pre-Crash Scenario**	**FYL**	**% FYL**
Front – Front	15,292	36.7%	**Rear End – Front to Back**	191,085	24.8%	**OD – Front to Front**	631,682	22.4%
Front – Left Side	8,544	20.5%	**OD – Front to Front**	106,091	13.8%	**Rear End – Front to Back**	357,304	12.7%
Front – Right Side	7,176	17.2%	**SCP – Front to Lt Side**	70,763	9.2%	**LTAP/OD – Front to Front**	252,022	9%
Front – Rear	4,598	11%	**SCP – Front to Rt Side**	63,948	8.3%	**SCP – Front to Lt Side**	232,877	8.3%
			Turning – Front to Lt Side	47,966	6.2%	**Turning – Front to Lt Side**	205,842	7.3%
			LTAP/OD – Front to Rt Side	47,277	6.1%	**SCP – Front to Rt Side**	202,451	7.2%

CDS: Crashworthiness Data System
FARS: Fatality Analysis Reporting System
FYL: Functional Years Lost
GES: General Estimates System

Based upon the crash data analysis conducted under this effort, the following crash priority rankings were selected for the CIB Project:

Vehicle-to-Vehicle Crashes:

1. Opposite Direction – Front to Front
2. Rear End – Front to Back
3. Left Turn Across Path / Opposite Direction (Front to Front and Front to Right Side)
4. Straight Crossing Path (Front to Left Side and Front to Right Side)
5. Turning – Front to Left Side

Vehicle-to-Object Crashes and Vehicle-to-Pedestrian Crashes:

1. Pedestrian
2. Road Departure – Pole
3. Road Departure – Tree
4. Road Departure – Ground
5. Road Departure – Structure

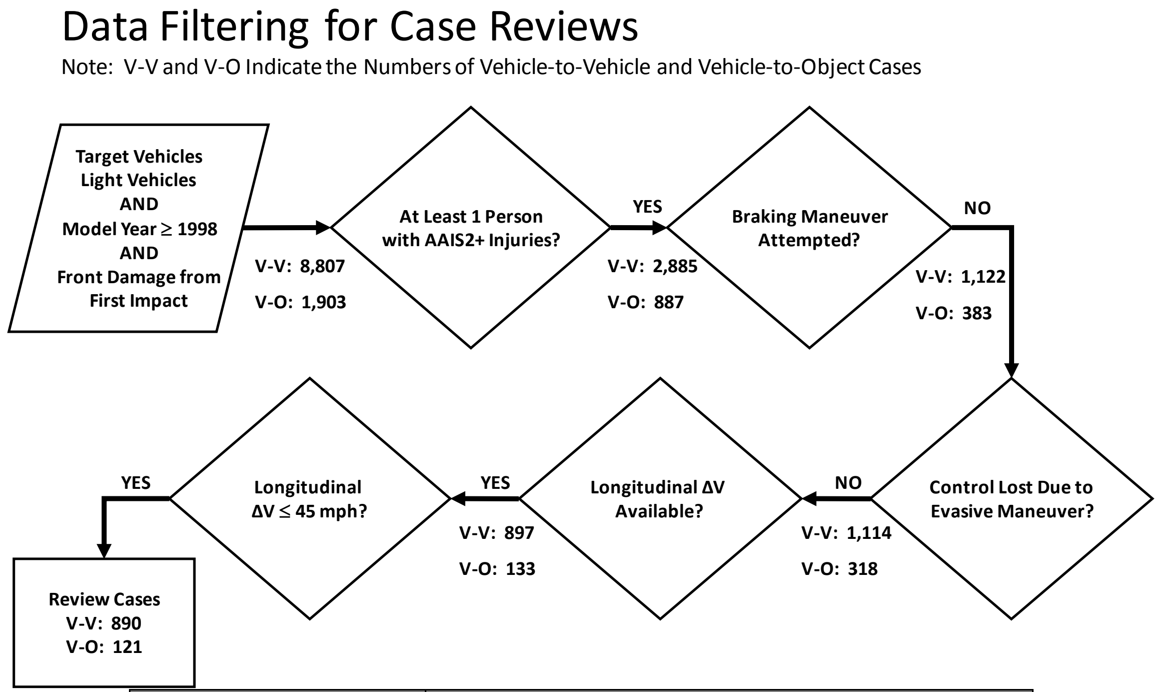
With these crash scenario priorities identified, the bottom-up analysis was then conducted, as outlined in Figure 1.

2.3 Apply Injury Severity Scale Filter to the Selected Databases

As previously described in Section 2.2, the FYL measure used for ranking the crash types is based upon AIS 2+ injuries of all persons involved in the crash with no age restriction placed on the initial data. This filter was selected based upon the key attributes of CIB system functionality. These systems mitigate crash energy severity by reducing the initial impact speed of the equipped vehicle. By reducing the initial impact speed, the severity of the entire crash sequence is reduced. Therefore, opportunities exist to reduce potential injuries for any persons involved in the crash, regardless of whether or not they are a passenger of the equipped vehicle. Finally, CIB systems may mitigate some of the less severe, but higher frequency, injury levels, including those associated with upper and lower extremities that can be difficult for existing restraint technologies to address.

2.4 Apply Additional Filters to Determine Predominant Crash Scenarios/Crash Elements

Figure 3 illustrates the steps taken in the data filtering process for individual case reviews. These additional filters were applied to determine the cases to be used for the bottom up analysis.



	Breakdown of Vehicle-to-Object Cases After CIB Filters Were Applied		
Object Type	Count	Weight	%
Tree	31	3,231	12%
Ground	24	15,555	58%
Structure	28	2,350	9%
Pole	38	5,878	22%
Total	121	27,014	100%

Figure 3: Data Filtering for Case Reviews

- *AIS 2+ Filter* – The project scope dictated a focus on injury-producing crashes. Thus, this filter eliminated cases with injury level below AIS2+, where CIB systems are likely to provide benefits in terms of property damage and lower-injury severity cases. This filter rather dramatically reduced the vehicle-to-vehicle cases from 8,807 to 2,885, and the vehicle-to-object cases from 1,903 to 887.
- *Braking Maneuver Attempted* – The “braking maneuver attempted” filter was used to eliminate CDS cases where the driver of the striking vehicle applied the brake before the impact with the collision partner (or struck vehicle). It should be stressed that driver braking may have occurred after a CIB system would have triggered automatic braking and that CIB systems may intervene even when the driver is braking. (Note: braking level is not available in the CDS database.) Consequently, use of this braking filter caused an underestimate of the CIB effectiveness (although it should be kept in mind that the contribution of other

related crash avoidance systems, such as Forward Collision Warning (FCW) and Panic Brake Assist (PBA), counteract this underestimation effect).

- *Control Loss Due to Evasive Maneuver* – This filter removed cases where loss of vehicle control occurred since such control loss could alter CIB system performance if vehicle stability control had already applied the brakes. Only 73 cases were removed for this reason (based on screening the "Pre-Impact Stability" variable in NASS).
- *Longitudinal* ΔV – Cases where ΔV was estimated to be 45 mph or higher, or if ΔV was unavailable, were excluded from further consideration. The former cases were eliminated based on the assumption that the CIB system would not have ultimately changed the societal harm outcome of the crash. Cases where ΔV were unavailable were eliminated since such cases could not be used in determining the effectiveness associated with a CIB system reducing impact speed (i.e., ΔIS) and, therefore, ΔV.

2.5 Identify Predominant Crash Factors for Maximum Harm Reduction from Crash Databases

The crash scenarios identified earlier in the top-down analysis were examined in greater detail and were ranked based on the number of FYL. After applying the filters noted In Section 2.4, a series of cases were identified for each crash scenario.

A bottom-up analysis of these identified crash cases from the CDS/NASS case database was completed to determine the predominant crash factors and crash elements. CDS/NASS cases were identified from 1998 to 2006 model years that fit the crash scenario types. In the case of pedestrians, the NHTSA PCDS was utilized for case analysis, which covers pedestrian crashes from 1994 through 1998. (Note: although cyclists were considered in the top-down analysis using NASS, the case data in the PCDS does not include data for cyclists.)

One of the key determinations in the bottom-up analysis was whether or not a CIB system could address a given case by affecting the crash outcome. The term used for capturing this system functionality was "CIB applicability," meaning the CIB system could potentially be effective at reducing impact speed and thus have a positive impact on injury outcome in the crash. First, Volpe analyzed each case to determine if a CIB system could affect the outcome of a crash case using a decision algorithm. Second, the CIB TMT also examined each crash case to determine CIB system applicability. Third, a comparison was made between the Volpe results and the CIB TMT results to determine whether or not the two independent analyses matched.

Once the bottom-up analysis was complete, a more thorough understanding of crash factors was achieved. The crash factors determined from the case analysis are presented below.

- Topography of crash scenes, object impacted, delta impact speed (ΔIS)
- Pre-crash braking of vehicles less than 10,000 pounds

- Timing factors of crash sequence (i.e., Time to Collision (TTC))
- Vehicle trajectory (pre-event maneuver) and frontal crash mode

The above summary of predominant crash factors influenced the selection of the appropriate pre-crash sensors and CIB braking functions for this project. These factors were taken into account when establishing performance metrics and functional requirements, which will now be described in Sections 2.6 and 2.7.

2.6 Development of Preliminary Functional Requirements

This section of the report describes the development of the preliminary functional requirements for CIB systems needed to address the priority crash scenarios identified above. The preliminary functional requirements are based upon a combination of statistical analysis of the crash data from the top-down analysis, the detailed case review data generated during the bottom-up analysis, and computer simulations of the most typical pre-crash events associated with the priority crash scenarios. These preliminary functional requirements are combined with CIB system technology data described in Chapter 3 to establish the technical specifications for the project test vehicle build combinations, referred to as PIP vehicles. These vehicles were then used during the development of the test procedures and benefits estimation methods for the remainder of the project.

2.7 Establish Performance Metrics for Crash Severity and Injury/Harm Reduction

Preliminary performance metrics were crafted for crash severity and injury reduction under the identified crash conditions from the filtered NASS-CDS database. This required development of surrogate metrics, such as measuring the reduction in impact velocity which then leads to injury mitigation. Understanding the predominant crash factors and crash elements of these cases assisted in the identification of the pre-crash sensors and braking systems capable of meeting the established performance metrics. As part of this effort, a crash scenario simulation tool was utilized to re-create crash scenarios. The simulation results were then used to analyze the effectiveness of multiple pre-crash sensor types. The crash scenario simulation tool provided an objective means to assess crash scenario dynamics and parameter limitations needed for test method development and initial system performance specifications.

The simulations were conducted in phases using selected NASS-CDS cases from the bottom-up analysis spreadsheets described in Section 2.5. Case simulations were completed for the priority scenarios identified in the major crash categories, including Vehicle-to-Vehicle (V-V), Vehicle-to-Object (V-O), and Vehicle-to-Pedestrian (V-P) crashes. There were a total of 14 scenarios, also referred to as archetypal models, identified for the crash scenario simulation work. The NASS-CDS case selected for each archetypal model was screened for reliable impact speed values, a well-constructed scene diagram with accurate scaling factor, clear scene photos, and a representative but not overcrowded scene environment. As shown in Table 3, eight simulations were required out of the 14 scenarios. Table 3 shows the simulation number that corresponds to the archetypal model and NASS-CDS case ID.

The order of the simulation shown in Table 3 does not reflect the prioritization of crash scenarios with respect to the FYL. This simulation work started with a straightforward model, the Rear End scenario, as a learning exercise. This preliminary simulation enabled the investigation of the features, functions and capabilities of the tool.

Table 3: Simulation Listing for Selected Archetypal Models

Simulation	Scenario	Archetypal Model			NASS-CDS case ID
		Type	Identifier.	Description	
1	1	V-V	RE-LVS	Rear End Lead Vehicle Stop	2004-12-007
	2	V-V	RE-LVM	Rear End Lead Vehicle Moving	
	3	V-V	RE-LVD	Rear End Lead Vehicle Decelerating	
2	4	V-V	RE-CI	Rear End Cut In	1999-11-196
3	5	V-V	LTAP-OD	Left Turn Across Path Opposite Direction	2005-12-217
4	6	V-V	SCP	Straight Crossing Path	2004-76-085
5	7	V-V	LTAP-LD	Left Turn Across Path Lateral Direction (Turning)	2004-12-012
6	8	V-V	OD	Opposite Direction	2006-82-004
7	9	V-P	P-IP	Pedestrian In Path	1997-90-628
	10	V-P	P-CP	Pedestrian Cross Path	
8	11	V-O	n/a	Pole	2004-43-355
	12	V-O	n/a	Structure	
	13	V-O	n/a	Tree	
-	14	V-O	n/a	Ground	eliminated

2.7.1 Methodology of the Crash Scenario Simulation Tool

The crash scenario simulation tool is made up of three main modules. The modules consist of the Pre-Processor, the Visualization Server, and the Run-time Environment. Figure 4 shows the features and functions that are built into each module. The crash scenario simulation tool provides a guideline to build an experimental model of a crash scenario. The building or developing of the experimental simulation model executes the following steps: 1) build scenarios, 2) add control system, 3) model the sensor systems, and 4) run the simulation. This is a highly simplified portrayal of the sequence but provides an overview of the steps needed to perform the crash scenario simulation and analysis.

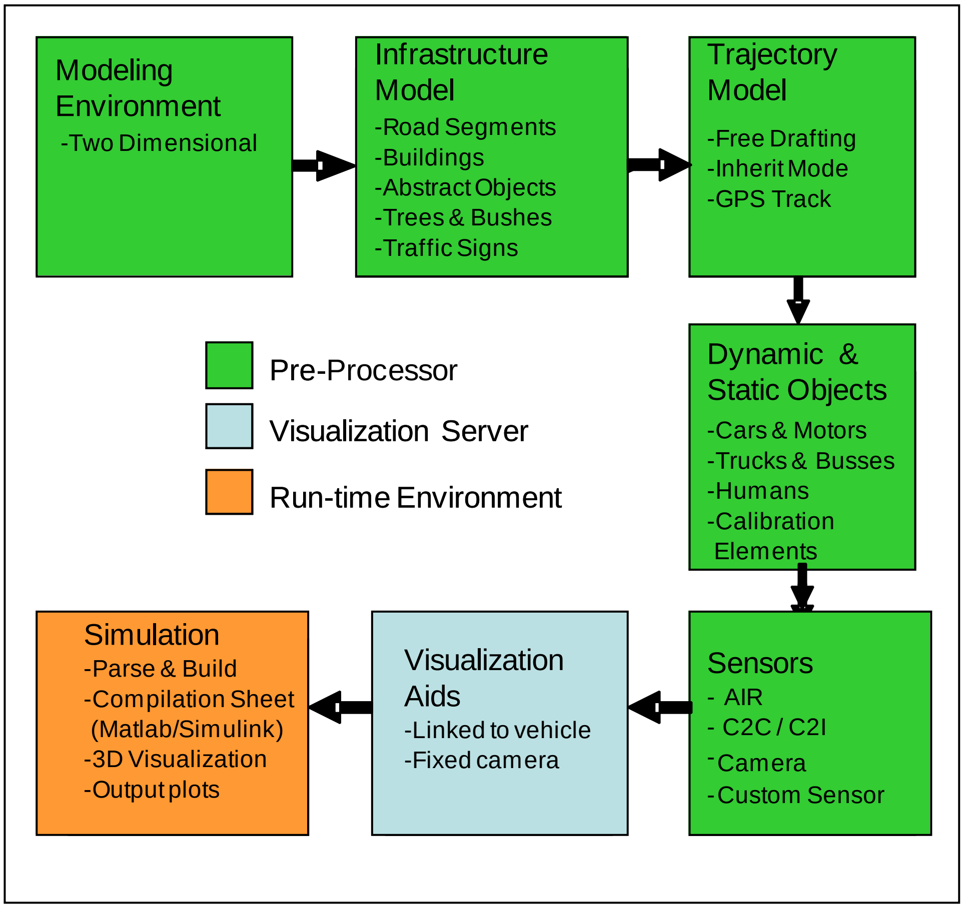


Figure 4: Crash Scenario Simulation Tool Building Blocks

Table 4 summarizes the desired performance metrics output for the simulations conducted. The majority of the models were run more than once in order to converge to a detection range and field of view (FoV) that appropriately detects the struck vehicle or object for each crash scenario. The less complicated models were run only once simply to confirm the prescribed parameters. Comments were added next to each run to describe whether the FoV resulted in an undetectable, marginal, desired, or excessive detection condition. Here, an excessive detection condition refers to a larger FoV than is actually necessary to detect the target given the scenario conditions.

Table 4: Summary of Simulation Models and Desired Performance Metrics

Simu-lation	Archetypal Model	Closing Speed, km/h (*mph*)		Run No.	Detection Range, m	FoV, deg	Comments
		Striking	Struck				
1	RE-LVS	72 (*45*)	0	1	50	15	**Desired**
				2	50	30	Excessive
2	RE-CI	80 (*50*)	56 (*35*)	1	50	15	**Desired**
				2	50	30	Excessive
3	LTAP-OD	72 (*45*)	21 (*13*)	1	50	15	Undetectable
				2	50	30	Marginal
				3	50	60	**Desired**
				4	50	90	Excessive
4	SCP	62 (*39*)	14 (*9*)	1	50	15	Marginal
				2	50	30	**Desired**
5	LTAP-LD	56 (*35*)	32 (*20*)	1	50	15	Undetectable
				2	50	30	Marginal
				3	50	60	**Desired**
6	OD	84 (*52*)	26 (*16*)	1	50	15	Marginal
				2	50	30	**Desired**
7	P-IP	58 (*36*)	5 (*3*)	1	50	15	**Desired**
	P-CP	58 (*36*)	10 (*6*)	1	50	15	Marginal
				2	50	30	**Desired**
8	Tree	43 (*27*)	0	1	50	15	**Desired**

2.8 Time to Collision (TTC) Discussion

Time-to-collision refers to the time it would take for a collision to occur at the prevailing speeds, distances, and trajectories associated with the driver's vehicle and the closest lead vehicle (van der Horst, 1990).One of the key metrics in CIB systems is determining when application of the brakes is warranted. The actuation of the brakes will be based upon an algorithm decision from the pre-crash sensing system after sensing a valid target in the vehicle path of motion. Autonomous braking can take place without any driver intervention in order to reduce impact speed and crash energy in the imminent crash. The time before impact at which to apply the brakes can be characterized by TTC and the amount of impact speed reduction to be achieved. For vehicle-to-vehicle collisions, the

TTC is a function of the striking vehicle velocity (V_s), the striking vehicle acceleration (a_s), and the struck or target vehicle velocity (V_t) and its acceleration (a_t). For vehicle-to-object collisions, the TTC is a function of the striking vehicle velocity (V_s), and its acceleration (a_s), since the struck or target object's velocity (V_t) and acceleration (a_t) are zero.

For the scope of the CIB Project, autonomous application of the brakes was considered to occur after a "point of no return" is reached where either braking or steering to avoid the collision would not be possible for the vehicle operator. Defined here is the time-based parameter "time to crash imminent" (T_{CI}) at which the point of no return is reached. T_{CI}, therefore, is the time at which the crash unavoidable state is reached. Because the total time to stop a moving vehicle includes t_a which encompasses the driver reaction time to apply brake (or steer for that matter), the time T_{CI} includes driver reaction time as well. T_{CI}, the crash imminent time is the minimum time the vehicle operator can either "steer-to-avoid" or "decelerate-to-avoid" a collision depending on which driver input is available. The CIB Project assumes that the driver has steering and braking available to avoid the crash. T_{CI} includes the driver reaction time to recognize the target and take evasive action by braking or steering. Figure 5 provides a pictorial representation of the crash imminent braking timing, and shows examples of time needed to reduce impact speed by 5, 10 and 15 mph. Application of the CIB system to reduce impact speed must occur earlier to achieve a higher level of impact speed reduction.

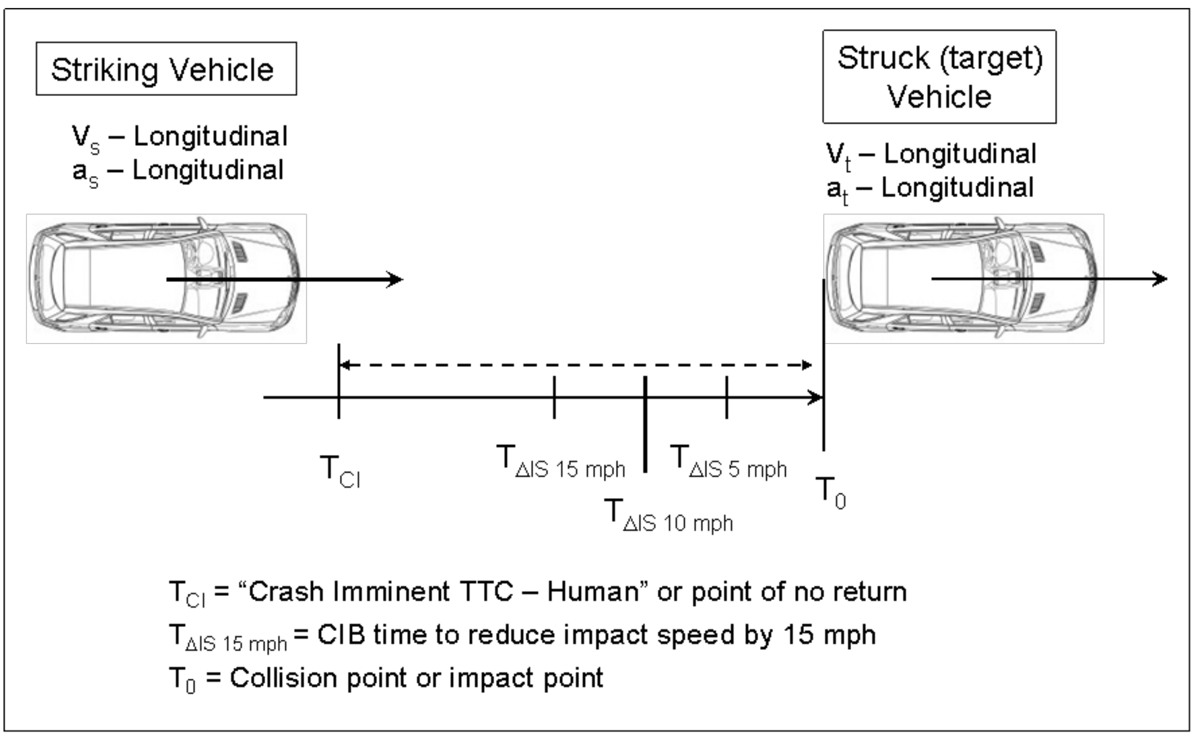


Figure 5: Time to Collision Nomenclature Diagram

It is important to briefly illustrate the relationship between steering and braking to avoid a crash. The minimum time to avoid a crash will be a function of the range to the target and the closing speed or range rate as well as the relative acceleration between the striking and struck vehicles. Based upon work by Fujii (2005), the minimum steering distance and minimum braking distance to avoid collisions were plotted (see Figure 6). Steer-to-avoid approach is best in driving situations with high relative velocity (closing speed) and high relative distance. In driving situations with low relative velocity and low relative distance, a decelerate-to-avoid approach would be more advantageous in terms of the amount of time available to take an action. In either case, the calculation for the minimum steer and minimum brake distance or TTC must be calculated in order to determine when the autonomous braking system should be triggered.

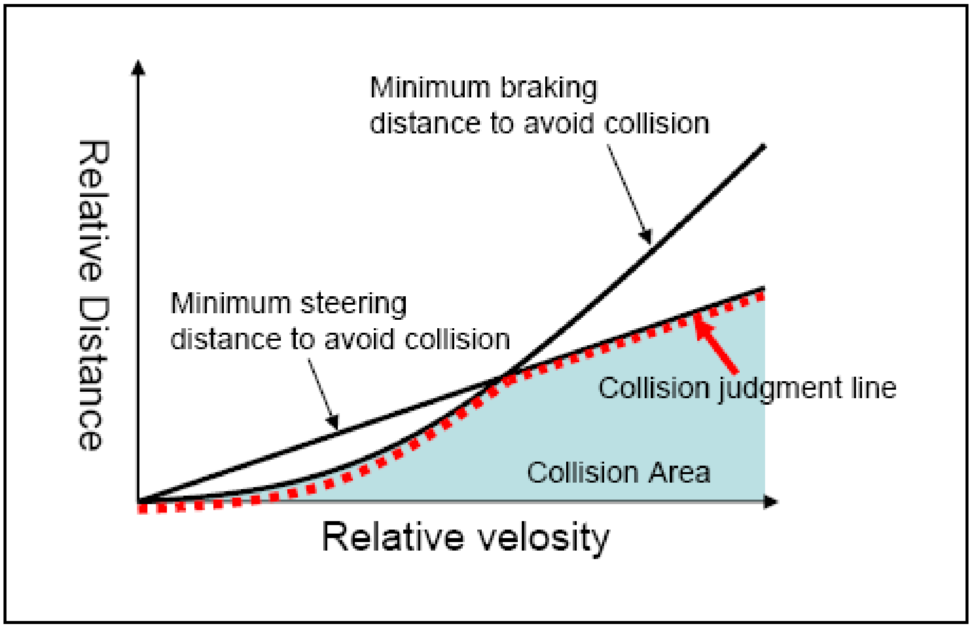


Figure 6: Steer-to-Avoid and Decelerate-to-Avoid Usage Areas (Fujii, 2005)

Thus, the CIB system must take into account the minimum braking distance (or time) and the minimum steering distance (or time) to avoid a collision before application of autonomous braking. The systems may also take into account the amount of autonomous braking level for the decision to be activated at a certain TTC. With a reduced deceleration level, the system may be activated earlier than T_{CI} because the crash is still avoidable by steering. These calculations must incorporate assumed human reaction times, system response time (e.g., for braking this is deceleration build time), and the period over which the deceleration occurs once the system reaches roughly a steady state. Depending upon the change in impact speed required, the autonomous brake system can be applied at times between T_{CI} and at deceleration levels below or at maximum vehicle deceleration.

2.9 Develop Preliminary Functional Requirements for Crash Imminent Braking Systems Based on Performance Metrics

The work described in the previous sections was used to determine a preliminary set of functional requirements. These preliminary requirements were used as a starting point for discussion of proposed system specifications and were further refined as more information became available during the subsequent tasks. The target scenarios were selected and recreated in the crash scenario simulation tool environment described in Section 2.7. These simulations, along with analysis of available crash data, were used to determine a range of proposed kinematic values that represented at least 90% of each of the different scenarios surveyed (see Tables 5 and 6).

Table 5: Performance Metrics for Vehicle-to-Vehicle Crashes

Vehicle-to-Vehicle		Target Size	Target Impact Trajectory	Struck Vehicle Lateral Velocity Relative to zero azimuth angle of striking vehicle	Pre Impact Trajectory Relationship (deg) Relative to zero azimuth angle of striking vehicle
1	Rear End -LVS	Motorcycle to Heavy Truck	F-B	0	0
2	Rear End -LVM	Motorcycle to Heavy Truck	F-B	0	0
3	Rear End - LVD	Motorcycle to Heavy Truck	F-B	0	0
4	Rear End - Cut in	Motorcycle to Heavy Truck	F-B	< 16 km/h (10mph)	up to 30
5	LTAP - OD	Motorcycle to Heavy Truck	F-F & F-S	8 – 32 km/h (5 – 20mph)	up to 90
6	LTIP/RTIP / LTAP-LD	Motorcycle to Heavy Truck	F-B & F-S	8 – 32 km/h (5 – 20mph)	up to 90
7	SCP	Motorcycle to Heavy Truck	F-S	8 – 72 km/h (5 – 45mph)	up to 90
8	OD	Motorcycle to Heavy Truck	F-F	< 16 km/h (10mph)	180

Notes:

- Definitions: RCS = radar cross section; F-B = front to back; F-S = front to side; F-F = front to front
- Zero azimuth angle is the longitudinal vehicle axis of the striking vehicle
- Table provided by the Volpe National Transportation Systems Center for the analyses conducted in the CIB Project

Table 6: Performance Metrics for Vehicle-to-Object and Vehicle-to-Pedestrian Crashes

Vehicle to Object	Target Size	Target Impact Trajectory	Struck Object Lateral Velocity Relative to zero azimuth angle of striking vehicle	Pre Impact Trajectory Relationship (deg) Relative to zero azimuth angle of striking vehicle
1. Pedestrian or Cyclist – in path	>30.8kg (68lb); >121.9cm (48in)	Front	0	0
2. Pedestrian or Cyclist – crossing path	>30.8kg (68lb); >121.9cm (48in)	Front	< 41.8km/h (26mph)	up to 90
3. Tree	≥ 10.2cm (4in), within one lane of paved roadway	Front	0	0
4. Pole	≥ 10.2cm (4in), within one lane of paved roadway	Front	0	0
5. Ground	Eliminated	n/a	n/a	n/a
6. Structure	Traffic barriers, impact attenuator, and guardrail	Front	0	0

Notes:

- Zero azimuth angle is the longitudinal vehicle axis of the striking vehicle
- Table provided by the Volpe National Transportation Systems Center for the analyses conducted in the CIB Project

At this point in the project, the relationship between injury reduction potential and system performance had not yet been determined. Further, for any desired system performance level, several trade-offs can be made between braking and sensor performance. In order to determine this preliminary set of CIB sensing system requirements, a set of system performance characteristics were chosen which define an amount of speed reduction to be achieved, and the rate of host vehicle deceleration representative of the current state-of the-art. An aggressive experimental braking system performance level was chosen for the preliminary experimental CIB system in order to minimize the range at which the object sensing system would need to detect and react. The approach, shown in Table 7, will allow for future evaluation of the trade-off between sensor capabilities and braking performance requirements.

Table 7: CIB Experimental System Capability

CIB System Parameter	Value
Speed Reduction	16 km/h (10mph)
Deceleration	0.9 g
Deceleration Build Rate	1.5 g/sec

Given these preliminary characteristics for an experimental CIB system, basic CIB Sensing System capabilities were chosen based solely on what is required to achieve the preliminary speed reduction value. The preliminary CIB functional requirements are shown in Tables 8 and 9.

Table 8: Preliminary Functional Requirements for Vehicle-to-Vehicle Crashes

Vehicle-to-Vehicle Crash Type	Sensing Range min	Sensing FOV min (Deg)	Closing Speed Max	CIB TTC ΔIS=16 km/h (sec)	CIB Decel Build Rate (g/sec)	Max Decel (g)
1. Rear End - LVS	25m	+/-7.5	65km/h (40mph)	0.72	1.5	0.9
2. Rear End - LVM	25m	+/-7.5	65km/h (40mph)	0.72	1.5	0.9
3. Rear End - LVD	25m	+/-7.5	65km/h (40mph)	0.72	1.5	0.9
4. Rear End - Cut in	25m	+/-7.5	65km/h (40mph)	0.72	1.5	0.9
5. LTAP — OD	30m	+/-30	80km/h (50mph)	0.72	1.5	0.9
6.LTIP/RTIP / LTAP-LD	35m	+/-30	90km/h (56mph)	0.72	1.5	0.9
7. SCP	25m	+/-15	65km/h (40mph)	0.72	1.5	0.9
8. OD	55m	+/-15	150km/h (93mph)	0.72	1.5	0.9

Notes:

- CIB TTC - defined as the crash imminent braking or autonomous braking system – no human element
- Minimum target acquisition time (detect / classify) 600 msec
- Definitions: FOV = Field of view; ΔIS = delta impact speed or velocity reduced by CIB
- Table provided by the Volpe National Transportation Systems Center for the analyses conducted in the CIB Project

Table 9: Preliminary Functional Requirements for Vehicle-to-Object and Vehicle-to-Pedestrian Crashes

Vehicle to Object	Sensing Range min.	Sensing FOV min. (deg)	Impact Speed Max	CIB TTC ΔIS=16km/h (sec)	CIB Decel Build Rate (g/sec)	Max Decel (g)
1. Pedestrian or Cyclist – in path	30m	+/-7.5	72km/h (45mph)	0.72	1.5	0.9
2. Pedestrian or Cyclist – crossing path	30m	+/- 30	72km/h (45mph)	0.72	1.5	0.9
3. Tree	30m	+/-7.5	80km/h (50mph)	0.72	1.5	0.9
4. Pole	30m	+/-7.5	80km/h (50mph)	0.72	1.5	0.9
5. Ground	Eliminated	n/a	n/a	--	--	--
6. Structure	25m	+/-7.5	57km/h (35mph)	0.72	1.5	0.9

Notes:

- Struck object longitudinal velocity = 0; All cases above.
- CIB TTC - defined as the crash imminent braking or autonomous braking system – no human element.
- Minimum target acquisition time (detect / classify) 600 msec.
- Definitions: FOV = Field of view; ΔIS = delta impact speed or velocity reduced by CIB
- Table provided by the Volpe National Transportation Systems Center for the analyses conducted in the CIB Project

This initial set of requirements identified minimum sensor/system performance thought to be required in order for the CIB system to perform its intended functions. The resulting specification is not sufficient to prevent unintended system activations (false events) or to define the system reliability. These requirements were to be determined later and are discussed in Chapter 4.

3 Development of Countermeasure Candidates

In this Section, efforts to identify, develop, and evaluate candidate CIB systems and test vehicles will be described. This equipment was used for the development of the required test plans (discussed in Section 4). The development work began with a thorough investigation and analysis of existing or near-term-deployable CIB systems. This effort supported the definition of technologies and the development of initial minimum performance requirements.

3.1 Conduct Technology Survey

A survey of available CIB system technologies provided the first step in selecting the CIB system configurations and preliminary functional requirements that were later used in the PIP vehicles and for test method development. To support this development, key, automotive, forward-looking sensor suppliers were contacted requesting an assessment of the performance capabilities of their sensing technologies in the priority crash modes identified in Chapter 2. A cover letter (presented in Appendix A) described the objectives of the CIB Project, which was accompanied with a four page survey form. The survey questionnaire is presented in Appendix B. This survey document included a page for high-level system configuration, performance and constraint descriptions, as well as three pages for specific sensor system characteristics. Sensor suppliers were encouraged to provide non-proprietary information regarding current production and near-term deployable systems that would assist in the definition of performance requirements and objective test procedures for CIB systems.

The technology data collected from the surveys was compiled and a comprehensive list of potential countermeasure technology ideas that are hardware-ready and capable of vehicle integration was prepared. Table 10 and Table 11 presents survey results from six supplier surveys. Table 11 provides a breakdown of survey respondents in terms of Radar, LIDAR (i.e., LIght Detection And Ranging) and Camera categories and the number of sensor technologies available.

Table 10: Crash Modes Potentially Detected by Technology Identified

	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6
Vehicle-to-Object and Vehicle-to-Pedestrian Crashes:						
Pedestrian	yes	yes	yes	yes	yes	no
Pole/Tree	unknown	yes	yes	no	yes	yes
Road Side Structure	yes	yes	unknown	no	yes	yes

	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6
Vehicle-to-Vehicle Crashes:						
Opposite Direction – Front-to-Front	yes	yes	yes	yes	yes	yes
Rear End – Front-to-Back	yes	yes	yes	yes	yes	yes
Left Turn Across Path / Opposite Direction	yes	yes	yes	yes	yes	unknown
Straight Crossing Path	yes	yes	yes	unknown	yes	yes

Table 11: Summary of Technology Survey Responses

	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6
Radar Data (#)						
Short Range (<10m)	0	1	0	0	0	0
Mid Range (<60m)	0	0	1	0	0	0
Long Range (>100m)	0	1	1	0	0	1
Combination	0	1	0	0	0	0
LIDAR data (#)						
Short Range (<10m)	0	1	0	0	0	0
Mid Range (<60m)	0	0	0	0	0	0
Long Range (>100m)	0	0	0	0	0	0
Combination	0	0	0	0	0	0
Camera Data (#)						
Mono	0	1	1	2	0	0
Stereo	1	0	0	0	1	0
Fusion of Technologies	0	0	1	0	0	0

When the CIB system determines that brake activation is required, the proper signal must be sent to the electronic brake controller. In addition to the surveys, brake actuator options were added by the CIB Consortium Participants as shown in Table 12 below.

Table 12: Braking Technologies and Their Relative Response Times

Braking Technology	Relative Response Time
Active Vacuum Booster	Medium
Hydraulic Accumulator	Short
Hydraulic Pump	Medium
Other (e.g., Electric Booster, Electro-Mechanical Brakes, etc.	Short to Long

In this context, response time means the ability of the brake technology to build brake line pressure and vehicle deceleration in an amount of time (pressure per unit time). All response times are for standard temperature and pressure conditions.

The CIB system candidate list was used to develop a more detailed set of initial system and component specifications in determining initial minimum performance specifications.

3.2 Determine the Initial Minimum Performance Specifications

Analysis of crash data (Chapter 2) identified the CIB system performance parameters required to address the priority crash scenarios. Next, the technology survey, discussed above, identified available CIB technologies. This section will combine these two sets of information to arrive at an overall set of initial minimum performance specifications for the project PIP vehicles based upon both the collision scenario(s) and the available sensing and braking technology(s). The minimum performance specifications for the CIB Project's PIP vehicles are shown in Table 13.

Table 13: CIB PIP Vehicle Minimum Performance Specifications

Parameter	System Specification	Comments
Vehicle-to-Vehicle Crash Scenarios	➢ Lead Vehicle Stopped (LVS) ➢ Opposite Direction (OD) ➢ Turning – Left Turn in Path (LTIP), Right Turn in Path (RTIP) ➢ Left Turn Across Path – Opposite Direction (LTAP-OD) ➢ Straight Crossing Path (SCP)	From CIB Analysis Plan Shown in Chapter 2
Vehicle-to-Object Crash Scenarios	➢ Pedestrian ➢ Poles ➢ Trees ➢ Structure	From CIB Analysis Plan Shown in Chapter 2
Vehicle Impact Speed Reduction	Approx. 16km/h (10 mph)	Surface with a high coefficient of friction (high mu, > 0.8) such as dry concrete or dry asphalt.
Wheel Slip Control	Maintain wheel slip control on all road surfaces	Ensure ABS control works when CIB system goes active and ABS is required to prevent wheel lockup. Only test high mu condition.
Yaw Control	Maintain yaw control on split mu surfaces	All PIP vehicles will include a yaw control algorithm in the antilock brake system.
Apply CIB on Any Surface Mu	CIB active on all road conditions	CIB must work on all road conditions. On low mu, the impact speed reduction can be less than the maximum expected on a high mu surface.

As part of the analysis in Chapter 2, crash scenario priorities were defined based upon FYL. Impact speed reduction of the striking vehicle by 16 km/h (10 mph) is the preliminary target established for the priority crash scenarios. Higher or lower values of impact speed reduction were examined and 16 km/h was selected as the preliminary value when considering tradeoffs with various other factors. Taken into consideration were differing travel speeds, false detections, crash imminent times (point of no return) and the time in which a driver may be able to steer or brake to avoid an accident. Vehicle testing conducted later in the project enables a better assessment of these preliminary minimum performance specifications.

From the list of technology candidates generated from the technology survey, combinations of pre-crash sensor and brake actuator components were selected to form potential candidate CIB systems. Since there were minimal hardware interfaces between the pre-crash sensing and braking actuators, the technology was divided into pre-crash sensing and braking technology and these two components were analyzed separately.

The technology survey suggested suppliers were using three pre-crash sensing technologies: radar, vision (camera) and LIDAR (see Table 14). These systems are designated as System A, System B, etc., as shown in the tables throughout this section. In these systems, fusion between technologies is possible to bring target data together as indicated in the last two columns of Table 14. The systems presented represent logical combinations of technologies based on the CIB TMT’s experience and are designated with an alphanumeric identification. In Table 14, the letters R, L and C refer to radar, LIDAR or camera systems, respectively. The numeric code is used to distinguish separate sensors of each type (i.e., R1 refers to Radar 1, R2 for Radar 2, etc.).

Table 14: Matrix of Candidate Pre-crash Sensing Systems

Task 4.2 - Sensing System									
System	Sensing System								
	Radar				Lidar	Camera			
	Short Range	Mid Range	Long Range	Mid&Long Combo Sensor		Mono	Stereo	Sensor Fusion Req'd	Sensor Fusion Avail
A	R1[1] Range: 40m FoV: 160°								
B			R2 150m FoV: 10.2°						
C	R1[1] Range: 40m FoV: 160°		R2 150m FoV: 10.2°					Y	N
D		R3 60m FoV: 56°	Range: 200m FoV: 18°	Y					
E	R1[1] Range: 40m FoV: 160°	R3 60m FoV: 56°	Range: 200m FoV: 18°	Y				Y	N
F					L1 10m FoV: 27°				
G						C1 Res: 752 x 480 FoV: 35° * 23°			
H		R3 60m FoV: 56°	Range: 200m FoV: 18°	Y	L1 10m FoV: 27°			Y	N
I		R3 60m FoV: 56°	Range: 200m FoV: 18°	Y		C1 Res: 752 x 480 FoV: 35° * 23°		Y	Y
J					L1 10m FoV: 27°	C1 Res: 752 x 480 FoV: 35° * 23°		Y	Y
K		R3 60m FoV: 56°	Range: 200m FoV: 18°	Y	L1 10m FoV: 27°	C1 Res: 752 x 480 FoV: 35° * 23°		Y	N
L	R1[1] Range: 40m FoV: 160°	R3 60m FoV: 56°	Range: 200m FoV: 18°	Y	L1 10m FoV: 27°	C1 Res: 752 x 480 FoV: 35° * 23°		Y	N
M		R4 60m FoV: 90°	Range: 200m FoV: 20°	Y					
N						C2 Res: 640 x 480 FoV: 50°-			
O		R4 60m FoV: 90°	Range: 200m FoV: 20°	Y		C2 Res: 640 x 480 FoV: 50°-		Y	Y
P			R5 150m FoV: 30°						
Q						C3 Res: 752 x 480 FoV: 40°			
R							C4 Res: ? FoV: ?		
S							C5 480 FoV: 48°		
T		R6 Generic	Generic	Y			C6 Generic	Y	N

The matrix of candidate, pre-crash braking systems was developed based upon the braking technology available from consortium members as shown in Table 15. The project consortium includes two major automotive suppliers of electronic braking systems that have various braking actuators representative of industry "state-of-the-art." Braking actuator technology available for near-term production consists of four groups (as discussed in detail below).

Table 15: Matrix of Candidate Pre-crash Braking Systems

Task 4.2 - Braking System

System	Brake System Description
A	Active Vacuum Booster w/ auto braking algorithm
B	Hydraulic Accumulator w/ auto braking algorithm
C	Hydraulic Pump w/ auto braking algorithm
D	EHB, EMB, Electric Booster w/ auto braking algorithm
E	Active Vacuum Booster w/ pre-fill & auto braking algorithm
F	Hydraulic Accumulator w/ pre-fill & auto braking algorithm
G	Hydraulic Pump w/ pre-fill & auto braking algorithm
H	EHB, EMB, Electric Booster w/ pre-fill & auto braking algorithm
I	Active Vacuum Booster w/ pre-brake & auto braking algorithm
J	Hydraulic Accumulator w/ pre-brake & auto braking algorithm
K	Hydraulic Pump w/ pre-brake & auto braking algorithm
L	EHB, EMB, Electric Booster w/ pre-brake & auto braking algorithm

3.2.1 Brake Components

The material below describes the potential brake system options available for consideration for the project PIP vehicles.

Active Vacuum Booster: The vacuum booster provides gain in the braking system to increase output from the brake pedal and is actuated with or without driver application of the brake pedal. There are several active boosters in production today and the component is considered a near-term technology.

Hydraulic Accumulator: An element that can be added to a brake system to allow autonomous braking is a Hydraulic Accumulator, or fluid pressure accumulator. This accumulator stores hydraulic pressure in a reservoir that can be applied in an autonomous braking situation and is charged via a fluid pump or compressor, normally driven by an electric motor. Since there are hydraulic accumulator systems in production today, this brake option was considered a near-term technology.

Hydraulic Pump or Modulator: This component is defined as a brake pressure modulator. This is used in many Antilock Braking Systems (ABS) today and normally consists of an electric motor driven hydraulic pump that increases brake pressure at the start of a controlled-braking (ABS) event. This is the most readily available component since there are millions of hydraulic pumps or modulators in production today.

Other - EHB, EMB, Electric Booster: Emerging braking technologies today consist of Electric Booster, Electromagnetic Braking (EMB) and Electro-hydraulic Braking (EHB), to name a few. These systems are commonly referred to as a “brake-by-wire” braking system and are not very common in the U.S. automobile fleet. These components are not considered here as a near-term technology.

3.2.2 Brake Algorithms

Brake Pre-fill Function: This algorithm activates a controlled-braking function which provides a buildup of brake pressure that will take up brake system compliance without decelerating the vehicle. This allows a faster vehicle deceleration build rate if an autonomous braking event occurs.

Autonomous Braking: This algorithm feature will apply the brakes based upon a pre-crash sensor signal and must be capable of applying several levels of braking decelerations designated as low, medium and high.

Brake Assist: This feature builds brake pressure and decelerates the vehicle faster when the system detects the driver is applying the brake pedal in a "panic braking" situation. More advanced systems are available which incorporate forward looking sensors for additional information which can tailor the applied brake pressure. Brake Assist features were not evaluated within the scope of this project since it requires the driver to apply the brake pedal.

Pre-brake: The pre-brake function is similar to the Pre-fill feature except vehicle deceleration can be achieved.

3.2.3 Minimum Performance Specifications

The minimum performance specifications for the sensor and brake components are listed in Table 16. These specifications allow the PIP vehicles to adequately exercise the CIB test methodology. One of the main challenges for the pre-crash sensing system is to identify and classify a potential threat in a minimum amount of time. Threat is defined as an in-path vehicle or object which potentially can collide with the subject (or following) vehicle. Detecting a target, classifying the target, tracking the motion of the target and assessing the potential threat must be completed quickly to allow effective autonomous braking to occur. Another important parameter for the CIB Project is that of lateral closing speed as it relates to the predicted path of the target vehicle.

Table 16: CIB Pre-Crash Sensor Component Minimum Performance Specifications

Parameter	System Specification	Comments
Field of View	Minimum +/- 30 degrees	Wide field of view needed for crashes such as Straight Crossing Path and turning with lateral movement between vehicles
Range	> 55 meters	Worst case is the Opposite Direction crash scenario
Longitudinal Closing Speed	> 150 km/h +/- 2 km/h	Worst case is the Opposite Direction crash scenario
Lateral Closing Speed	< 72 km/h	For Straight Crossing Path-type cases
Target Acquisition Time (detect/classify)	< 0.600 sec	Time estimated – 3 samples to identify/classify and to track motion
Object Classification Categories	➢ Light Vehicle, Motorcycle ➢ Pole/Tree > 4 inches ➢ Concrete Pillar, Bridge Supports ➢ Guardrails ➢ Sign Posts ➢ Pedestrians	
Impact location	Left, center, right of front end	Goal of development systems
Approach or Impact Angle – Vehicle-to-Vehicle	< +/- 5 degrees	Goal of development systems
TTC Signal to Brake Control Module	Approximately 0.7 sec before impact	Preliminary goal of development systems
TTC Signal to Advanced Restraints Control Module	Approximately 0.5 sec before impact	Preliminary goal of development systems: 5% probability of false activation of re-settable restraints. Advanced Restraint Systems (ARS) Project requirements.
Average Deceleration Build Rate	> 1.5 g/sec	Required to achieve impact speed reduction of 16 km/h (10 mph)
Average Decel after Deceleration Build Period	0.9 g	Average deceleration assuming a high coefficient of friction surface (mu>0.8). Desired decal to prove out CIB test methods.

Information was collected from suppliers for each of the candidate CIB systems with respect to prototype component relative costs, integration complexity, and component availability lead time. A rating of low, medium and high was assigned each of the factors summarized in Table 17.

Table 17: Summary of Cost, Integration Complexity and Lead Time Ratings Used

Rating	Relative Cost	Integration Complexity	Component Lead Time
Low	Available in mass production	Mature and stable hardware and software	Component available in production today
Medium	Low volume production	Moderate hardware and software development needed	Component available by Dec. 31, 2008
High	Limited quantities available	Complex hardware and software development needed	Component not available until early 2009

As shown in Appendix C, the rating information was applied to the Matrix of Candidate Sensing Systems and the Matrix of Candidate Pre-Crash Braking Systems. This information was used as part of the sourcing decisions for building the project PIP vehicles, which were used for developing the objective test procedures and potential benefits estimation methodology. It should be noted that the information contained in Appendix C represents a snapshot in time of the industry’s capability in terms of pre-crash sensing and braking components. While CIB-related technology is improving and developing rapidly, the information was applicable for project decisions.

The candidates sensing and braking systems were developed based on the technology available from the CIB Participants. The expected ability for each system to detect and classify the listed various crash scenarios was also assessed. This information is presented in Appendix D for the sensing systems, and in Appendix E for the braking systems. “Detectable” is defined as sensing of the object, and “classifiable” is defined as sensing of the object plus determining if the object is a threat. Appendix E provides information on the ability of the braking systems to meet the performance specifications, and the ranking for the candidate braking systems (low, medium and high) corresponds to the relative performance of the system. For example, high performance reflects a short response time to build brake line pressure and vehicle deceleration, while low performance equates to a long system response time.

3.3 Evaluation and Ranking of Technology Candidates

This section focuses on the implementation of a technical methodology to rank and select the systems which were later built into the project PIP vehicles. This selection process involved defining the criteria and weighting factors for system ranking, performing computer simulations to generate data for evaluating the candidate systems, conducting the ranking process to select appropriate systems to build, and obtaining agreement with NHTSA on the selected systems. Several different types of sensing technology were considered, including LIDAR, radar (short- mid- and long-range radar and both 24 GHz and 77 GHz systems) and mono- and stereo-vision camera systems.

Criteria for evaluating the candidate CIB sensing systems were grouped based upon the following categories: 1) overall system assessment, 2) predicted performance in detecting the priority crash scenarios based on simulation results, and 3) predicted performance in classifying the priority crash events based on the data provided by the sensing suppliers. Groupings for the brake controller candidates included: 1) overall system assessment and 2) system functional performance. The defined groupings enabled a more complete ranking assessment of the candidate technologies by allowing clearer comparisons of the strengths and weaknesses of each of the systems based on the experience and engineering expertise of the CIB TMT.

The Pugh Analysis tool was selected for rank ordering candidate CIB systems. Pugh Analysis (Pugh, 1996; Taguchi et al., 2004) is a tool from the Design for Six Sigma process used for rank ordering potential design options. This tool provides a method of collectively evaluating subjective and objective assessment criteria. Data from efforts described in previous subsections was incorporated into the Pugh Analysis. The potential candidates and assessment criteria are then combined into a matrix format. Within each of the matrices, one candidate sensing system and one candidate brake system is designated as the 'DATUM.' The datum is a baseline candidate system selected either as an existing design or as a potential 'best case' based on engineering judgment. It is against this datum that all other candidate systems are compared during the Pugh Analysis process. Systems which are expected to perform significantly better than the datum for a given assessment criteria are given a '+' for that cell. Systems which are expected to perform significantly worse than the datum receive a '-' for that cell. 'S' is entered where a system is expected to perform about the same as the datum. Subtotals under each group of assessments are generated for comparison of the candidate sensing systems and brake systems, respectively, with a grand total included at the bottom of the matrix.

Weighting factors are not typically used during an ideal Pugh Analysis. This is done to avoid skewing of the assessment to a predetermined preferred system. Instead, in cases where two or more systems result in similar rankings, weighting factors may be employed strictly to break a tie between systems which ranked very closely to each other.

As shown in Table 18, the overall assessment criteria groupings included the factors associated with integrating these systems into the PIP development vehicles. These factors include the cost, integration complexity, interface factors and timing factors. Also included in the sensing system criteria is an assessment of fusion algorithm risk. This assessment refers to the availability of fusion algorithms when required for combinations of different sensing technologies. This distinction is important since the scope of the CIB Project does not allow for the development of new CIB technologies, including fusion algorithms.

One of the key attributes to pre-crash sensing systems is the ability of the system to not only detect a target but to determine the target's classification. Target classification is important due to its value in discriminating between threatening and non threatening targets. The computer simulation analyzing pre-crash sensing system capabilities for "detection" of a target, as documented in Chapter 2, was employed. For analyzing pre-crash sensing system capabilities for "classification" of a target sensor, component data from the supplier technology survey (as described in Section 3.1) was used.

The assessment groupings for evaluating sensing system candidates shown in Table 18 include 'Ability to Detect' and 'Ability to Classify' across various targets and conditions. The 'Ability to Detect' refers to the candidate systems' abilities to identify that a potential target is present. The 'Ability to Classify' refers to the candidate systems' abilities to correctly categorize a specific target type and condition in order to take an appropriate response action. The 'Functional Performance' section of the assessment criteria for braking systems includes factors identified within the minimum performance specifications (as defined earlier in this chapter). These factors include the brake controller capabilities needed within the PIP development vehicle systems for developing and validating functional performance tests for CIB systems.

After defining the assessment criteria for selecting candidate sensing systems for the PIP vehicles, subjective weighting factors were then assigned to the sensing system. It should be noted that these weighting factors were used strictly to aid in the assessment of systems which ranked very closely to each other. Table 18 contains the criteria and the weighting factors assigned to each of the candidate sensing systems. The lower section of Table 18 contains the matrix used to rank the 22 candidates in terms of their ability to classify targets based upon the pre-crash sensing components making up the system.

A conference call was conducted on July 16, 2008 with NHTSA to explain the proposal of using Pugh Analysis as the ranking method for evaluating candidate CIB system configurations. This analysis method was approved by NHTSA and the initial system rankings were completed as presented in Table 18. System I, consisting of a combination mid- and long-range radar sensor plus a mono-vision camera, was selected as the Datum.

The final step of Pugh Analysis involves conducting a confirmation run to verify the results of the initial selection process. For the confirmation run the highest ranking system, System T, was selected as the new datum. (Any low-ranking systems were eliminated from this step since they will not affect the results and in order to simplify the confirmation evaluation). The Pugh Analysis is then repeated and if a different candidate system arises as a higher ranking system, then this new Datum is confirmed as the preferred system choice. As shown in Table 19, the detailed Pugh evaluation resulted in all remaining systems being similar to the datum. This completed the sensing system analysis.

Table 18: Completed Pugh Analysis for Candidate CIB Sensing Systems

			System																					
	Assessment	**Weight**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**
Overall	Relative cost	3	+	+	+	+	+	+	+	+		+	S	S	+	+	S	+	+	+	+	S	S	S
	Package size	1	+	+	S	+	+	+	+	S		S	-	-	+	+	S	+	+	+	+	S	S	S
	Electrical/communication interface	3	+	+	S	+	S	+	+	S		S	-	-	+	+	S	+	+	+	+	S	S	S
	Compatibility with data acquisition system	5	S	S	S	S	S	S	S	S		S	S	S	S	S	S	S	S	S	S	S	S	S
	Technical support from supplier	3	S	S	S	S	S	S	S	S		S	S	S	S	S	S	S	-	-	S	-	-	-
	Mechanical interface with vehicle	1	+	+	S	+	S	+	+	S		S	-	-	+	+	S	+	+	+	+	S	S	S
	Fusion algorithm risk	5	+	+	-	+	-	+	+	-		S	-	-	+	+	S	+	+	+	+	-	S	S
	Production field expertise/technical maturity	3	-	+	-	S	-	+	S	S		S	-	-	S	+	S	S	-	-	-	-	-	-
	Component lead time	3	+	+	+	S	S	+	+	S		+	S	S	S	+	S	S	S	S	S	S	S	S
	Variation in range measurement	1	-	S	S	S	S	-	-	S		S	+	+	S	-	S	S	-	-	-	S	S	S
	Variation in range rate measurement	1	S	S	S	S	S	-	-	S		-	S	S	S	-	S	S	-	-	-	S	S	S
	Variation in field of view (FOV) measurement	1	-	-	-	-	-	S	S	S		S	S	S	-	S	S	-	S	S	S	S	S	S
	Environmental performance	1	S	S	S	S	S	-	-	S		-	S	S	S	-	S	-	-	-	-	S	S	S
	Working relationship w/CIB Technical Team	3	S	S	S	S	S	S	S	S		S	S	S	S	S	S	-	-	-	S	S	S	S
	Σ +		6	7	2	5	2	7	6	1		2	1	1	5	7	0	5	5	5	5	0	0	0
	Σ -		3	1	3	1	3	3	3	1		2	5	5	1	3	0	3	6	6	4	3	2	2
	Σ S		5	6	9	8	9	4	5	12		10	8	8	8	4	14	6	3	3	5	11	12	12
Ability to DETECT (based upon PreScan)	V-to-O: Pedestrian cut-in	3	S	-	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-O: Pedestrian in-path	3	S	S	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-O: Tree	1	S	S	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-O: Pole	1	S	S	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-O: Roadside structure	1	S	S	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Rear end, lead vehicle stopped	5	S	S	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Rear end, lead vehicle moving	5	S	S	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Rear end, lead vehicle decelerating	5	S	S	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Rear end, cut-in	5	S	-	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Left turn across path (LTAP), opposite direction	3	-	-	-	S	S	-	S	S	DATUM	S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: LTIP/RTIP/LTAP, lateral direction (turning)	3	-	-	-	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Straight crossing path	5	S	S	S	S	S	S	S	S		S	S	S	+	S	+	S	S	-	S	S	-	-
	V-to-V: Opposite direction	5	-	-	-	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	Σ +		0	0	0	0	0	0	0	0		0	0	0	1	0	1	0	0	0	0	0	0	0
	Σ -		3	5	3	0	0	12	0	0		0	0	0	0	0	0	0	0	13	0	0	13	13
	Σ S		10	8	10	13	13	1	13	13		13	13	13	12	13	12	13	13	0	13	13	0	0
Ability to CLASSIFY (based upon surveys)	V-to-O: Pedestrian cut-in	3	-	-	-	-	-	-	S	S		S	S	S	-	S	S	-	S	-	S	S	-	-
	V-to-O: Pedestrian in-path	3	-	-	-	-	-	-	S	S		S	S	S	-	S	S	-	S	-	S	S	-	-
	V-to-O: Tree	1	-	-	-	-	-	-	S	S		S	S	S	-	-	-	-	-	-	S	S	-	-
	V-to-O: Pole	1	-	-	-	-	-	-	S	S		S	S	S	-	-	-	-	-	-	S	S	-	-
	V-to-O: Roadside structure	1	-	-	-	-	-	-	S	S		S	S	S	-	-	-	S	-	-	S	S	-	-
	V-to-V: Rear end, lead vehicle stopped	5	S	S	S	S	S	S	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Rear end, lead vehicle moving	5	S	S	S	S	S	S	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Rear end, lead vehicle decelerating	5	S	S	S	S	S	S	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Rear end, cut-in	5	S	S	S	S	S	S	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Left turn across path (LTAP), opposite direction	3	S	-	S	S	S	-	-	S		-	S	S	S	S	S	-	S	-	S	S	-	-
	V-to-V: LTIP/RTIP/LTAP, lateral direction (turning)	3	S	-	S	S	S	-	-	S		-	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Straight crossing path	5	S	S	S	S	S	-	-	S		-	S	S	S	S	S	S	S	-	S	S	-	-
	V-to-V: Opposite direction	5	-	S	S	S	S	-	S	S		S	S	S	S	S	S	S	S	-	S	S	-	-
	Σ +		0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0
	Σ -		6	7	5	5	5	9	3	0		3	0	0	5	3	3	5	3	13	0	0	13	13
	Σ S		7	6	8	8	8	4	10	13		10	13	13	8	10	10	8	10	0	13	13	0	0
	TOTAL: Σ +		6	7	2	5	2	7	6	1		2	1	1	6	7	1	5	5	5	5	0	0	0
	TOTAL: Σ -		12	13	11	6	8	24	6	1		5	5	5	6	6	3	8	9	32	4	3	28	28
	TOTAL: Σ S		22	20	27	29	30	9	28	38		33	34	34	28	27	36	27	26	3	31	37	12	12

Pugh Analysis Key

- = Much Worse than Datum

S = About the Same as Datum

+ = Much Better than Datum

Table 19: Completed Pugh Analysis for Candidate CIB Sensing Systems Following Confirmation

		System																					
Assessment	**Weight**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**
Relative cost	3			+	+				+	S						S				+			
Package size	1			S	+				S	S						S				+			
Electrical/communication interface	3			S	+				S	S						S				+			
Compatibility with data acquisition system	5			S	S				S	S						S				S			
Technical support from supplier	3			S	S				S	S						S				S			
Mechanical interface with vehicle	1			S	+				S	S						S				+			
Fusion algorithm risk	5			S	+				S	+						+				+			
Production field expertise/technical maturity	3			S	+				+	+						+				S			
Component lead time	3			+	S				S	S						S				S			
Variation in range measurement	1			S	S				S	S						S				-			
Variation in range rate measurement	1			S	S				S	S						S				-			
Variation in field of view (FOV) measurement	1			-	-				S	S						S				S			
Environmental performance	1			S	S				S	S						S				-			
Working relationship w/CIB Technical Team	3			S	S				S	S						S				S			
Σ +				2	6				2	2						2				5			
Σ -				1	1				0	0						0				3			
Σ S				11	7				12	12						12				6			
V-to-O: Pedestrian cut-in	3			S	S				S	S						S				S			
V-to-O: Pedestrian in-path	3			S	S				S	S						S				S			
V-to-O: Tree	1			S	S				S	S						S				S			
V-to-O: Pole	1			S	S				S	S						S				S			
V-to-O: Roadside structure	1			S	S				S	S						S				S			
V-to-V: Rear end, lead vehicle stopped	5			S	S				S	S						S				S			
V-to-V: Rear end, lead vehicle moving	5			S	S				S	S						S				S			
V-to-V: Rear end, lead vehicle decelerating	5			S	S				S	S						S				S			
V-to-V: Rear end, cut-in	5			S	S				S	S						S				S			
V-to-V: Left turn across path (LTAP), opposite direction	3			-	S				S	S						S				S	DATUM 2		
V-to-V: LTIP/RTIP/LTAP, lateral direction (turning)	3			-	S				S	S						S				S			
V-to-V: Straight crossing path	5			S	S				S	S						+				S			
V-to-V: Opposite direction	5			-	S				S	S						S				S			
Σ +				0	0				0	0						1				0			
Σ -				3	0				0	0						0				0			
Σ S				10	13				13	13						12				13			
V-to-O: Pedestrian cut-in	3			-	-				S	S						S				S			
V-to-O: Pedestrian in-path	3			-	-				S	S						S				S			
V-to-O: Tree	1			-	-				S	S						-				S			
V-to-O: Pole	1			-	-				S	S						-				S			
V-to-O: Roadside structure	1			-	-				S	S						S				S			
V-to-V: Rear end, lead vehicle stopped	5			S	S				S	S						S				S			
V-to-V: Rear end, lead vehicle moving	5			S	S				S	S						S				S			
V-to-V: Rear end, lead vehicle decelerating	5			S	S				S	S						S				S			
V-to-V: Rear end, cut-in	5			S	S				S	S						S				S			
V-to-V: Left turn across path (LTAP), opposite direction	3			S	S				S	S						S				S			
V-to-V: LTIP/RTIP/LTAP, lateral direction (turning)	3			S	S				S	S						S				S			
V-to-V: Straight crossing path	5			S	S				S	S						S				S			
V-to-V: Opposite direction	5			S	S				S	S						S				S			
Σ +				0	0				0	0						0				0			
Σ -				5	5				0	0						2				0			
Σ S				8	8				13	13						11				13			
TOTAL: Σ +				2	6				2	2						3				5			
TOTAL: Σ -				9	6				0	0						2				3			
TOTAL: Σ S				29	28				38	38						35				32			

<u>Pugh Analysis Key</u>
- = Much Worse than Datum
S = About the Same as Datum
+ = Much Better than Datum

Once the Pugh Analysis for the sensing system was completed, the same process was used for analyzing the candidate brake systems (as shown in Table 20). For this analysis, System E, which consists of an active vacuum booster with a pre-fill and auto-braking algorithm, was selected as the Datum. The detailed Pugh evaluation resulted in all systems being the same as the Datum. This indicates that the performance criteria can be met by all defined systems when compared to an Active Vacuum Booster with pre-fill and auto-braking algorithm. This was expected, since all the candidate brake system hardware is based on current production brake systems.

Table 20: Completed Pugh Analysis for Candidate CIB Braking Systems

		System											
	Assessment	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Overall	Relative cost	S	-	S	-	DATUM	-	S	-	S	-	S	-
	Integration complexity	S	-	S	-		-	S	-	S	-	S	-
	Component lead time	S	-	S	-		-	S	-	S	-	S	-
	Electrical/communication interface	S	S	S	S		S	S	S	S	S	S	S
	Mechanical interface with vehicle	S	S	+	-		S	+	-	S	S	+	-
	Production field expertise/technical maturity	S	S	S	-		S	S	-	S	S	S	-
	Σ +	0	0	1	0		0	1	0	0	0	1	0
	Σ -	0	3	0	5		3	0	5	0	3	0	5
	Σ S	6	3	5	1		3	5	1	6	3	5	1
Functional Performance	Ability to self-apply up to 0.9 g's	S	S	S	S		S	S	S	S	S	S	S
	Ability to apply ~0.1 g gradients of decel up to 0.9 g's	S	S	S	S		S	S	S	S	S	S	S
	Ability to achieve 1.5 g/sec decel build rate	S	S	S	S		S	S	S	S	S	S	S
	Ability to maintain control brake functions: ABS, DRP, etc	S	S	S	S		S	S	S	S	S	S	S
	Ability to provide multi-tiered braking gradients	S	S	S	S		S	S	S	S	S	S	S
	Σ +	0	0	0	0		0	0	0	0	0	0	0
	Σ -	0	0	0	0		0	0	0	0	0	0	0
	Σ S	5	5	5	5		5	5	5	5	5	5	5
	TOTAL: Σ +	0	0	1	0		0	1	0	0	0	1	0
	TOTAL: Σ -	0	3	0	5		3	0	5	0	3	0	5
	TOTAL: Σ S	11	8	10	6		8	10	6	11	8	10	6

Pugh Analysis Key
- = Much Worse than Datum
S = About the Same as Datum
+ = Much Better than Datum

As a result of this Pugh Analysis, two systems were selected for build into the PIP development vehicles. System O, which was very similar to the Datum I, was selected for one vehicle. This system includes a combination mid- and long-range radar sensor plus a mono-vision camera. This system was selected for a few reasons. First, the system ranked near that of the comparison baseline system datum I. Secondly, this system was also submitted as an existing candidate system from one of the supplier responses, thus reducing some of the risks associated with developing a sensor combination independently. Thirdly, System O includes a combination of sensor technologies, rather than relying on a single sensor type. This difference in sensor types was expected to aid in test method development in later tasks where it was important to ensure that the methods developed are applicable to the various sensing system technologies. Finally, use of System O allows a larger number of suppliers' technology to be utilized in the project, which would not be the case if the datum System I were used.

System T was selected for the second PIP vehicle. This system includes a combination mid- and long-range radar sensor plus a stereo vision camera sensor and showed very similar results to the datum System I. This system, however, had three negative ratings, including one for ‘Fusion Algorithm Risk’ with a ‘Very Significant’ weighting factor and one for ‘Production Field Expertise/Technical Maturity’ with a ‘Moderately Significant’ weighting factor. The primary benefit of this system selection is that it allows for the potential flexibility of acting as multiple different sensing systems, depending on whether a fusion algorithm is available from the supplier(s). If one were available, the system could potentially represent not only a combination of radar and stereo vision together, but separate radar and stereo vision systems, such as Systems S and D. Without the fusion algorithm, Systems S and D would still be represented by this selection. It should be noted that the radar from System T is the same mid- and long-range radar as in System I, the Datum. As with the first system (O) selected above, this system (T) also includes a combination of sensor technologies rather than relying on a single sensor type. This difference in sensor types was expected to aid in test method development, once again, to ensure that the methods developed are applicable to the various sensing system technologies. In addition, a mono-vision camera was added to the second system because a fusion algorithm for the radars and mono-vision camera is available and could be used without significant refinements.

These selected systems, plus an additional sensor set from a new member that joined the CIB Consortium in June 2008, were used. This vehicle was equipped with a combination of long-, mid- and short-range radars, similar to one of the candidate systems considered for the PIP vehicles. Each of these three radar systems, however, is produced by different suppliers and use different algorithms, which further aided in the development of the test methods. It should be noted that these selections were contingent upon receiving supplier quotes compatible with the project’s timing and resources, component availability and supplier support assessed during the fabrication phase of the vehicle builds.

3.4 Fabrication of Prototype Systems for Testing

This section details the sourcing and building of the project vehicles and the target systems needed for testing. This task involved identifying the basic test types needed and defining requirements for test vehicles, target systems, system hardware, and data acquisition and ground truth measurements. System suppliers were also identified under this effort. The test systems were fabricated and other needed equipment was acquired. Based upon results from initial testing, the test systems were subsequently modified as needed to meet the Project requirements.

Beyond the test vehicle builds, this section includes a description of the development of the test target requirements that were developed to address the priority crash scenarios established in Chapter 2. These requirements include a combination of stationary and moving targets designed to represent vehicle-to-vehicle, vehicle-to-object and vehicle-to-pedestrian crash scenarios. These requirements were refined further as the design of the targets evolved during the project.

3.4.1 Identify Basic Test Types Needed

Table 3, discussed earlier in Chapter 2, presents the 14 vehicle-to-vehicle, vehicle-to-object and vehicle-to-pedestrian crash scenarios identified for the CIB Project. These 14 crash scenarios represent the cases containing the theoretical maximum potential benefit that may be addressed by a CIB system. Ten, on-track test types were defined around these scenarios and the PIP vehicles were fabricated and tested according to the defined test types. These test types were chosen for the on-track portion of testing with the PIP vehicles, and included both lateral and longitudinal motion and non-vehicular objects.

3.4.2 Identify Test Vehicle Requirements

Several key factors were identified for selecting candidate test vehicles for this project. These include:

- The vehicles must be produced by the CIB participant companies
- A Controller Area Network (CAN) electrical architecture is required in order to transmit and receive electrical command signals between the CIB sensing systems, the vehicle chassis sensors, the CIB algorithm, and the brake controllers
- The test vehicles must have electronic stability control to ensure that the brake system is capable of providing the type of brake response needed. Preferably, the brake systems should be produced by CIB participating team members. This will allow easier and less expensive interfaces between the vehicles' existing brake system hardware and the installed CIB systems.
- Vehicles with sufficient cargo space to accommodate the installed CIB system hardware and data recording equipment are also required, as are useable rear seats
- Vehicle models which have been previously used as CIB system or other exterior sensing system development platforms are preferred. This experience will allow quicker and less expensive vehicle retro-fitting for the CIB Project.

After the development of these requirements, the CIB TMT selected three vehicle models upon which to build the PIP vehicles, which are discussed later in this section. Additionally, three production vehicles were identified which are currently available to the US market and offer optional CIB systems. As described later in this report, these vehicles were tested by NHTSA/Vehicle Research and Test Center (VRTC) with support from the CIB TMT. This step provided baseline CIB system performance data to aid in the builds of the PIP vehicles and early assessments of initial test method proposals.

3.4.3 Identify Data Acquisition and Ground Truth Measurement Requirements

In order to capture data for the CIB tests that were conducted, a suitable data acquisition system and ground truthing system for each vehicle was developed. In the context of this project, a ground truthing system refers to an accurate reference system to which sensor data can be compared during CIB testing. Three critical areas of data were needed to support this project, which are described in the following sections. A global positioning system (GPS) based ground-truth equipment was selected for the project and installed in the PIP vehicles. This system was used to acquire data for the on-track testing portion of the project and to record vehicle location data over the six-week Real-world Operational Assessment Data (ROAD) Trip.

3.4.3.1 Recording and Processing of Identified Data Signals

A list of signals was developed for the purpose of assessing the performance of CIB systems during crash scenario testing. Data collection from the three production vehicles consisted of the available data from the GPS ground-truth system, since access to each of the production-based vehicles CAN communication bus would have been difficult and time intensive to obtain. It should also be noted that the CIB team was not allowed to modify the mechanical and electrical systems of the production vehicles since the vehicles were to be returned without modification or damage.

An agreed upon signal list was developed during the project in several stages during the course of testing with the baseline and PIP vehicles. This signal list is shown in Table 21 and identifies critical parameters, as well as the data desired from the ground truthing measurement system. The following specific requirements of the ground truthing system were defined:

- Measurement of both vehicle dynamics and vehicle positioning data
- High measurement accuracy with differential corrections to less than 2 cm for distance measurements
- Capture data in the vehicle-to-vehicle (“non-fixed-point” test cases) and vehicle-to-object and vehicle-to-pedestrian (primarily “fixed-point” test cases) crash scenarios
- Capable of reporting information regarding the relative positions of two or more targets with regard to the host vehicle in real time with an accuracy of 3 cm

Table 21: Signal List for Three CIB PIP Vehicles

CIB Sensor Parameters Recorded	Comments
Vision System Video sensor data	Forward scene vision system data available in each PIP vehicle. Data can be used for cross check of GPS data or used on a test by test basis. Raw Sensor data is proprietary to each manufacturer and is not to be shared.
Radar Sensor Data for relevant targets • ***Range*** • ***Range rate*** • ***TTC*** • ***Target speed*** • ***Target probability***	Radar parameters are available on each PIP vehicle CAN bus. Data can be used for cross check of GPS data or used on a test by test basis. Raw Sensor data is proprietary to each manufacturer and is not to be shared.
Vehicle Parameter(s) Recorded	
Brake switch	Available on each PIP vehicle CAN bus
CIB brake command (brake state)	Available on each PIP vehicle CAN Bus
Audible collision warning (i.e., the Human Machine Interface (HMI))	Available on each PIP vehicle CAN Bus
Vehicle dynamics • ***Longitudinal. acceleration*** • ***Yaw*** • ***Lat acceleration*** • ***Long velocity*** • ***Steer wheel angle***	Use vehicle CAN bus vehicle dynamics data signals, available in each PIP vehicle
Brake Pressure • ***Master cylinder pressure***	Use vehicle CAN bus brake pressure data signals available in each PIP vehicle
GPS Parameter(s) to Record	**Comments** (number of data points)
Longitudinal acceleration	Max: target and test vehicle accels (2)
Velocity(s)	Max: target and test vehicle velocities (2)
Range	Test vehicle to the target (1)
Range rate or closing speed	Test vehicle to the target (1)
Target impact point	Point not recorded but via data reduction when Range = 0
Yaw	Max: target and test vehicle (2)
Yaw Rate	Max: target and test vehicle (2)
Lateral acceleration	Max: target and test vehicle (2)
GPS data	Max: target and test vehicle (4)
Date	Test vehicle and target vehicle will be the same (2)
Time(UTC)	Test vehicle and target vehicle will be the same (2)

UTC: Coordinated Universal Time

3.4.3.2 Storage of Large Quantities of Signal Data

Another critical requirement of the data acquisition system was the ability to store large quantities of data during the testing phase. Two sets of capabilities were included in this requirement. First, data storage capable of recording large numbers of short sequences of data in 15 – 20 second intervals was needed to support on-track testing. Second, data storage capable of recording large quantities of continuous sensor and vehicle information was needed to support on-road data acquisition tasks performed later in the project. This activity encompassed weeks of data gathering and thousands of kilometers of driving. This required several terabytes of data storage capacity for recording GPS, CAN, vehicle CAN, and video file data.

3.4.3.3 Post Processing Data Format Requirements for Re-simulation

The signals captured in the data acquisition system were required to be in a format which allowed simulation replay using a computing cluster. The data format needed to be compatible with simulation software that allowed parametric changes to simulation models (as shown in Figure 7). The data collection block contains the data files acquired from the data acquisition system during the on-track scenario testing and on-road data acquisition activity. The data files containing vehicle data and CIB sensor data were used as inputs to the algorithm block to re-run CIB algorithms with "adjusted" parameters for re-simulating test scenarios. After running a simulation, a new data set was created containing new CAN logs which contained the data in CAN format and showed the effects of the parameter changes in the algorithm.

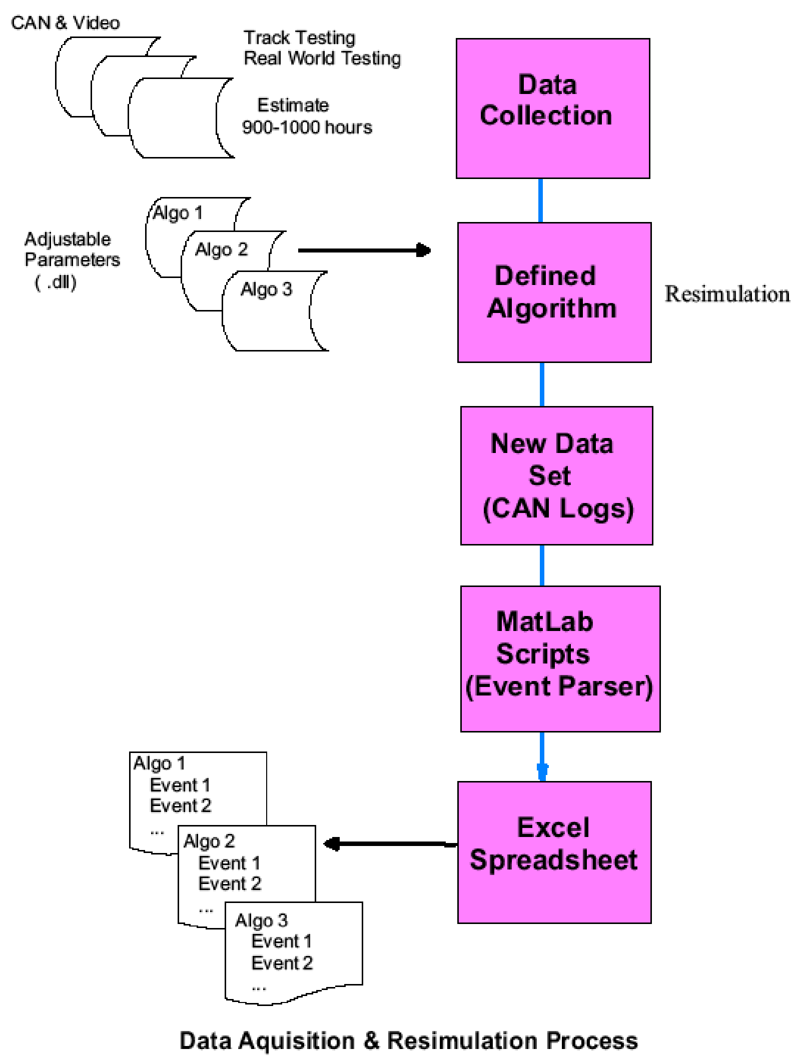


Figure 7: Simulation Process for On-Track and ROAD Trip Data

Following installation of the CIB sensor systems in the test PIP vehicles, the vehicles were instrumented with additional data acquisition and ground-truth measurement systems, as discussed in the PIP vehicle build section below.

3.4.4 Identify and Quote System Suppliers

Once candidate systems were selected, the vehicle test and hardware requirements were identified and the data acquisition and ground truth requirements were defined, supplier quotes were needed. These quotes involved work to build the PIP vehicles along with any outside engineering services required for the prototype system integration, surrogate target development, and/or data acquisition system integration. As a result of this activity, the PIP vehicles described in Section 3.5 were developed.

3.5 Vehicles Used for Testing

Three production vehicles with representative CIB systems were selected for initial testing. The data from these vehicles provided "baseline" data to which data from the prototype CIB systems developed later in the project (see Chapter 4) could be compared. Each production system was capable of autonomous crash-imminent braking using forward object-detection sensing. Based upon manufacturer literature, these systems were primarily designed to address Rear End – Front-to-Back collisions and were not designed specifically to address all of the priority crash scenarios identified in Chapter 2. The baseline tests focused on the Rear End – Front-to-Back test scenarios and false activation tests. However, initial scenarios and test apparatus were developed for all of the priority crash scenarios identified in Chapter 2. These baseline vehicles were designated as "Vehicle A," "Vehicle B," and "Vehicle C" and included the characteristics shown in Table 22.

Table 22: Vehicles and Sensor Sets for Baseline Testing

Vehicle	Sensors and Characteristics of Systems
A	• Long-range radar mounted behind the grill with a range of 200 meters • Mono-camera mounted at the upper part of windshield with a range of approximately 60 meters • Forward Collision Warning, including audible alerts and visual alert below the windshield • Single-stage braking with maximum deceleration of 5 m/s²* • Brake activation above 7 km/h**
B	• Long-range radar mounted behind the grill with a range of 100 meters • Forward Collision Warning with audible alerts and flashing letters in the cockpit • Reversible belt tensioners • Two-stage braking with maximum deceleration of 6 m/s²* • Brake activation above 15 km/h**
C	• Long-range radar mounted behind the grill with a range of 150 meters • Two short-range radar sensors mounted behind the front bumper with a range of 30 meters • Forward Collision Warning with audible alerts and symbol displayed in the cockpit • Reversible belt-tensioners (front seats) • Pre-Crash positioning of the front passenger and rear seats • Single-stage braking with maximum deceleration of 4m/s²* • Brake activation between 30 km/h and 180 km/h**

Notes

* Measured during baseline testing. Single stage braking refers to a CIB system that ramps up to the maximum deceleration rate in a single step and holds that rate. Two-stage braking refers to a CIB system that ramps up to a lower, intermediate braking rate, then increases to its maximum level, depending on the scenario conditions.

** Based on information obtained from owner's manual

The second iteration of testing used for developing the test methods included prove-out tests using the project PIP vehicles. During the baseline tests, data from the production vehicle sensing systems was not available. This limited the ability to assess system responses for different targets, as well as variation in Time-to-Collision and Range at Brake Initiation, and Impact Speed Reduction. More detailed response data was needed to better assess, correlate, and finalize test target definitions and test methods. This additional information was attained by using the PIP test vehicles. Detailed descriptions of the PIP vehicle configurations and capabilities are further documented below and highlights of these vehicles are shown in Table 23. Note that for Vehicle E the TTC and deceleration settings were adjustable to differing levels via two switches on the vehicles console. Also, Vehicle F had a 2-stage CIB system such that 0.4 g deceleration was applied at approximately 1.6 second TTC and followed by 0.9 g deceleration (if needed) at approximately 0.6 second TTC (depending on the duration of the event).

Table 23: Vehicles and Sensor Sets for PIP Testing

Vehicle	Sensors and Characteristics of Systems
E	• Long- & Mid-Range Radar • Mono-Vision • Long- & Mid-Range Radar & Mono-Vision Fusion • Stereo-Vision* • Adjustable TTC and Deceleration Settings
F	• Fusion System w/ Long-/Mid-Range Radar & Two Short-Range Radars • 0.4g/0.9g 2-stage system**
G	• Long- & Mid-Range Radar • Mono-Vision • Long- & Mid-Range Radar & Mono-Vision Fusion • Adjustable TTC and Deceleration Settings

Notes

* The stereo vision system installed in vehicle E included a limitation. During the first round of PIP vehicle testing, output from the stereo vision system did not yet include a functional autonomous brake command. Therefore, the test results and conclusions available from this system were limited to assessments of the system's capability to track the various test targets and the accuracy of the sensor measurements. For the second round of PIP vehicle tests, the stereo vision system includes an embedded CIB control algorithm which output a recordable signal indicating when the system would have initiated a brake command (but this signal did not physically trigger CIB brake activations).

** The two-stage system refers to a system with a 0.4 g deceleration applied at approximately 1.6 second TTC followed (if needed) by a 0.9 g deceleration applied at approximately 0.6 second TTC (depending on the duration of the event). The system maintains the 0.4 g deceleration if the second stage is not activated.

3.5.1 PIP Test Vehicle E

3.5.1.1 System Architecture

Sensor Combinations (See Figure 8)

- Long- and Mid-Range Combination Radar
- Mono Camera
- Long- and Mid-Range Radar, and Mono Camera Fusion
- Stereo Vision System

PIP Test Vehicle E, as defined in Table 23, was outfitted with an automotive grade radar system, two vision sensor systems, and algorithms for processing the sensor inputs and controlling the brake system. The CIB system on this vehicle consisted of the component architecture shown in Figure 8.

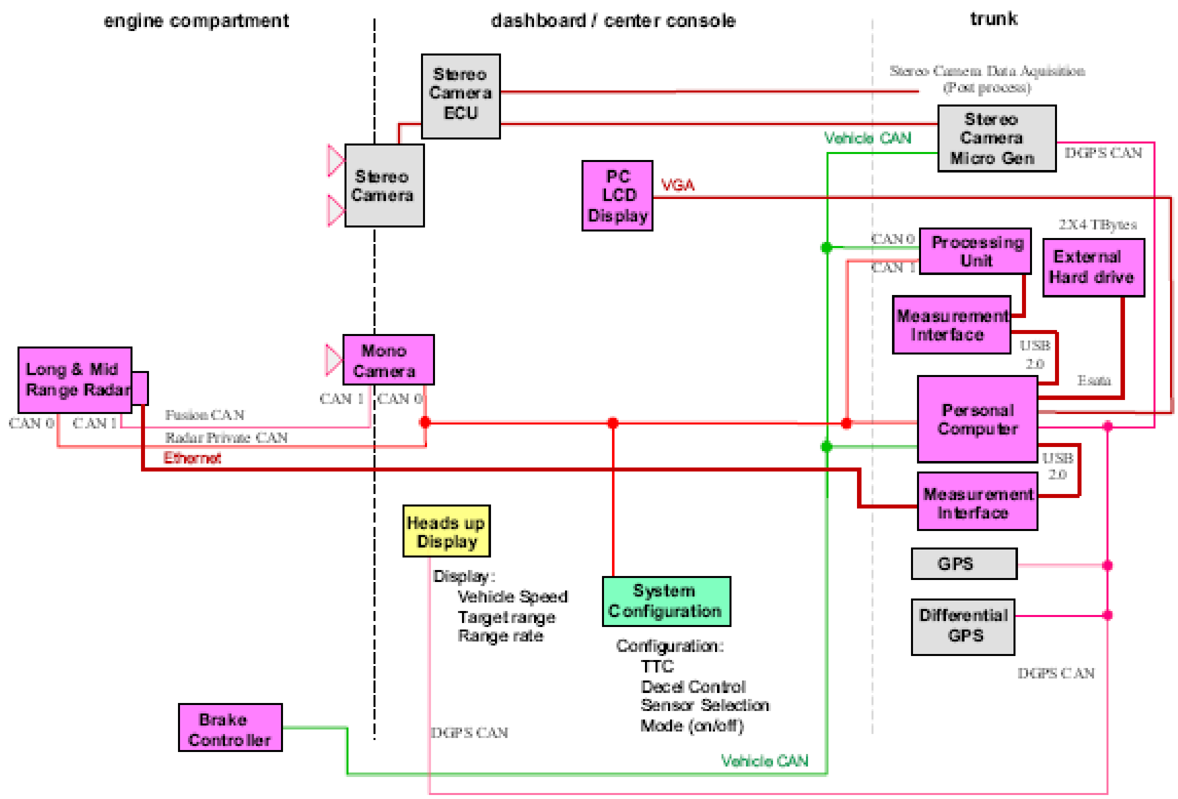


Figure 8: System Architecture Diagram for PIP Vehicle E

3.5.1.2 Braking System

The braking system in PIP Vehicle E was based upon the standard production system with a modified development brake controller. The system is capable of ABS, traction control and electronic stability control with CIB functionality that provided auto braking with selectable deceleration levels from 0.1 g up to full ABS in 0.1 g increments.

3.5.1.3 Ground Truth System

The ground truth system chosen was GPS-based. This system allowed assessment of the accuracy of the CIB system data. This system was portable and was transferred from vehicle-to-vehicle as testing was conducted. This system, described in more detail later in the report, incorporated the following features:

- Common mounting configurations located near each vehicle's center of gravity that enabled quick mounting and dismounting of the system. The mounting system and installation brackets were added to each PIP vehicle to enable the quick change feature.
- CAN bus connection provided such that ground-truth data is captured simultaneously with sensor data. CAN was the primary method of communicating to the data acquisition systems.
- Differential GPS base station was added for enabling the higher accuracy needed for CIB testing

3.5.1.4 Data Acquisition System

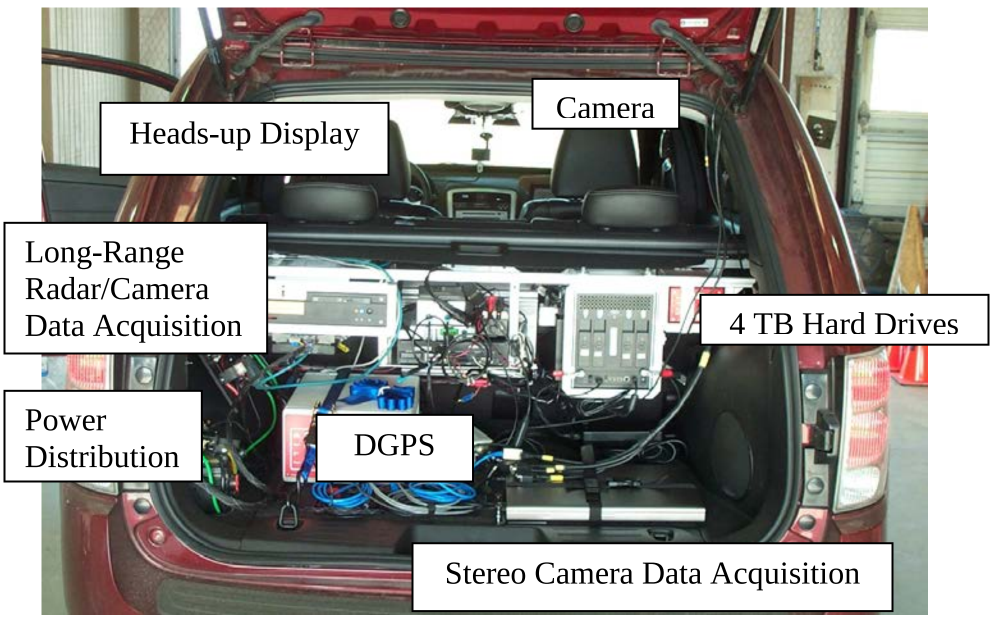
In addition to acquiring and recording the defined vehicle signals, the acquisition system of PIP Test Vehicle E consists of several additional components listed below:

- Expanded storage to provide capacity for a minimum of one week of continuous sensor data (video and radar)
- Signal processing and recording of GPS-based, ground-truth data via dedicated CAN bus link from GPS
- Acquisition and recording of radar sensor data from the radar sensor located in the front of the vehicle
- Acquisition and recording of mono-vision sensor system located near the rear-view mirror inside the vehicle passenger compartment
- Acquisition and recording of the stereo-vision sensor system located near the rear-view mirror inside the vehicle passenger compartment. The stereo vision system functions as a separate sensing system from the radar and mono-vision sensors. Therefore, this data is collected and processed through a separate data collection laptop independent of the other sensor data. Vehicle CAN and ground-truth GPS data are also collected on this laptop.
- Command control of the brake actuator located under the hood in the front of the vehicle. Also, acquisition and recording of CAN data from the brake actuator, such as vehicle deceleration.
- The data acquisition interfaces with the LCD display located near the passenger seat for receiving inputs from a keyboard and displaying data
- Logging video camera installed near the rearview mirror for additional test scenario information
- The data acquisition system software needed to capture radar, vision and CAN data in a format compatible with post-processing routines to be used in re-simulation
- Stereo Camera data acquisition system software to capture stereo vision and CAN data. This system then transmits the stereo vision target report to the vehicle CAN

for collection with the vehicle data acquisition system in a format compatible with post-processing routines to be used in re-simulation

In order to reduce the number of vehicle test runs required, post processing was performed on data from PIP Vehicle E. To enable this post processing, the data acquisition system was configured to collect and store all CIB sensor data and vehicle CAN data channels simultaneously during the test scenarios.

PIP Vehicle E was provided to the supplier for a 16-week build process (completed at the end of January 2009). All sensors, data acquisition equipment, wiring, and related components were installed and the brake system was modified. Numerous joint meetings between the TMT and the camera suppliers were needed to discuss the optimal physical integration of mono- and stereo-camera systems, data acquisition and related equipment. In addition, the integration of all the supporting electronics and power feeds into the rear trunk area were finalized. The completed vehicle is shown in Figure 9.



DGPS: Digital Global Positioning System

Figure 9: Completed PIP Test Vehicle E

3.5.2 PIP Test Vehicle F

3.5.2.1 System Architecture

Sensor Combinations (See Figure 10)

- Long- and Mid-Range Radar
- Mono-Vision
- Long- and Mid-Range Radar and Mono-Vision Fusion

- Flexible TTC and Deceleration Settings

The equipment used for this vehicle consists of three radar sensors with different ranges. The sensors are located in the front grille (long- and mid-range combination radar) and behind the front bumper (two short- range radar sensors) on the left and right side. The sensors are configured with a fusion algorithm.

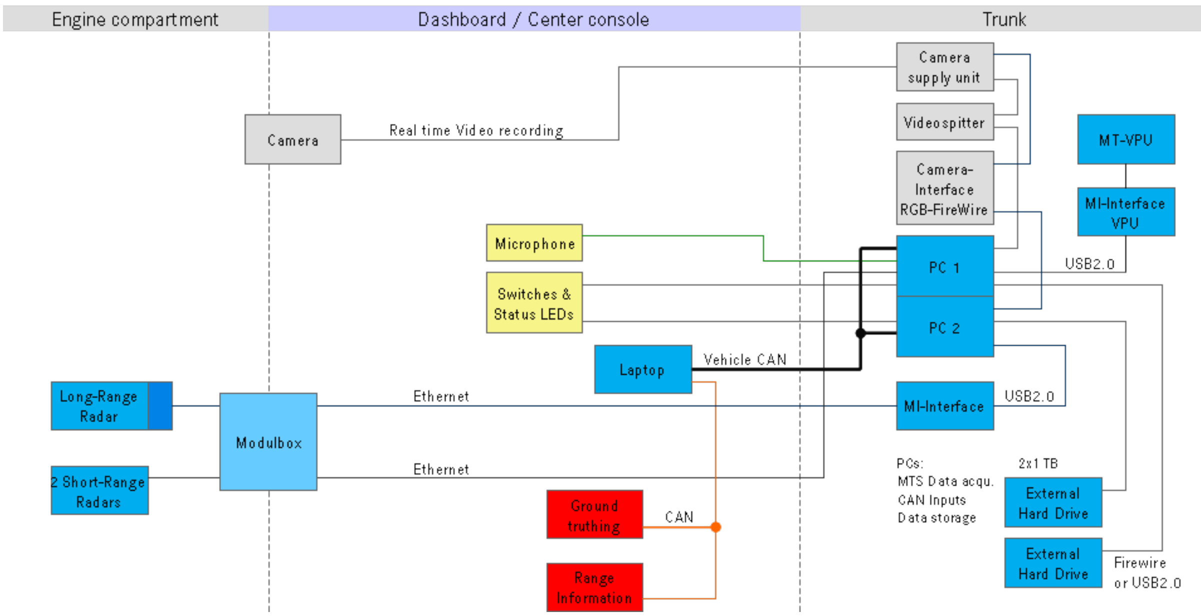


Figure 10: Architecture Diagram PIP Test Vehicle F

3.5.2.2 Braking System

PIP Test Vehicle F has an autonomous braking-capable, next–generation, electronic brake control system with integrated traction control and dynamic handling control systems.

3.5.2.3 Ground Truth System

The GPS-based ground-truth system, previously described for PIP Test Vehicle E, was also used in PIP Test Vehicle F.

3.5.2.4 Data Acquisition System

PIP Test Vehicle F data acquisition system collects all the vehicle and sensor signals as defined. Additionally, CAN traces were used to collect ground truth data and defined vehicle CAN signals. Main components of the data acquisition system included:

- Radar sensors and brake controller equipped with measurement interfaces
- PCs including external hard drives. Hard drives were capable of data storage for all planned track tests with this vehicle without deleting or overwriting any data.

- Logging video camera behind the windscreen for additional test scenario information
- Data acquisition system is automatic triggered by CIB events or can be started manually by a push button
- The main components communicate over CAN bus or Ethernet

PIP Test Vehicle F was delivered complete, so no major work was required prior to testing. Minor modifications were made to integrate and synchronize the GPS equipment with the data acquisition system. The complete equipment installation is shown in Figure 11.

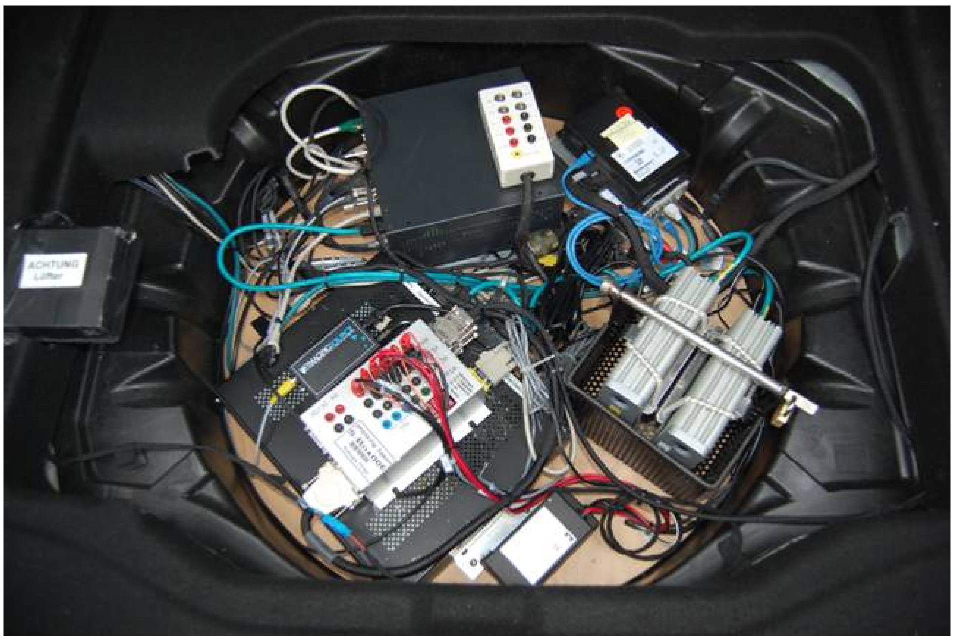


Figure 11: Equipment Installed in PIP Test Vehicle F

3.5.3 PIP Test Vehicle G

3.5.3.1 System Architecture

PIP Test Vehicle G was outfitted with an automotive-grade radar and vision sensor and algorithms for processing the sensor inputs and controlling the brake system. The key components of the CIB system on PIP Test Vehicle G are described below.

Sensor Combinations (See Figure 12.)

The main sensors include the following:

- Long and Mid-Range Combination Radar
- Mono Camera with machine vision processor
- Long and Mid-Range Radar and Mono Camera Fusion

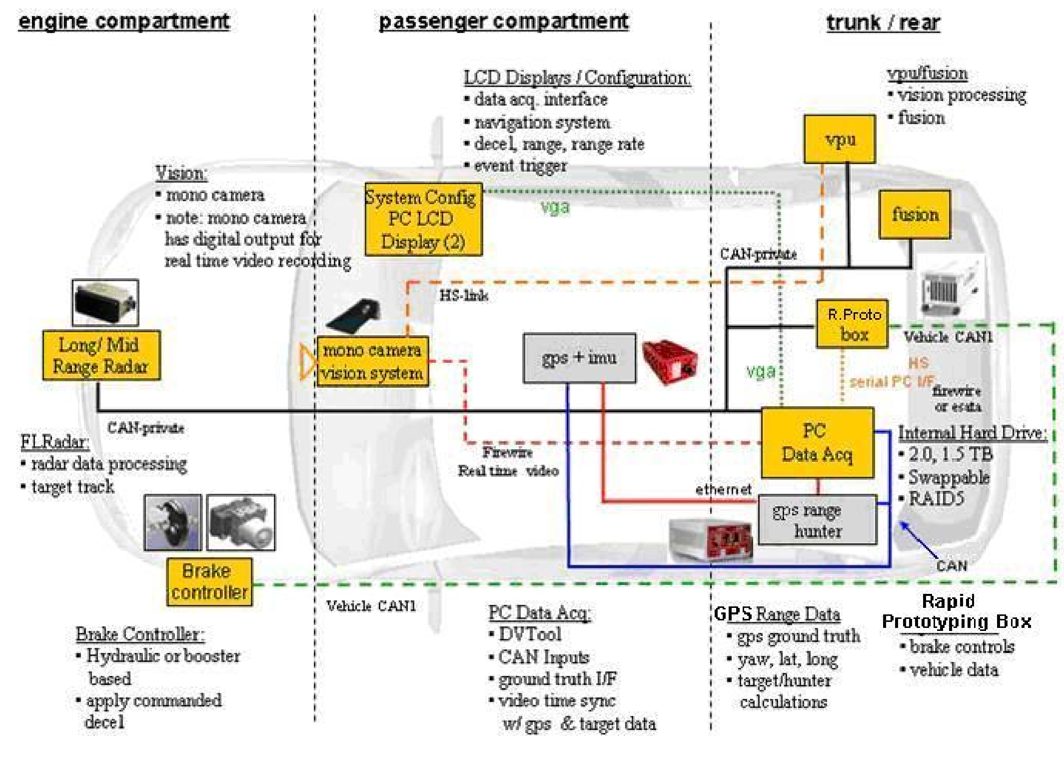


Figure 12: System Architecture Diagram for PIP Test Vehicle G

3.5.3.2 Braking System

The braking system in PIP Test Vehicle G was based upon the standard production system. The system is capable of ABS, traction control and electronic stability control with CIB functionality added. The CIB system was capable of varying the amount of brake pressure and deceleration, as well as the duration of braking required for the test condition.

3.5.3.3 Ground Truth System

The GPS-based, ground-truth system that was previously described for PIP Test Vehicle E was also used in PIP Test Vehicle G.

3.5.3.4 Data Acquisition System

The data acquisition system consists of several key components which acquire and record ground truth, sensor, vehicle dynamics and additional vehicle CAN bus data. The following are the key components to the onboard data acquisition system used for the testing with PIP Test Vehicle G:

- Storage to provide capacity for a minimum of one week of continuous sensor data (video and radar)
- Signal processing and recording of GPS-based, ground-truth data via dedicated CAN bus link

- Acquisition and recording of radar sensor data from the radar sensor located in the front of the vehicle
- Acquisition and recording of vision sensor system located near the rear view mirror inside the vehicle passenger compartment
- Command control of the brake actuator located under the hood in the front of the vehicle. Also, acquisition and recording of CAN data from the brake actuator, such as master cylinder pressure
- The data acquisition interfaces with the LCD display located near the passenger seat for receiving inputs from a keyboard and displaying data
- Data acquisition system that runs the required software to capture radar, vision and CAN data in a format compatible with post-processing routines to be used in re-simulation

An existing test vehicle was identified which required some modification, which reduced both cost and build time compared to a new vehicle build. The selected PIP Test Vehicle G already included the sensing system, data acquisition system and supporting components, as described above. However, some updates to the installed hardware and software were required to improve the sensing system performance prior to testing (as defined in the next section). System updates to the brake controller and software were completed, which added the capability of varying the amount and timing of deceleration commanded in response to the perceived threat. The equipment installed in PIP Test Vehicle G is shown in Figure 13.

Figure 13: Completed PIP Test Vehicle G

During test method development, it was also determined that PIP Test Vehicle G would utilize post-processing of the vehicle data according to the process of re-simulation identified earlier in this report. The data acquisition system was configured in the same manner as PIP Test Vehicle E, which enables simultaneous collection of all CIB sensor and vehicle CAN signals for later separation and processing into the different CIB configurations combinations. In addition, a 16-processor computing cluster was specified and built to handle post-processing of the data for the project. The computing cluster contained sufficient data storage space to accommodate and record the nearly 30 terabytes of vehicle, CIB system and video data. The computing cluster also provided the simulation environment in which test sequences could be re-run while changing sensor parameters.

In early development of the CIB test methods, some scenarios presented issues in determining the time at which the vehicle made contact with the target, primarily in the test methods involving towed balloon cars. The GPS generally provided the contact point information based upon the time at which the range parameter reached zero. An alternative method was evaluated on PIP Test Vehicle G using a proximity sensor mounted to the front bumper bar. This contact switch could then be used in the data acquisition system as a flag for the time when the target impacted the front of the vehicle. This provided an additional recorded input confirming that contact was made to the target system.

3.6 Target Investigations for Baseline and PIP Vehicle Testing

The following section discusses the development of the target systems that were used for evaluating CIB systems during various vehicle testing phases. Using the data from the baseline production CIB systems, a smaller number of targets were selected for use in PIP vehicle testing that provided test repeatability and flexibility in replicating each of the priority crash scenarios.

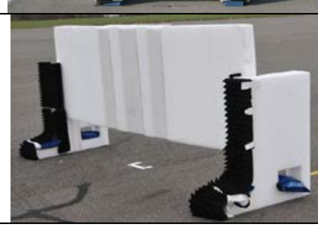
Several types of CIB targets were tested and evaluated during the baseline production vehicle testing. For the vehicle-to-vehicle scenarios, these included various “vehicle-like” balloon cars and foam pillows, flip-down and hanging target simulators as well as a balloon car carrier and a crash simulator that emulate moving vehicle targets.

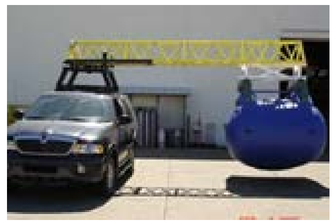
This analysis is compiled as shown in Appendix F. The evaluation criteria included radar reflection and camera detection, sensor repeatability, ease of use, set up time and costs.

3.6.1 Targets Used in Vehicle-to-Vehicle Testing

The following tables identify the various targets that were used in the baseline vehicle testing and the PIP vehicle testing at the test sites used for the CIB Project. Table 24 describes the targets used in vehicle-to-vehicle testing for the baseline test sequence.

Table 24: Summary of Target Systems Used for Vehicle-to-Vehicle Testing

Name	Brief Description	Photograph	Used In Baseline Tests?	Used In PIP Vehicle Tests?
Flip Down Target	Radar systems only; static target. The corner reflector flips down when triggered by a light beam and driven over by the test vehicle.		Yes	No
Balloon Car 1	Static balloon type target that is struck; used with radar and camera systems. (Style 1)		Yes	No
Balloon Car 2	Static balloon type target that is struck; used with radar and camera systems. (Style 1a)		Yes	Yes
Balloon Car 3	Static balloon type target that is struck; used with radar and camera systems. (Style 2)		No	Yes
Vehicle Foam Pillow	Static target for Radar and camera systems; 12" foam block with representation of a vehicle		Yes	No
Foam Block	Static target for Radar-only systems; 12" foam block with internal corner reflectors.		No	Yes
Balloon Car 1 with Flip Down Target	Combination of Balloon Car 1 and Flip Down target		Yes	No
Hanging Target	Radar systems only: Static and moving target that is struck.		Yes	No

Name	Brief Description	Photograph	Used In Baseline Tests?	Used In PIP Vehicle Tests?
Crash Simulator	Radar and camera systems; A moving target that utilizes a vehicle dummy, manually activated that flips out of the way before being struck.		Yes	No
Balloon Car Carrier	Radar and camera systems; A moving Balloon target that is carried along into path of vehicle under test. Balloon car decouples from structure when impacted due to special clamping mechanism.		Yes	No
Towed Balloon Car 2	Balloon Car 2 towed along the track by cables moved by a motorized conveyance system		Yes	Yes

Within each of the three PIP vehicles, measurements of radar power return for tracked targets were recorded from the respective radar systems. Target visual characteristics were also assessed for camera-based systems using the target reports from the three vision systems, including the stereo- and mono-camera systems installed in two of the PIP vehicles.

3.6.2 Targets Used in Vehicle-to-Object Testing

The various targets that were used for the vehicle-to-object test scenarios during the baseline vehicle testing and the PIP vehicle testing are shown in Table 25, below. An overview of the targets selected for the vehicle-to-object testing is discussed in Appendix F.

Table 25: Summary of Targets Used for Vehicle-to-Object and Vehicle-to-Pedestrian Testing

Name	Brief Description	Photograph	Used In Baseline Tests?	Used In PIP Vehicle Tests?
Small Pole (Type 1)	Pole that simulates a 4- inch diameter, stationary pole utilizing the Hanging Target vehicle. Material – hard foam		Yes	No
Large Pole (Type 1)	Pole that simulates a 10- inch diameter, stationary pole utilizing the Hanging Target vehicle. Material – hard foam		Yes	No
Small Pole (Type 2)	Pole that simulates an approximate 4-inch diameter stationary pole. Material – hard foam		No	Yes
Large Pole (Type 2)	Pole that simulates an approximate 10-inch diameter stationary pole. Material – hard foam		No	Yes
Pedestrian	Pedestrian that simulates a human adult target. Moving object lateral to direction of vehicle travel		No	Yes

3.6.3 Targets Used in Non-Activation Testing

Just as important as the test scenarios that activate the CIB system are the non-activation tests and related equipment. Non-activation tests refer to tests which assess false positive (or false alarm) activations. False positive tests evaluate a system's ability to not activate under driving conditions in which the occupant would not benefit from system activation and such activations may lead to unintended consequences. The ROAD Trip described in Chapter 4 (Section 4.5.1) tested more, fully false-activation scenarios, since data obtained from this effort was gathered over a much richer set of conditions representative of on-road driving.

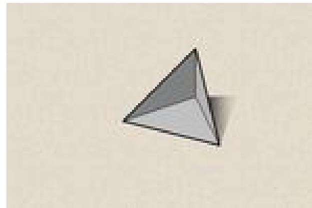
The targets identified below are a preliminary set of targets that were used to develop baseline non-activation test data with the production vehicles. This test data was used as an early assessment of the production vehicles' sensor performance prior to and in preparation for the ROAD Trip. Whenever possible, the natural features of the test track were utilized for the non-activation tests. Targets used in the evaluations included the following:

- Corner Reflector (simulation of a worst case man-hole cover)
- Additional Vehicles, as required
- Concrete Barriers and Steel Guardrails
- Signs and Signposts
- Tunnels and Bridges
- Buildings

Table 26 provides details of the targets used for non-activation testing. This table identifies the various targets that were used in the baseline vehicle and PIP testing across various test facilities.

Table 26: Summary of Objects Used for Non-Activation Testing

Name	Brief Description	Photograph	Used In Baseline Tests?	Used In PIP Vehicle Tests?
Vehicle – Ford Expedition	Vehicle used in curved path non activation scenarios		Yes	No
Vehicle – Buick LeSabre	Vehicle used in straight path non activation scenarios		Yes	No
Vehicle – Ford Taurus	Vehicle used in curved path non activation scenarios		No	Yes

Name	Brief Description	Photograph	Used In Baseline Tests?	Used In PIP Vehicle Tests?
Paper Corner Reflector	Corner reflector laid on the ground to test for system non activation as target is run over by test vehicle		Yes	No
Balloon Car	Balloon car for late avoidance cut out maneuver with test vehicle		Yes	No

3.6.4 Dynamic Target Systems

3.6.4.1 Towed Balloon Car

The balloon car (as previously described) was placed on a tarp and pulled by a secondary vehicle at the defined test speed. In order to maintain the correct heading, the tarp was guided by cables secured to the test track. This target is shown in Figure 14.

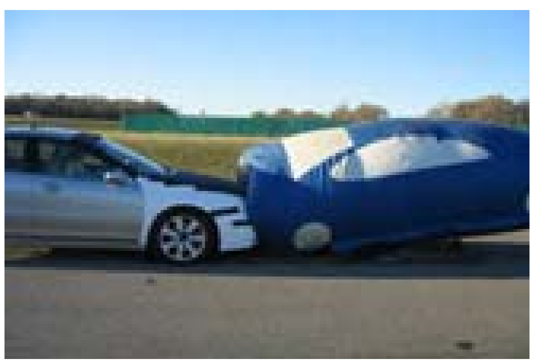


Figure 14: Towed Balloon Car

For moving (dynamic) vehicle tests, the Balloon Car Carrier and the Target Crash simulator were used for initial testing for the Lead Vehicle Moving and Lead Vehicle Decelerating scenarios. This equipment is very specialized and was available for a limited amount of time, so a solution that could be used to support project needs was developed utilizing the towed balloon car. It became immediately apparent that better control of the movement of the balloon car was required, which led to the development of the Target Conveyance system.

3.6.4.2 Target Conveyance System for Vehicle-to-Vehicle Tests

For the dynamic vehicle-to-vehicle scenarios, a system was developed to convey the test targets in a manner representative of the priority crash scenarios. A tow system for the inflatable targets (which was also used for vehicle-to-object targets) was designed and fabricated. This system is depicted in Figure 15. The tow system major components are highlighted in the block diagram in Appendix F, while Appendix G presents a detailed description of the system.

Figure 15: Vehicle-to-Vehicle Target Conveyance Setup

3.6.4.3 Target Conveyance System for Vehicle-to-Object Tests

For the vehicle-to-object tests, consisting of both dynamic and stationary scenarios, the target puller system described in the previous section was modified to include the following additional equipment (see Figure 16).

- Support posts
- Tension cable between support posts
- Tension cables from posts to ground
- Tow / support rope
- Pulleys
- Guide hardware between upper tension cable and tow / support rope
- Guide line between posts at the track surface

The puller system for vehicle-to-object tests allowed targets to be suspended from cables over the roadway. The test setup in this case allowed the test vehicle to move perpendicular to the conveyance system, which is required for the pedestrian crossing path scenarios of interest in the project. The system also provided a suitable method for suspending stationary targets, such as trees and poles, in the test vehicle's path. In such test scenarios the targets will rotate up after being contacted by the test vehicle allowing the vehicle to pass beneath the target.

Figure 16: Vehicle-to-Object Target Conveyance Setup

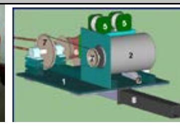
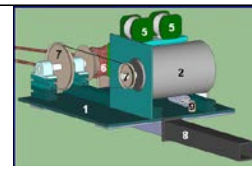
3.6.5 Modify Systems Based Upon Test Method Requirements

As test methods were developed, several modifications to the production and PIP test vehicles were required. One common change identified in early testing was the importance of adding front-end protection to each test vehicle to reduce damage induced by striking test targets, especially in high-closing speed test scenarios. This included the addition of foam blocks, body tape and bumper bars. The addition of these items did not interfere with the field of view of any of the CIB sensor systems. Additionally, network cards were utilized in the vehicle data acquisition computers in order to provide fast data transfer and technical support for the test vehicles.

Overall, the target systems shown in Table 27 were ultimately refined and used for the demonstration and validation of the test methods. These targets included two balloon cars, two simulated pole/tree targets and an inflatable pedestrian mannequin. The 2nd-generation balloon car was used in several of the early crash scenarios tested prior to when the 3rd-generation balloon car became available. For all dynamic maneuvers, the target tow system developed during this project was used to provide the proper movement of the target relative to the test vehicle.

Additional information regarding the target characteristics can be found in the appendices to this report. The screening of candidate pedestrian mannequins is presented in Appendix H. Appendix I presents additional details regarding the radar and visual properties of the inflatable balloon car. Appendix J discusses the correlation of the balloon car radar return to an actual passenger car.

Table 27: Test Methods and Target System Used for Test Method Validation

	Test Method	Category	Target System Used In Final Test
1 2 3 4 5 6	LVS LVM LVD OD SCP LTAP-OD	Vehicle-to-Vehicle	 2nd-Generation Balloon Car  Tow System  3rdGeneration Balloon Car
7 8	Pedestrian In-Path Pedestrian Crossing-Path	Vehicle-to-Pedestrian	 Inflatable Mannequin  Tow System
9	Pole/Tree	Vehicle-to-Object	 Large pole  Small Pole

4 Development, Validation and Finalization of Test Methods

The development of test methods for evaluating CIB system performance was segregated into two major categories: functional tests designed to measure the systems' capabilities to mitigate the severity of potential crash scenarios, and operational tests designed to examine the propensity of a CIB system for undesirable false activations. The process used for developing, validating, and finalizing the functional tests is documented in the following sections. The process used for gathering real-world data and establishing related operational test methods is detailed in Section 4.5. This activity involved the collection of six-weeks of operational data intended to represent a real-world user profile (e.g., the breakdown of road types traveled represented those of a typical driver). The data analysis from this trip identified potential driving conditions under which the various CIB system configurations tested were potentially prone to false activations.

4.1 Functional Test Method Development Process

In Chapter 2, the selection of the priority crash scenarios based upon the societal harm associated with the individual scenarios and the potential applicability and benefit opportunities provided by CIB systems was discussed. During the ensuing project work, test methods were developed which emulate the priority crash scenarios and were capable of assessing and differentiating the functional performance of various CIB systems. Development of these test methods was then divided into the following three iterations of testing:

1. **Initial Prove-out Tests using Representative Baseline CIB Systems**. The baseline tests were performed by NHTSA as an independent test series with vehicles equipped with representative CIB systems. The CIB TMT recommended and specified performance characteristics to be tested and the specific test procedures. NHTSA collaborated and agreed to the testing approach. NHTSA selected and obtained the vehicles to perform this test series. CIB TMT representatives attended these tests and assisted with test set-up, instrumentation, etc. Results of the testing were given to the CIB Consortium with vehicle brand information masked. These tests were performed at a NHTSA test site. The goals of this activity included:

    a. Assess and develop preliminary test methods based on the priority crash scenarios to analyze the practicality of the procedures, verify that the instrumentation and ground truth measurement method is acceptable, determine if the maneuvers are executable, and determine whether the performance criteria were reasonable and verifiable.

    b. Generate baseline data to assist with the test method development during later testing phases and ensure that the PIP vehicles were capable of adequately representing the selected systems.

   c. Evaluate the variation and performance characteristics associated with various test target types. Early test method development included different combinations of potential surrogate targets. Evaluating these different target types with the baseline systems provided data for assessing the test repeatability and functionality of each of the candidate options.

2. **Prove-out Tests using the Project PIP Vehicles**. During this phase, an extensive test matrix including multiple TTC and system deceleration settings was utilized for each of the available PIP vehicle sensor combinations and test targets evaluated. The goals of this testing included:

   a. Further develop and refine the functional test methods

   b. Evaluate the variation and performance characteristics associated with a refined set of test targets using the newly fabricated PIP vehicles

   c. Incorporate the collection of CIB sensor data and vehicle CAN data from the PIP vehicles into the test method development and evaluation of test targets. Since this information could not be obtained from the baseline systems, the PIP vehicles were able to provide enhanced insight into the target and test parameters which most influenced the CIB system performance and test method development.

3. **Validation of the Test Methods and Selected Targets using the PIP Vehicles**. During this final phase of testing, CIB system parameter settings, including TTC and deceleration levels, were restricted to one per vehicle per sensor set, as shown in Table 28. Additionally, to streamline the number of tests and available combinations of results, the performance of some sensor combinations were later simulated based upon the sensor and braking data collected during other tests. Test results shown in this report describe the outcome of both the real tests and the simulation results. These two types of data are subsequently identified with the codes "TRK" for track results and "SIM" for simulated results. The main objectives for these tests included:

   a. Develop the data necessary for validating the final CIB test methodologies and selected target designs

   b. Confirm the ability of the test methods to differentiate performance differences among assorted CIB systems

Table 28: Sensor Sets and System Settings for CIB Test Method Validation

Vehicle	Sensors	TTC Setting	Deceleration Setting
E	E1: Long & Mid Range Radar	0.6 sec	0.9g
	E2: Mono-Vision	0.6 sec	0.9g
	E3: Long & Mid Range Radar & Mono-Vision Fusion	0.6 sec	0.9g
	E4: Stereo-Vision	0.6 sec	0.9g
F	F1: Fusion System w/ Long/Mid Range Radar & Two Short Range Radars	1.6 sec	0.4g/0.9g 2-stage system*
G	G1: Long & Mid Range Radar	1.0 sec	0.6g
	G2: Mono-Vision	1.0 sec	0.6g
	G3: Long & Mid Range Radar & Mono-Vision Fusion	1.0 sec	0.6g

* The two-stage system refers to a system with a 0.4 g deceleration applied at approximately 1.6 second TTC followed by a 0.9 g deceleration applied at approximately 0.6 second TTC (depending on the duration of the event).

Following the conclusion of the validation test phase, each test method was categorized as follows:

Test Methods Validated – This category included the scenarios for which repeated test runs resulted in similar CIB system performance, the test data distinguished the performance levels between the various CIB system characteristics evaluated, and sufficient CIB system activations were recorded to enable the measurement of system performance.

Test Methods Not Validated (Further Development Required) – This category included the scenarios for which test method development was initiated, but was not sufficiently validated within the timing and scope of the current project. Test methods were placed in this category either because the performance of the CIB systems evaluated was insufficient for full test-method validation or because known test-method improvements are needed.

Test Methods Not Validated (Beyond Scope of CIB Project) – This category included the scenarios for which test-method development was initiated but found to be incompatible with the capabilities of near-term deployable features of CIB systems. Scenarios in this category could potentially be better addressed by other crash mitigation or crash avoidance technologies.

4.2 Functional Test Method Procedures

For the functional test scenarios, the Requirements for Standard Test Conditions and Equipment are listed in Appendix K. The test procedures are organized based upon their assigned validation category.

4.2.1 Test Methods Validated

The test methods for the validated scenarios are covered below for the functional tests. Three test methods were validated in this project, including Rear End scenarios for LVS, LVM and LVD.

4.2.1.1 Rear End – Lead Vehicle Stopped (LVS)

To test the capability of the test vehicle CIB system in a Rear End – Lead Vehicle Stopped Scenario, the test vehicle was driven in a straight and level lane toward a stationary target at a constant forward velocity, as shown in Figure 17. Multiple test speeds were evaluated within each test phase. Detailed test specifications can be seen in Appendix L, Section L.1. The validation phase for this test scenario utilized the 3rd-generation balloon car shown in Table 27.

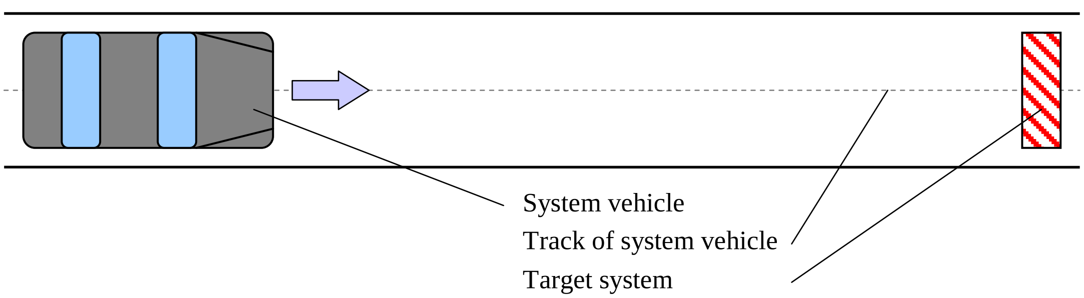


Figure 17: System Vehicle with a Stationary Target

4.2.1.2 Rear End – Lead Vehicle Moving (LVM)

For development of LVM scenarios, a straight, flat test track was needed. The test vehicle and the target system move with a constant speed in this scenario, as shown in Figure 18. The target system moves at a slower speed than the test vehicle. Multiple test speed combinations were evaluated within each test phase. Detailed test specifications can be seen in Appendix L, Section L.2. For the validation test phase, a target tow system was developed to provide controlled target movement (for more details, see Figure 19 and Appendix G – Target Tow System).

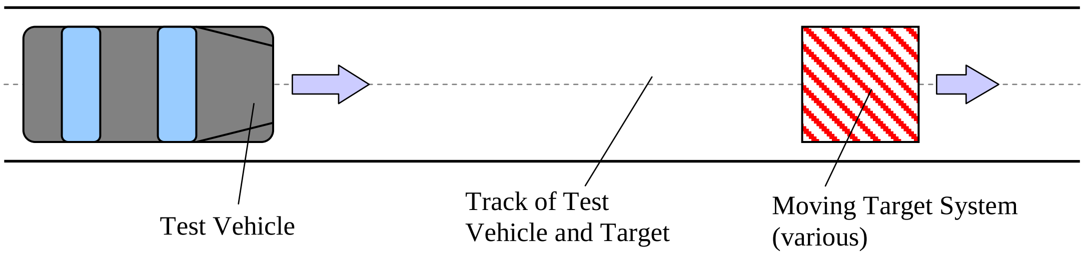


Figure 18: Test Vehicle with Moving Target

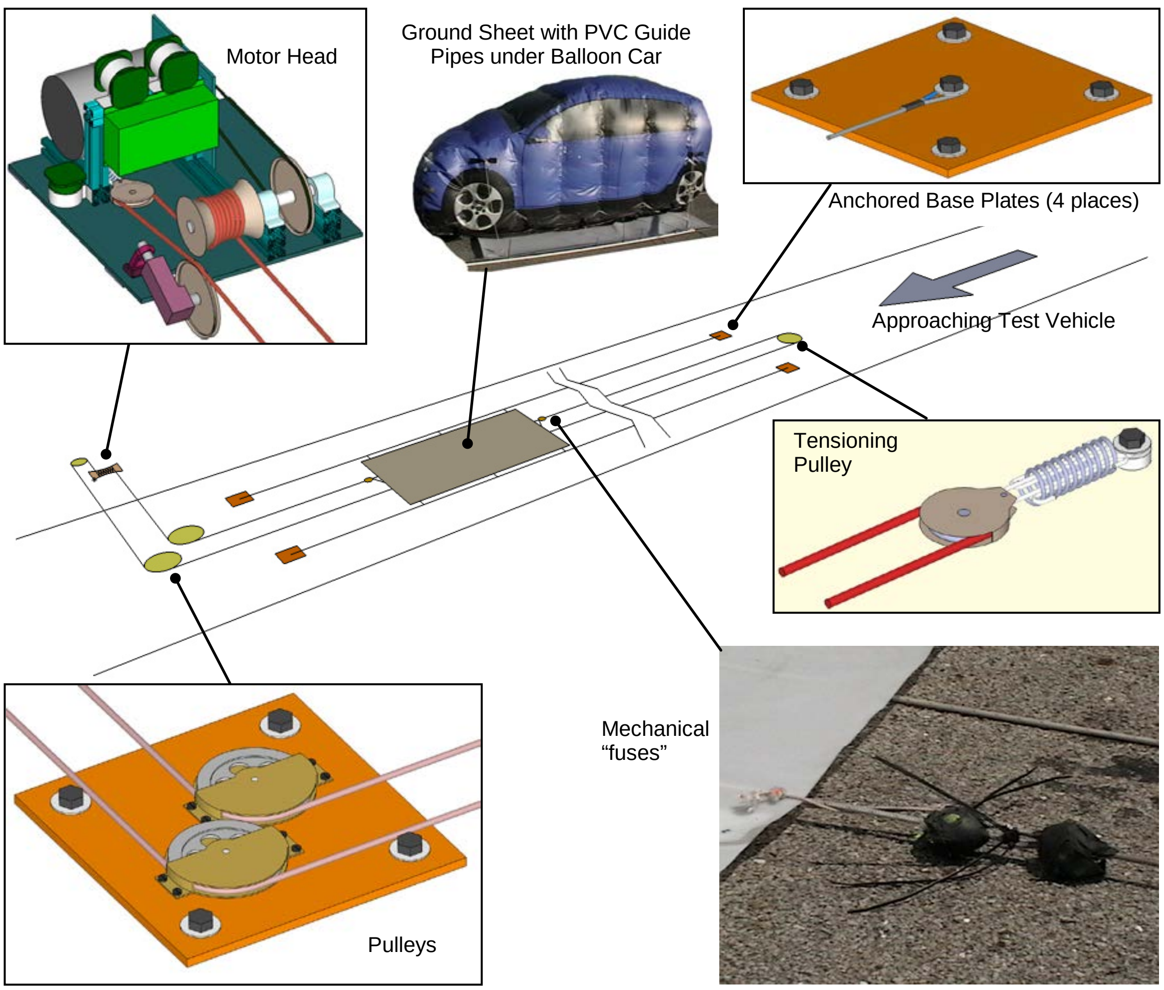


Figure 19: Lead Vehicle Moving Setup

4.2.1.3 Lead Vehicle Decelerating (LVD)

Like the LVM scenario, the test vehicle and the target system move with the same, constant speed in the LVD test. After maintaining an initial distance, the target system performs a defined deceleration to a complete stop, as shown in Figure 20. Multiple combinations of test speeds, following distances, and target decelerations were evaluated within the test phases. Detailed test specifications can be seen in Appendix L, Section L.3.

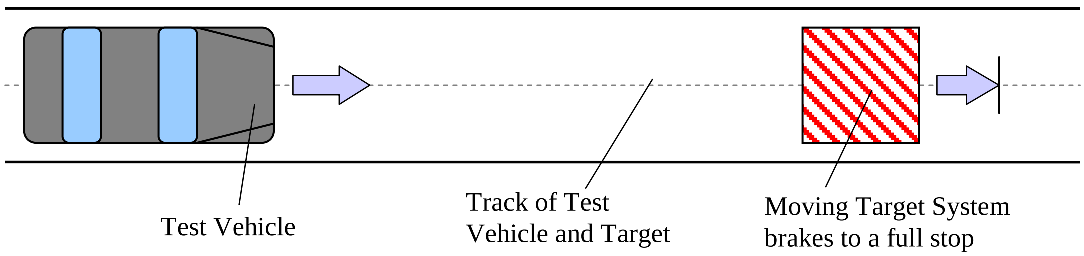


Figure 20: Test Vehicle with Decelerating Target

This scenario was one of the most difficult of the validated test methods to execute due to the large number of variables that needed to be controlled simultaneously. The factors included test target speeds, initial headway distance between the test vehicle and the target and the relative accelerations.

4.2.2 Test Methods Not Validated (Further Development Required)

The test methods designated as ‘Not Validated – Further Development Required’ are described below for the functional tests. These tests included the Pedestrian In-Path and Crossing-Path scenarios.

During the first two phases of testing, an acceptable test mannequin target (i.e., a pedestrian representation) was not available that provided adequate CIB sensor response correlation to a human. Therefore, a mannequin (i.e., a pedestrian representation) correlation development project was conducted with an independent research lab to develop appropriate test target mannequins using controlled radar response testing. The goal was to identify and select commercial off-the-shelf mannequins which could be struck by the test vehicle and could be correlated to 50^{th} percentile adult humans with limited modifications. The CIB sensors that were used in this work included a 24 GHz, ultra-wide band, short range radar (provided by the research facility), two 76 GHz, mid/long range radars (provided by the CIB Consortium), and a data logging camera. Visual characteristics of the proposed mannequins were then verified using the pedestrian classification algorithms contained within the mono- and stereo-camera vision sensors built into the PIP vehicles (see Appendix L, Section L.4).

Following the development of a potential target mannequin, a test method was developed during the test validation phase to represent Pedestrian In-Path and Pedestrian Crossing Path scenarios. This test method utilized the target towing system for moving the pedestrian mannequins. Unlike the balloon cars, a pedestrian mannequin was supported from a high anchorage point utilizing two boom cranes to maintain proper movement (see Figure 21 and Figure 22).

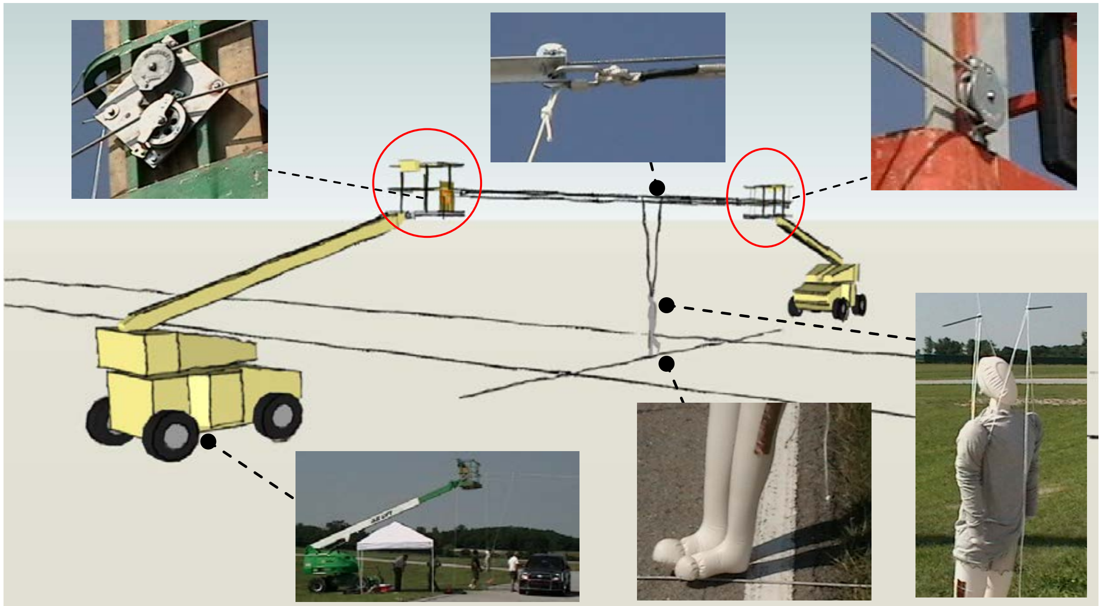


Figure 21: Test Equipment and Setup for Pedestrian Crossing-Path Testing

Note: The towing system is not shown in this figure. The towing system was positioned along the track and connected with a looped rope through the pulleys attached to the booms.

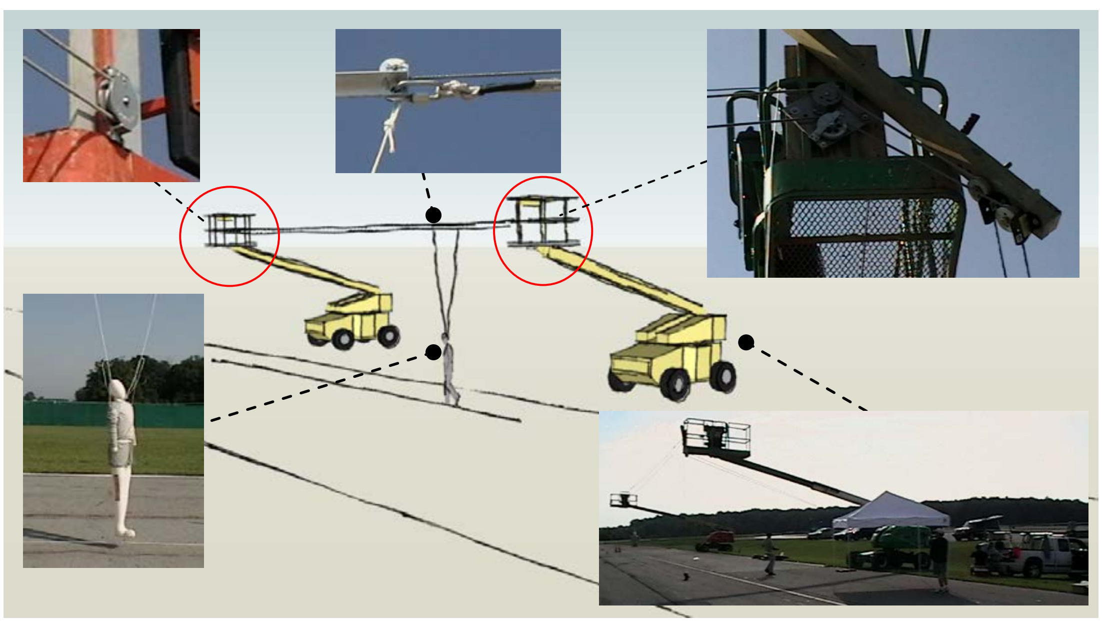


Figure 22: Test Equipment and Setup for Pedestrian In-Path Testing

Note: In the scenario shown in this figure, the towing system is located on the rear hitch of the white truck in the lower right photo.

4.2.3 Test Methods Not Validated (Beyond Scope of CIB Project)

The test methods designated as 'Not Validated – Beyond Scope of CIB' are described below for the various functional tests. These tests included the SCP, LTAP-OD, OD and the Pole/Tree scenarios.

4.2.3.1 Straight Crossing Path (SCP)

The SCP test method simulates an intersection collision where two vehicles collide at 90 degrees, as shown in Figure 23. The final test methodology utilized a balloon car target and an automated target tow system to move the target in the desired manner (see Appendix L, Section L.5 for a more detailed description).

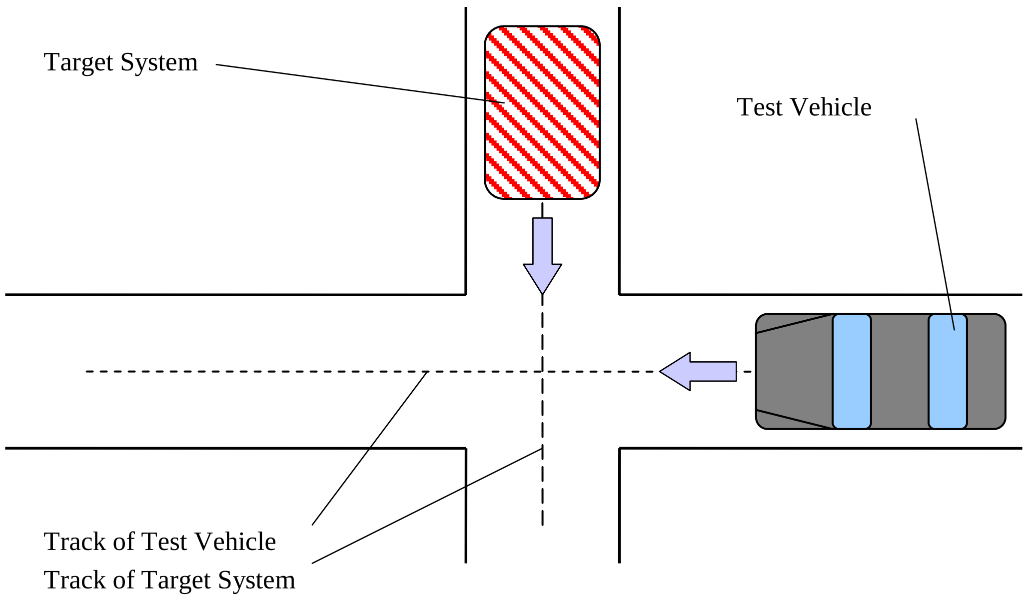


Figure 23: Test Vehicle with a Movable Target - Across Path

4.2.3.2 Left Turn Across Path (LTAP-OD)

LTAP-OD represents the only test scenario that involved turning targets struck by the test vehicle developed within this project. The final test methodology utilized a balloon car target and an automated target tow system to move the target in the desired manner. Figure 24 shows the preliminary scenario graphic for the LTAP-OD test scenario. Detailed test specifications can be seen in Appendix L, Section L.6.

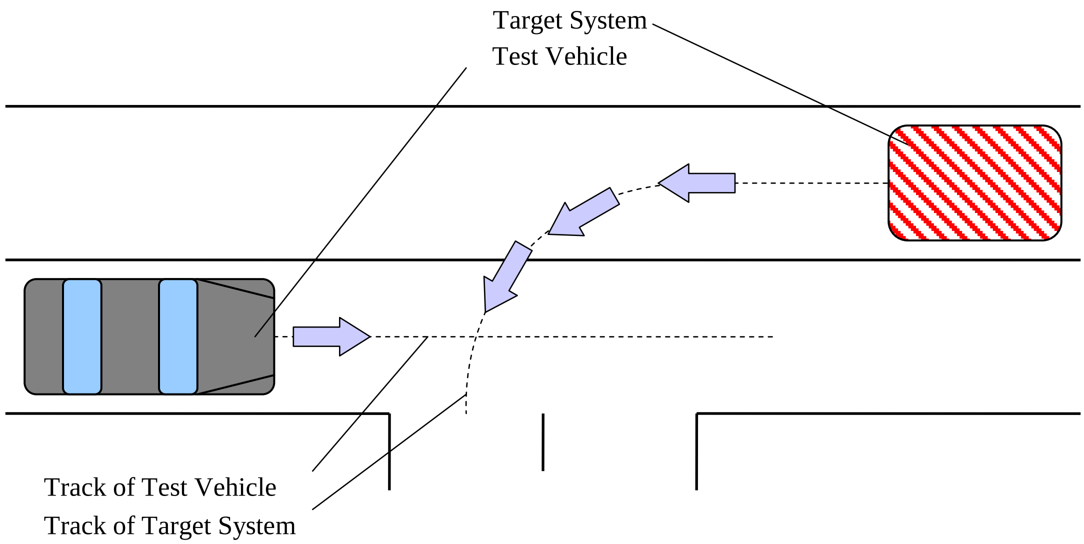


Figure 24: Overview of Test for LTAP-OD

4.2.3.3 Opposite Direction (OD)

The opposite direction (OD) test method simulates a head-on crash scenario, as shown in Figure 25. The final test methodology utilized a balloon car target and an automated target tow system to move the target in the desired manner. Detailed test specifications can be seen in Appendix L, Section L.7.

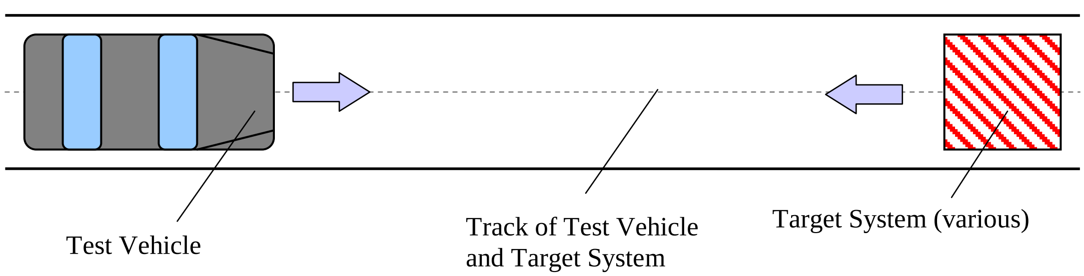


Figure 25: Test Vehicle with Movable Target - Opposite Direction (OD)

4.2.3.4 Pole/Tree

Based on the crash data analysis discussed in Chapter 2, two pole sizes and configurations were selected for testing in this scenario. These included representations of a 10 cm metal pole and a 30 cm wooden pole/tree. This scenario represented a new test configuration with no established test target options. Therefore, additional work was needed to develop target designs. These tests involved suspending a surrogate target representing a pole or tree in the path of the test vehicle. The target must be suspended in a manner which isolates the target as much as practicable from the surrounding environment as well as from the suspension structure. The target and support structure must also perform in a manner which prevents damage to the test vehicle upon impact with the target. Figure 26 contains a simple diagram of the support structure and targets used. Appendix L, Section L.8 presents additional detail of the test apparatus and methodology developed for this phase of testing.

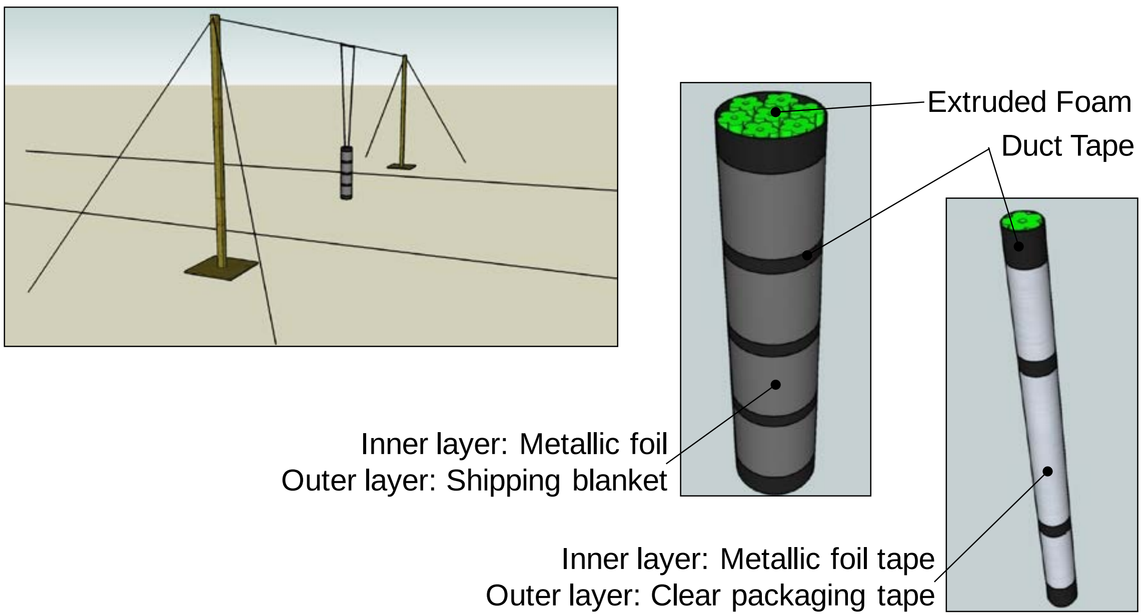


Figure 26: Pole/Tree Target Configurations

The graph shown in Figure 27 displays the radar correlation measurements made between the simulated wood pole/tree target and sample pole and trees measured. Upper and lower bounds were developed using 4^{th}-order polynomial trend-lines of the average sample pole measurements ± 1 standard deviation. These trend lines, the average values of all of the sample pole measurements and the large pole target measurements, are highlighted in Figure 27.

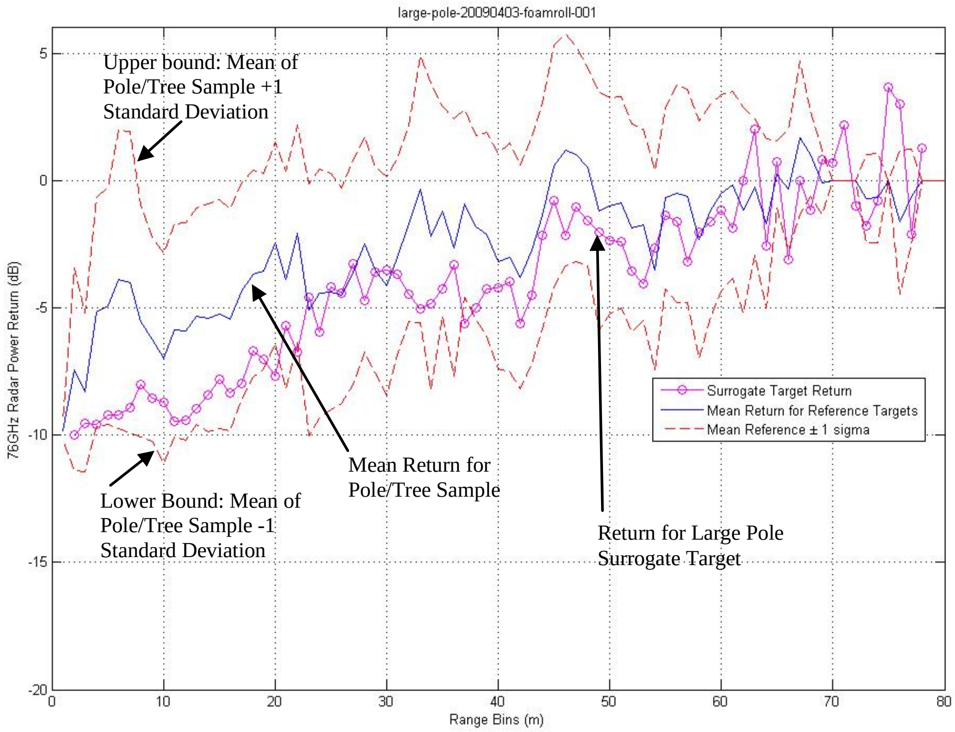


Figure 27: Correlation between Simulated Pole/Tree Target and Actual Poles

4.3 CIB Functional Test Method Results

The following sections provide overviews of the test results generated during the various phases of the CIB test method development. Test results are organized based upon the assigned validation category of the associated test scenario. Appendix L, Section L.10 contains a complete set of test results for each scenario from all test phases.

The test data associated with the Stereo-Vision system in PIP Vehicle E is reported separately in Section 4.3.4 for the following reasons. Due to the developmental nature of this technology, the Stereo-Vision system exhibited an operational limitation which affected the level of information available during testing. Because of this limitation, direct comparison of the test data between the Stereo-Vision system and all other CIB sensor combinations was not possible (and hence, is reported separately).

4.3.1 Test Methods Validated

The following sections highlight the test results for each of the validated test methods.

4.3.1.1 Lead Vehicle Stopped (LVS)

Detailed LVS test results for each of the test development and validation phases are included in Appendix L, Section L.1. For the test validation phase, each of the PIP test vehicles was tested with the sensor sets described previously in Section 3.5, Table 23. Each vehicle was tested at three different initial approach speeds. For each initial approach speed, the tests were repeated a minimum of 10 times in order to assess the repeatability of the system performance.

Some sensor sets were evaluated based on simulated runs. That is, the collected data was structured such that it could be replayed through a software simulation of the sensing system. This allowed the system performance to be analyzed for different sensor combinations without the added time and expense of running additional track tests. For example, as shown in Figure 28, two sets of test track data for Vehicle E were used to simulate the data for two additional sensor combinations, resulting in a total of four sensor combinations.

For each set of runs, this diagram shows the average speed reduction in m/s and the corresponding standard deviations. The speed reduction scale is located on the left. The diagram also displays the distribution of brake / no brake situations. The x-axis provides information about the test vehicle used for the tests, the test vehicle and target system initial test speeds, the sensing system tested, TTC and system deceleration settings. This explanation applies to all track and simulation result diagrams in this section.

Under the LVS test condition, Vehicle E showed very small speed reduction values despite the high deceleration setting used on that system. This was due to the short TTC setting combined with a relatively high lag time within the autonomous braking system. In the Mono-Vision condition, braking activations for Vehicle E occurred in approximately 50% of the tests. Speed reductions for Vehicle F tended to decrease in this test scenario as test vehicle speed increased. However, the system in Vehicle F activated during 100% of the LVS tests conducted. Vehicle G, on the other hand, provided a relatively consistent speed reduction of approximately 5 m/s when it activated, but the activation rate was approximately 75% for all test speeds. Variations in test speeds were relatively small for all vehicle configurations tested, with Vehicle G variation trending higher than the others.

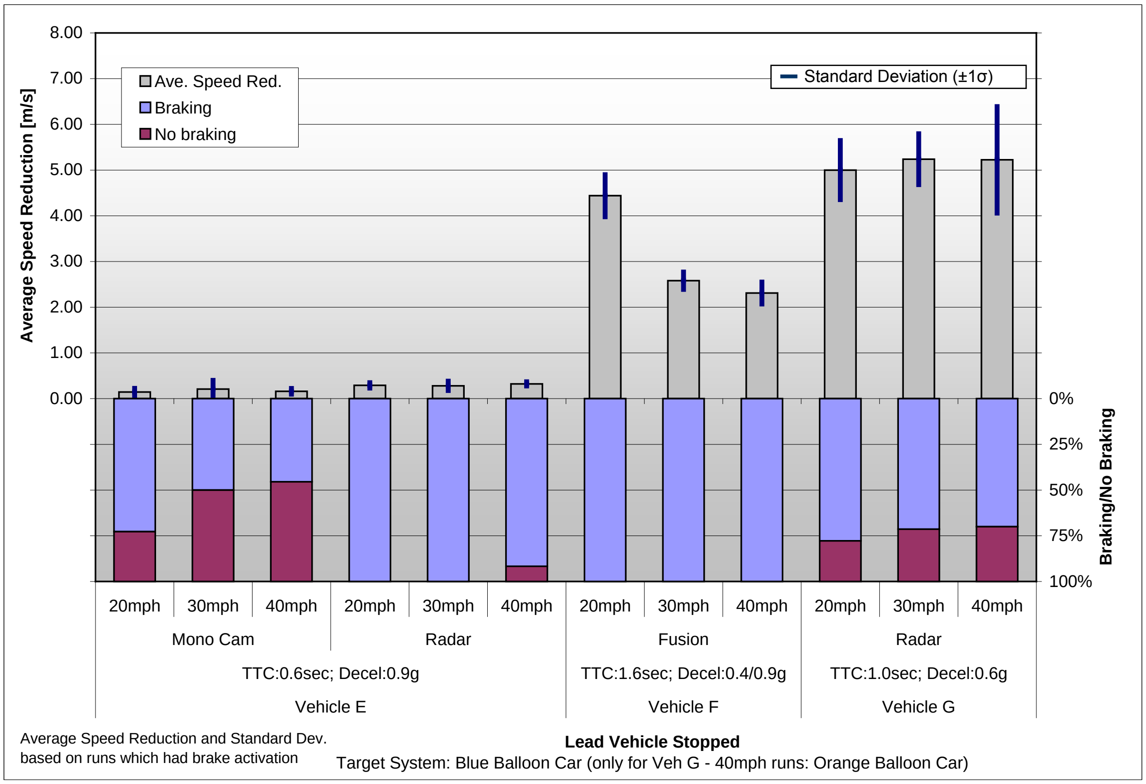


Figure 28: All Test Track Results for LVS Scenario

4.3.1.2 Lead Vehicle Moving (LVM)

Detailed LVM test results for each of the test method development and validation phases are included in Appendix L, Section L.2. The results from the validation tests of the LVM scenario (see Figure 29) are comparable to those found with the LVS scenario (Figure 28). Similar to the LVS results, Vehicle E showed very small speed reduction values in this test scenario. In the Mono-Vision condition, braking activations often did not occur with Vehicle E. Vehicle F had about a 6 m/s speed reduction across all tests, whereas Vehicle G provided the single highest speed reduction in a test where a 40 mph vehicle approached the target moving at 20 mph. Relative to the LVS scenario, results were more variable in the LVM scenario owing to the additional variation caused by the movement of the balloon car and the sensing of this movement. For all vehicles, this resulted in a wider variance of the measured speed reductions for a given test run set.

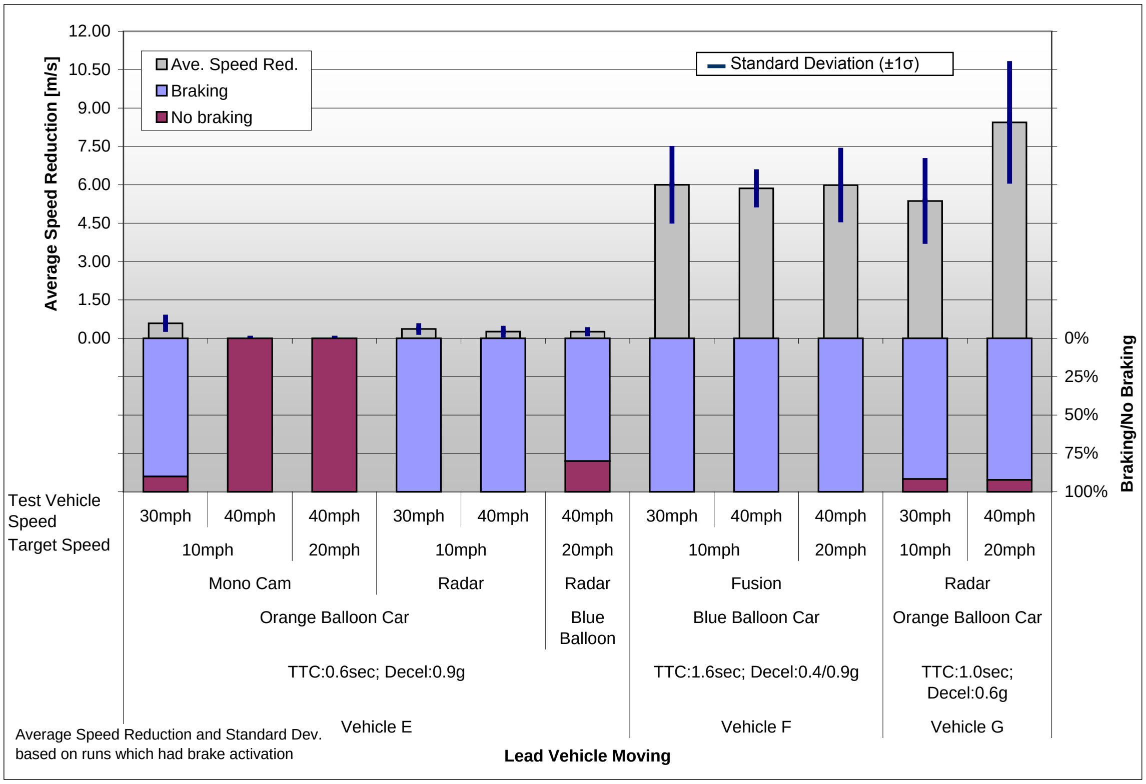


Figure 29: All Track Test Results for LVM Scenario

4.3.1.3 Lead Vehicle Decelerating (LVD)

Detailed LVD test results for each of the test development and validation phases are included in Appendix L, Section L.3. For this set of tests, a time headway (or following time) of two seconds between the vehicle and the balloon car was used. A 2-second following time equates to 17.8 m of separation for the initial test speed of 20 mph. After the defined separation distance and initial speeds were stabilized, the tow system decelerated the balloon car at a specified rate. In these LVD tests, Vehicle F and Vehicle G exhibited high numbers of brake activations and higher speed reduction values than Vehicle E (see Figure 30).

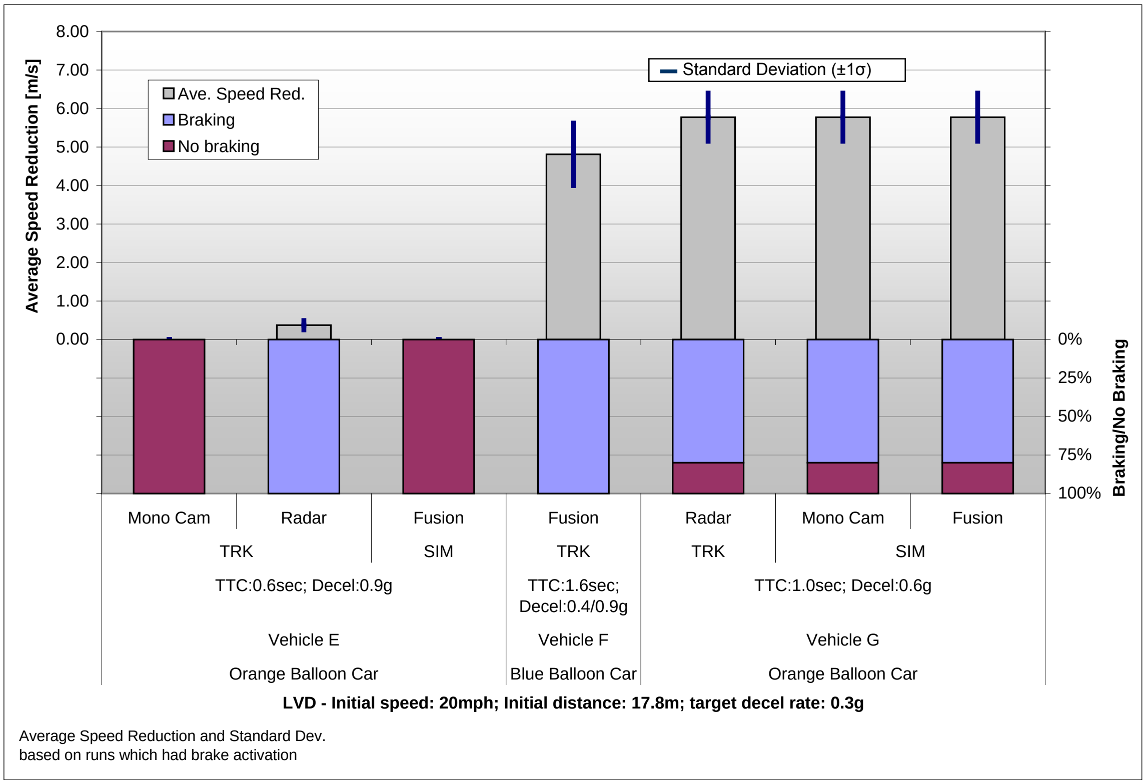


Figure 30: All Track Test and Simulation Results for LVD Scenario

4.3.2 Test Methods Not Validated (Further Development Required)

The following section highlights the test results for the test methods designated as 'Not Validated – Further Development Needed.' The Pedestrian In-Path and Pedestrian Crossing Path were the two test methods that were included in this category.

Since an acceptable test mannequin target was not available during the Baseline Vehicle testing or the PIP development testing, no testing for Pedestrian scenarios was conducted during these testing phases. Detailed test results for the test method validation phase are included in Appendix L, Section L.4. No brake activations (and hence, speed reductions) occurred in the Pedestrian Cross-Path scenario. For the Pedestrian In-Path runs, only Vehicle G exhibited brake activations. Results from the Pedestrian Cross-Path scenarios are provided in Figure 31. Note that Fusion results are fully dependent on (and identical to) the Radar results because radar information was used to establish the Fusion performance.

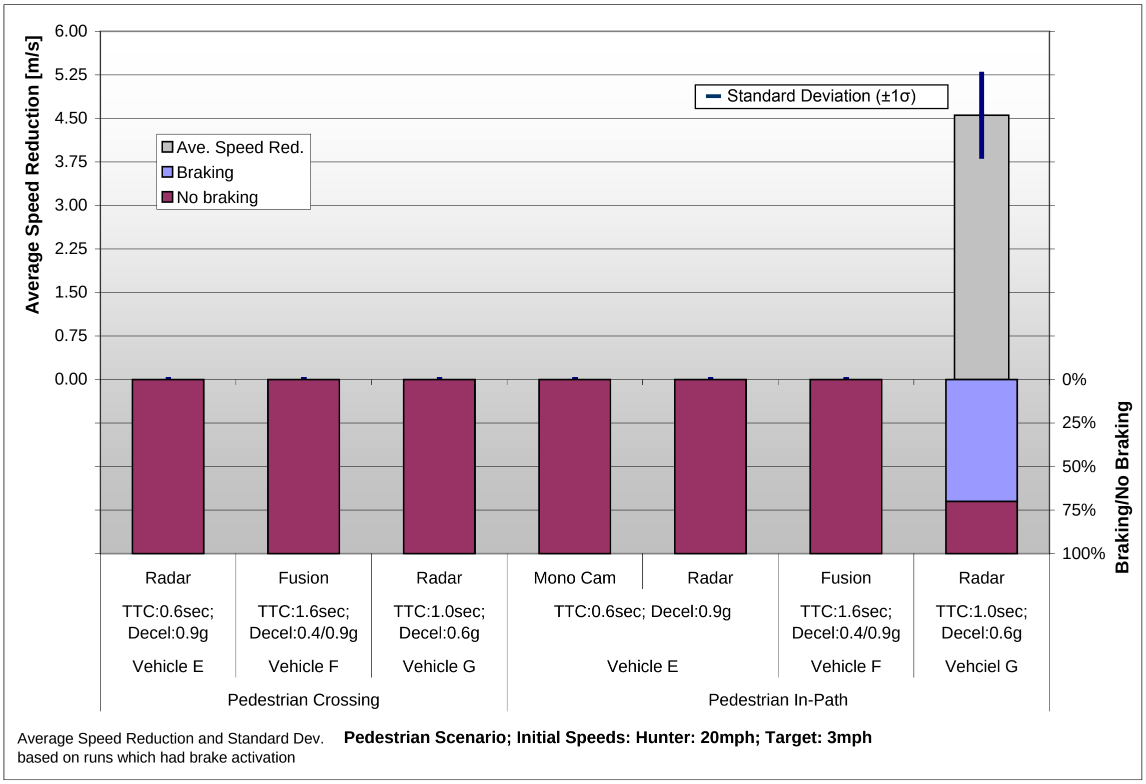


Figure 31: All Track Results for Pedestrian Cross-Path and Pedestrian In-Path Testing

4.3.3 Test Methods Not Validated (Beyond Scope of CIB Project)

The following sections highlights the test results for the test methods designated as 'Not Validated – Beyond Scope of CIB Systems.'

4.3.3.1 Straight Crossing Path (SCP)

Detailed SCP test results for each of the test method development and validation phases are included in Appendix L, Section L.5. Analysis of the baseline data indicates that the three baseline CIB braking systems did not respond to a straight crossing path test. Only vehicle C had triggered a warning in the testing but this was due to a late impact where the target vehicle entered the intersection prematurely. Vehicles A, B and C did not provide any autonomous braking for the test target used over the speed ranges tested.

Testing for the PIP vehicles during the test method development phase showed that none of the vehicles responded to the straight-crossing path target and test process. Furthermore, during this phase of testing, insufficient data was available from the Stereo-Vision system installed on Vehicle E to determine whether any of the sensing technologies and algorithms was capable of responding to this test scenario.

For the test method validation phase, Vehicle E was the only vehicle tested for the SCP scenario, primarily to assess whether this scenario could potentially be applicable to the Stereo-Vision system. The test data from the Stereo-Vision system for all test scenarios is documented later in Section 4.3.4. For data collected from the radar and mono-camera systems, there were very few activations of the system and all activations came from the radar sensor. For cases in which braking did occur, very little speed reduction was observed, as shown in Figure 32. Only four of the 31 runs resulted in brake activations, all of which occurred during the 20 mph test vehicle and 10 mph target test scenario.

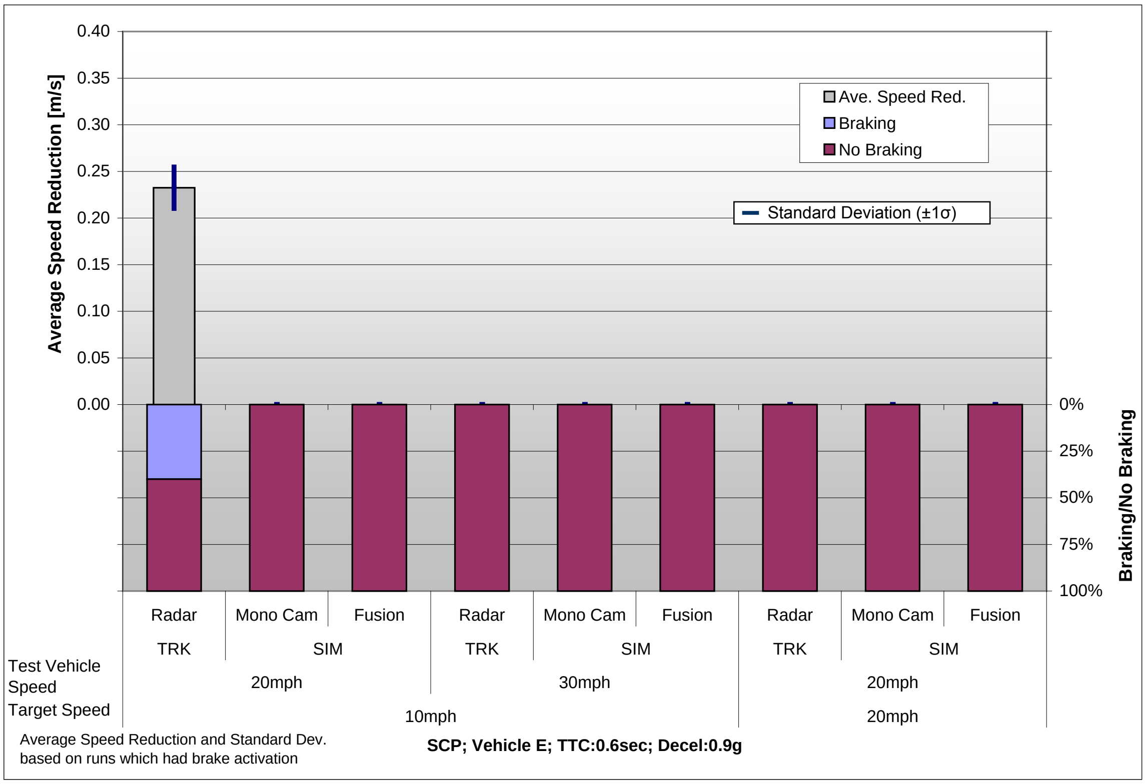


Figure 32: Track Test Results for SCP Scenario

4.3.3.2 Left Turn Across Path (LTAP-OD)

Detailed LTAP-OD test results for each of the test method development and validation phases are included in Appendix L, Section L.6. From the baseline vehicles tested, a total of seven runs were completed at the selected test speeds. None of the vehicles reacted to the LTAP-OD test scenario. Vehicle A was tested two times with no reaction, Vehicle B was tested three times with no reaction and Vehicle C was tested two times with no reaction.

For the PIP test method development phase, the automated balloon car tow system described in Appendix G was available. That made it possible to conduct several test series with different test speeds and all three PIP vehicles. Tested speed combinations were 20 mph for the test vehicle versus 10 mph for the target, 30 mph for the test vehicle versus 10 mph for the target, and 20 mph for both. None of the vehicles' systems reacted with any braking in this scenario regardless of which sensor combinations, TTC and deceleration settings were used. Overall, 32 test runs were completed. During this phase of testing, insufficient data was available from the Stereo-Vision system installed on Vehicle E to determine whether this system was capable of responding to this test scenario.

Since the remaining two vehicles had demonstrated in earlier testing that they would not brake for this test condition, Vehicle E was the only vehicle tested for this scenario in the test method validation phase. This was done primarily to assess whether this scenario could potentially be applicable to the Stereo-Vision system. The test data from the Stereo-Vision system for all test scenarios is documented in Section 4.3.4. For Vehicle E there were no brake activations from the radar, mono-camera, or fusion systems and hence, no speed reductions observed.

4.3.3.3 Opposite Direction (OD)

Detailed OD test results for each of the test method development and validation phases are included in Appendix L, Section L.7. From the baseline test vehicles, two of the CIB systems did not respond to an opposite direction test. Vehicles A and C did not provide any autonomous braking for any of the test targets used. The third vehicle, Vehicle B did respond to each of the oncoming test targets used for this testing. Braking for this vehicle was higher at lower closing speeds relative the higher closing speeds used for the testing.

The testing for the PIP vehicles indicated that none of the vehicles responded to the opposite direction targets and test process. There was also no speed reduction, since none of the systems activated the braking system.

Vehicle E was utilized to conduct a set of 10 runs for each of the three different initial/target speed combinations primarily to assess whether this scenario could potentially be applicable to the Stereo-Vision system. The test data from the Stereo-Vision system for all test scenarios is documented in Section 4.3.4. During these test runs, both the Radar and Stereo-Vision systems were active, whereas the Mono-Vision and Fusion results were later simulated. No braking events were noted in these test runs and, therefore, no speed reductions were observed. This is consistent with earlier testing from the baseline and development phases of the project. As indicated above, Vehicles F and G were also not used in this OD testing because PIP test data indicated they would not have brake activations for this test scenario.

4.3.3.4 Pole/Tree

Detailed pole/tree test results for each of the test method development and validation phases are included in Appendix L, Section L.8 As shown in Figure 33, results with the small Pole target indicated that only Vehicle G exhibited brake activations (and hence, any speed reductions). For this vehicle, the percentage of brake activations and speed reductions were similar across initial test speeds.

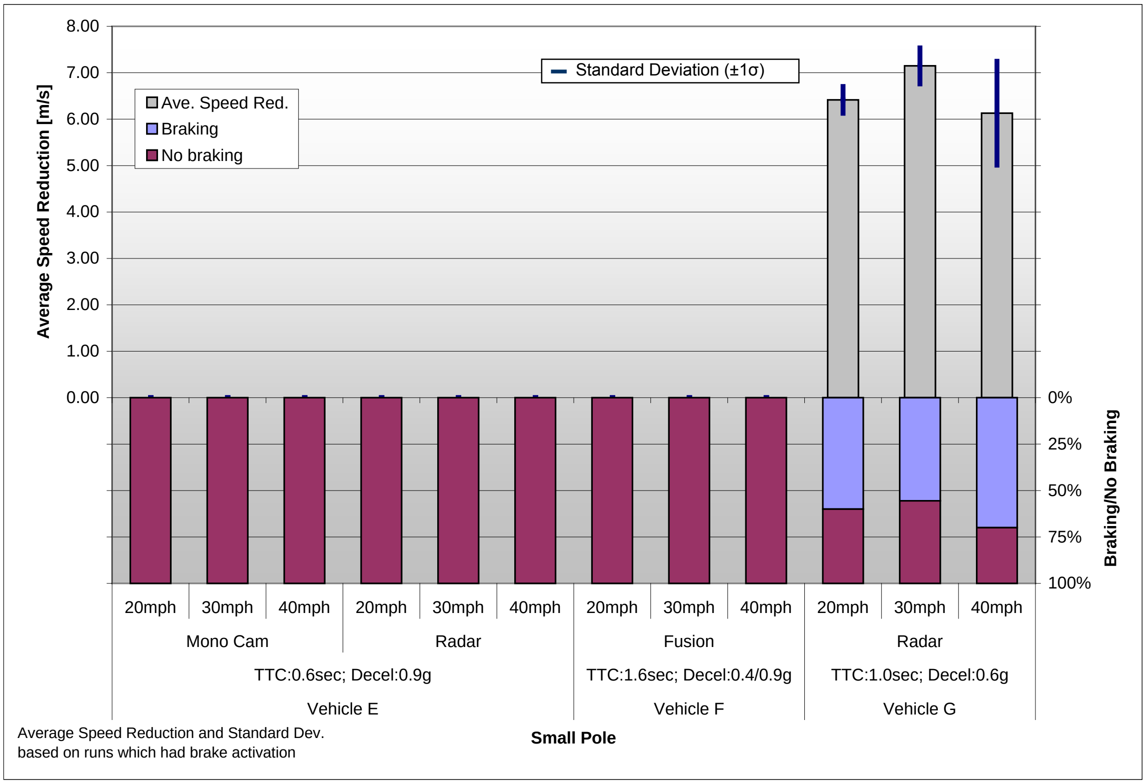


Figure 33: All Track Test Results for Small Pole

As shown in Figure 34, results with the large pole target indicated that overall, brake activations either did not occur or only occurred rarely with about half of the Vehicle-Sensor Combinations evaluated. Vehicle G had a higher amount of brake activations across all initial speeds. The Vehicle F Fusion system had a few activations at the lower speeds and the Vehicle E Radar system activated more often at higher speeds.

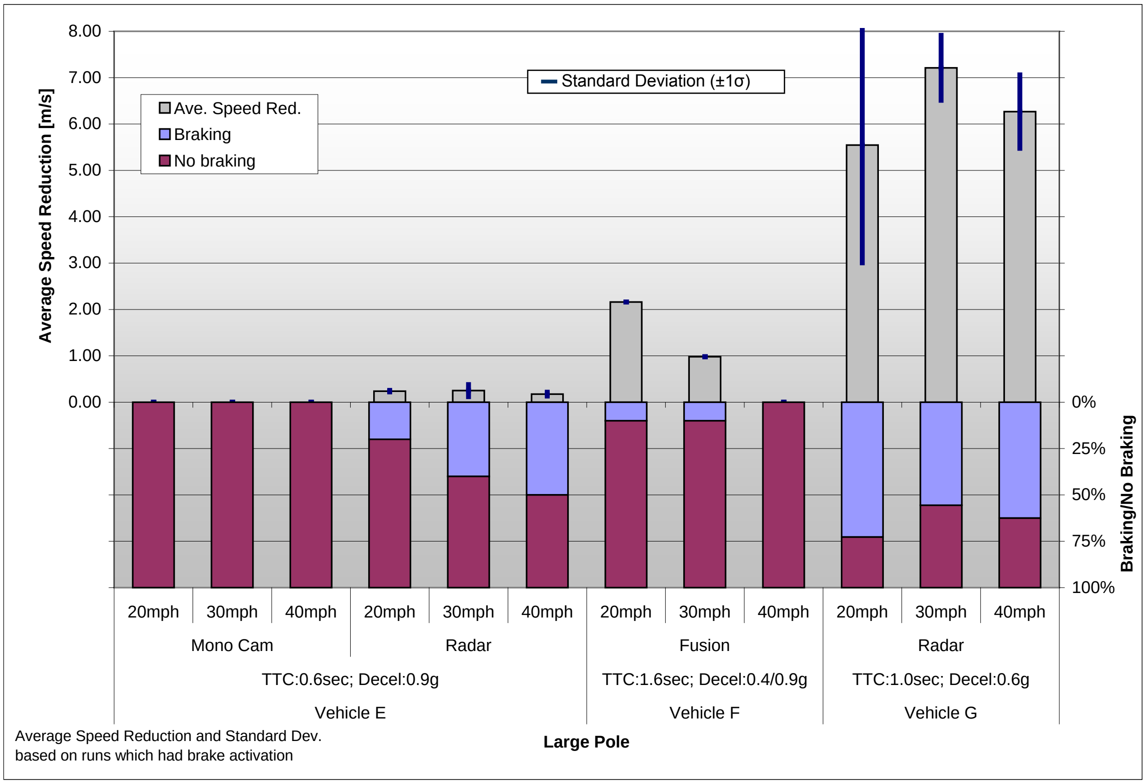


Figure 34: All Track Test Results for Large Pole

4.3.4 Stereo-Vision Test Data

The developmental nature of the Stereo-Vision system installed in Vehicle E exhibited an operational limitation which affected the level of information available from that system. During the PIP test method development phase, output from the Stereo-Vision system did not include a functional autonomous brake command since the vehicle interface system was not yet developed. Therefore, the tests during that phase of the project were limited to assessment of the capability of that system to track various targets and the accuracy of the sensor measurements. During the test method validation phase, an embedded CIB control algorithm was added to the Stereo-Vision system that enabled output of a recordable signal which indicated when the system would initiate a brake command at various TTC levels (without triggering actual CIB system brake activations). Consequently, this data on braking "trigger point" was used along with the test results collected from the other CIB functions of the vehicle to determine expected system performance associated with the Stereo-Vision sensors (and algorithm) for each of the test scenarios.

Table 29 provides results across the various test scenarios for the Stereo-Vision sensors. This table indicates the percentage of tests in which the test target was detected, the percentage of tests in which brake commands were sent at each of three TTC settings, and the percentage of sensor measurements which fell within the accuracy limits of the manufacturer as compared to the ground-truth data. The "Performance Limit" measurements refer to the percentage of tests where sensor range measurements fell within ± 10% of the ground-truth data.

Table 29: Test Data Summary for Stereo-Vision System in Vehicle E

Data Set Name	Valid Sequences	Target Tracked	Braking Command			Performance Limit		
			TTC=1 sec	TTC=0.6 sec	TTC = 0.3 sec	TTC=1 sec	TTC=0.6 sec	TTC = 0.3 sec
Small Pole	30	100%	100%	100%	100%	80.0%	83.3%	96.7%
Large Pole	30	100%	100%	100%	100%	90.0%	90.0%	96.7%
LVM	47	100%	100%	100%	100%	N. A.	N. A.	N. A.
LVS	42	100%	100%	100%	100%	98.0%	100%	100%
LTAP-OD	9	100%	55.6%	77.8%	100%	N. A.	N. A.	N. A.
Pedestrian Crossing	4	100%	50.0%	100%	100%	50.0%	75.0%	100%
Pedestrian In-Path	21	100%	100%	100%	100%	N. A.	N. A.	N. A.
OD	35	100%	100%	100%	100%	N. A.	N. A.	N. A.
SCP	15	93.3%	53.3%	73.3%	93.3%	N. A.	N. A.	N. A.

This data shows that in cases where the targets crossed the path of the test vehicle (i.e., LTAP-OD, Pedestrian Crossing, SCP), CIB system braking commands were issued in less than 100% of the test runs. There appears to be a trend for low activation rates at the higher TTC settings. This may be due to the more limited length of time in which the target is within the sensing system field of view prior to target impact. In the remaining "straight ahead" vehicle-to-vehicle, pole, and pedestrian in-path scenarios, braking commands were always recorded across all TTC settings.

Furthermore, performance limits shown in Table 29 indicate that potential measurement errors would likely affect overall CIB performance. Unfortunately, in slightly more than half of the test conditions, performance limits could not be determined due to insufficient synchronization between the ground truth measurement system and the Stereo-Vision data acquisition system. This synchronization issue became apparent during post-processing of the test data.

Overall, although these results demonstrate the capability of the Vehicle E Stereo-Vision system to detect the test targets and trigger a brake command, insufficient data exists to determine CIB system performance with this system. Due to this limitation, as was mentioned earlier, test results from this system are not included within the specific test scenario sections detailed earlier in the report.

4.4 Functional Test Method Conclusions

The following sections provide summaries of the functional test method conclusions based upon the results documented above. Conclusions are organized based upon the assigned validation category of the associated test scenario. Appendix L, Section L.10 contains a complete set of test methodologies for each scenario.

4.4.1 Validated Test Methods

The following sections summarize the conclusions for the test methods designated as 'Validated.'

4.4.1.1 Lead Vehicle Stopped (LVS)

Results from the LVS scenario testing support the feasibility and repeatability of the LVS test method across a wide variety of CIB sensing technologies. By employing a variety of TTC and deceleration settings as CIB system braking criteria and using different CIB sensor configurations, the robustness of LVS test method was demonstrated. It was also shown that this method is applicable to CIB systems using either 1-stage or 2-stage automatic braking approaches. Overall, the large number of system activations and analysis show that the LVS test method is repeatable and able to distinguish between CIB system performance levels/settings. Based on these LVS results, this test scenario was classified as a validated test method.

4.4.1.2 Lead Vehicle Moving (LVM)

As with the LVS test method, the LVM scenario was proven to be accurate and repeatable. This test method was also shown to be capable of differentiating between various CIB system configurations and settings. These favorable results were enabled by the automated balloon car tow system, the target towing control unit and accurate GPS data. The tested systems typically exhibited either many CIB activations or almost no activations. As noted in the data analysis, the speed reduction values display a greater variation than in the Lead Vehicle Stopped scenario. This is attributed to the additional variation introduced by the balloon car movement and the sensing of this movement by the tow system. Based on these LVM results, this test scenario was classified as a validated test method.

4.4.1.3 Lead Vehicle Decelerating (LVD)

The LVD test scenario was successfully developed and performed on all three test vehicles, and was able to invoke CIB activations consistently. However, the accuracy of the balloon car speed and distance measurements needs to be addressed in future research (see Appendix M for more information). As the deviations across measurement systems within the data indicate, the precise timing of the balloon car deceleration relative to the approaching test vehicle was difficult to reproduce accurately. That said, the LVD test scenario speed reduction results were proven to be repeatable even with these deviations in the data. The test data also indicates that the LVD test method is able to distinguish between various CIB system configurations and settings. Based on these LVD results, this test scenario was classified as a validated test method.

4.4.2 Test Methods Not Validated (Further Development Required)

Although the Pedestrian scenario testing successfully demonstrated this test method could be executed in a repeatable manner, further development work is recommended to provide a smoother and more realistic movement for the simulated pedestrian (including improvements to target stability and attachment friction). Due to the low frequency of braking activations during these tests, the capability of this method for being sensitive to different levels of CIB system performance could not be fully established. Hence, the Pedestrian In-Path and Crossing Path test scenarios were classified as “Not Validated.” However, sufficient evidence exists that suggests this test method may still be applicable for CIB system technologies, although more likely for future applications. Therefore, additional research is recommended to more fully develop a more representative set of pedestrian scenario tests.

4.4.3 Test Methods Not Validated (Beyond Scope of CIB Project)

The test methods representing Straight Crossing Path, Left Turn Across – Opposite Direction, Opposite Direction, and pole/tree crash scenarios were all designated as ‘Test Method Not Validated – Beyond Scope of CIB Project.’ While test scenarios were developed and demonstrated for these crash conditions, CIB system performance, regardless of system configuration or settings, were not capable of reliably responding to these tests. Due to the difficulty in predicting the pre-crash events that lead up to these crash types, the difficulty in balancing CIB activations for these crashes with potential increases in undesirable false activation, and many other factors, these scenarios are also not likely to be near-term deployable features of CIB systems and may be better addressed through other active safety technologies.

4.5 Non-Activation Tests for Operational Scenarios

4.5.1 Real-World Operational Assessment Data (ROAD) Trip Overview

CIB systems need to be able to quickly and accurately sense and analyze emerging crash situations. A wide variety of CIB sensing technologies have been employed by various original equipment manufacturers (OEMs) and suppliers. Each of these solutions has unique strengths and weaknesses. For example, environmental factors may lead to unintended responses with the various sensing systems. Furthermore, these factors may not be the same for different sensing technologies and can also be region specific (e.g., color of aggregate in the road surface, cactus, tumbleweeds, Bott’s dots, roadside signs, highway patching methods, traffic flow, etc.). In order to evaluate the sensitivity and robustness of various sensors examined in this project, it is necessary to expose them to a wide a variety of situations and environments. In general, the kinds of situations that can result in CIB system false positive actuations tend to be subtle and highly dependent on both the sensor type(s) and environment. In order to develop a useful test method for detecting a system’s robustness to false CIB system brake activations (i.e., “false positives”), it is important to understand how each sensor type responds to a rich set of realistic driving environments. To this end, a Real-World User Profile (RWUP) was derived (shown in Table 30) based on research conducted by Hu and Young (1999) for the Federal Highway Administration (FHWA). This previous research formulated a general driving mix (e.g., miles per road type) of a typical driver over their lifetime.

Table 30: Real-World User Profile

Road Type	Description	Examples in Metro Detroit	Assumptions	% of Time Driven (approx)	% of Miles Driven (approx)
Interstate/ Freeways/ Expressways	Freeways, Interstates and Expressways, usually divided, with at least two lanes in each direction, and full or partial access control	I-75, I-94, Southfield, M14, etc.	high average speed	20%	30%
Urban Arterials	A road whose principal function is to serve major through-traffic movements between major traffic routes (collectors). Often divided with median. Parking is often prohibited on these roads and driveway placement is severely restricted.	Telegraph Rd, Ford Rd, etc.	medium average speed	20%	30%
Rural Arterials	A road whose principal function is to serve major through-traffic movements between major traffic routes (collectors). In rural areas, arterials link cities and larger towns.	Plymouth Rd from Plymouth to Ann Arbor	medium average speed	15%	15%
Urban Collectors	A road whose principal function is to provide direct access between local roads and arterials. Collectors may provide some access to adjacent properties; however, more restrictions are placed on on-street parking and driveway placement.	Rotunda, Oakwood, Pelham, etc.	medium average speed	15%	10%
Rural Collectors	A road whose principal function is to provide direct access between local roads and arterials. In rural areas, collectors serve intra-county rather than statewide traffic.	Michigan State Route 12	medium average speed	10%	5%
Locals	Business, residential, and rural roads not classified in above categories.	Neighborhood and Subdivision Streets	low average speed	20%	10%

In this task, a plan was devised to use two vehicles with differing sensor sets (see Table 31) to gather approximately 22,000 miles of combined total driving data on roads across the United States. As shown in Figure 35, the route stretched from coast to coast and included spending significant time in 10 major cities. The balance between different driving environments (city/highway, interstate/rural, day/night, etc.) was determined by the RWUP described in Table 30.

Table 31: Sensor Sets and System Settings for the ROAD Trip

Vehicle	Sensors
E	Long & Mid Range Radar
	Mono-Vision
	Long & Mid Range Radar & Mono-Vision Fusion
	Stereo-Vision
H	Long & Mid Range Radar
	Mono-Vision
	Long & Mid Range Radar & Mono-Vision Fusion

As shown in Figure 35 the route driven by each test vehicles was not always identical. The route traveled by Vehicle E is shown in blue in the figure while the route of Vehicle H is shown in red. Using somewhat different routes across vehicles resulted in a richer data set than would have been obtained by employing an identical route for each vehicle, since different roadways and local features of interest could be independently gathered within the higher-level trip plan. It should be noted that the discontinuities in the route of Vehicle H shown in Figure 35 are due to GPS drop outs and that other vehicle and CIB system data continued to be collected during these drop out periods.

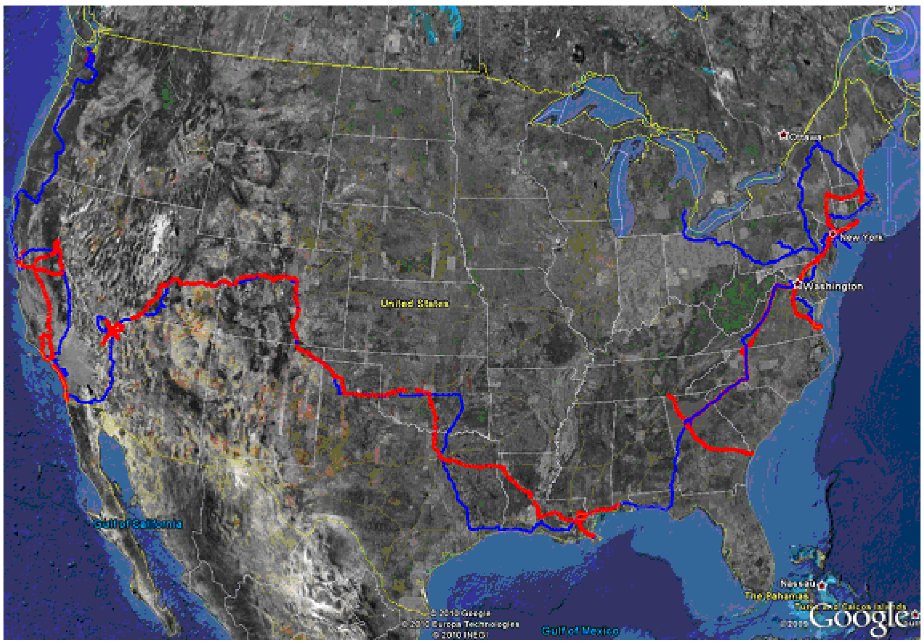


Figure 35: Actual Route Driven by Vehicle E (in Blue) and Vehicle H (in Red)

The collected data was structured such that it could be replayed through a software simulation of the sensing system. This process is referred to as "re-simulation," which allowed system performance to be analyzed for different sensitivities and sensor combinations. The CIB algorithms used can be characterized as less refined than would be typically used in production systems. Consequently, these algorithms may be more likely to identify (due to their "over-sensitivity") the types of false positive scenarios that may need to be addressed by CIB systems.

4.5.2 ROAD Trip Data Analysis

The trip was made up of a combination of "City-driving" days and "Transit" days. City-driving days were used to collect information on driving conditions in 10 major cities across the United States. This data typically included a mix of driving in downtown business areas, suburban neighborhoods and city freeways. Transit days were used to travel between major cities along the route and consisted of a balance of interstate and secondary highway driving.

Figure 36 shows a comparison of the actual speed distribution for the entire trip as compared to the expected distribution derived from the RWUP shown in Table 30. Although there are some differences shown in Figure 36 (e.g., for Vehicle E in the 0-10 mph category), overall the comparison of actual speeds traveled versus the predicted speeds is generally quite good.

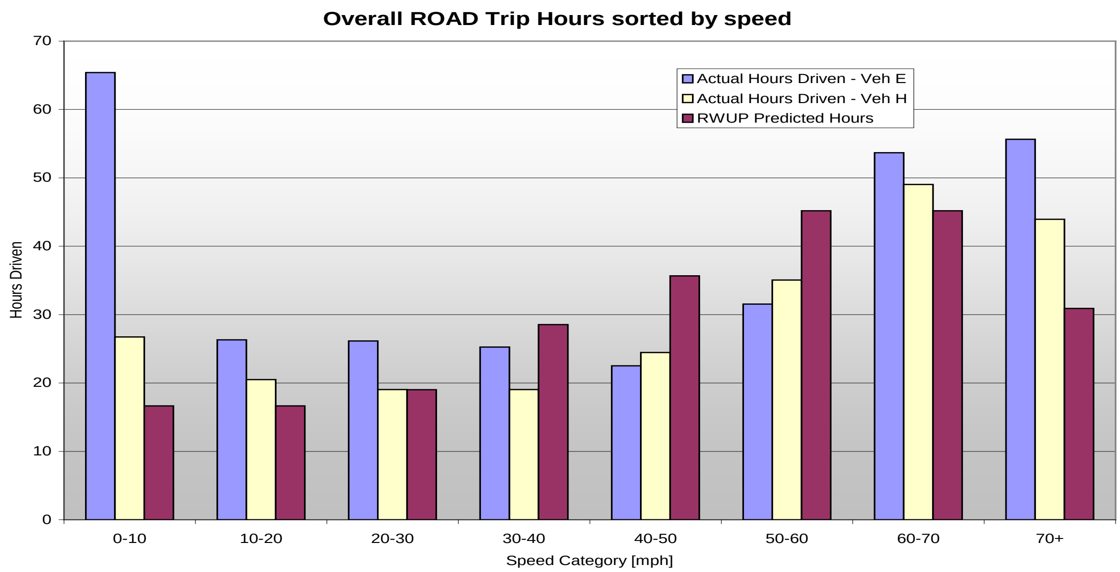


Figure 36: Actual ROAD Trip Speed Distribution vs. RWUP Predicted Distribution

As indicated in Table 31, both vehicles used for the ROAD Trip (Vehicle E and Vehicle H) incorporated sensing systems that included Long/Mid-Range Radar and a Mono-Vision system. Data from these systems was taken continuously for the entire trip and with sufficient detail to allow reprocessing later to isolate the performance of the systems in different configurations (i.e., Radar-only, Vision-only and Fused Vision and Radar). Vehicle E was also equipped with a stand-alone Stereo-Vision sensing system. Since this system did not have sufficient storage capacity to allow continuous data capture, data "snapshots" were captured for a pre-defined amount of time before and after an event of interest.

4.5.2.1 Analysis of Stand-Alone Long/Mid-Range Radar Based System

In order to evaluate the ROAD Trip data for a single radar sensor typology, it was necessary to distinguish radar-only targets from fused (radar plus vision) targets. Although a re-simulation of the ROAD Trip data provided the ability to distinguish radar-only targets from fusion targets, it should be noted that all CIB alerts recorded on the ROAD Trip were based on the fused (radar plus vision) target output. Therefore, it became necessary to create a rudimentary threat assessment algorithm for the radar-only target data based on the TTC with the closest in-path stationary, moving, or moveable target. A moveable target is one that was initially observed to be moving and has become stationary. The equations used for the TTC calculations can be found in Appendix N, Section N.2.1.

Table 32 presents the three sensitivity settings used in assessing false activation occurrence with the radar-only setup. It should be noted that determination of system sensitivity is generally considered to be a highly proprietary aspect of CIB system design and cannot be described in detail here. In this case, sensitivity is related to simple TTC (i.e., range divided by range rate), but often takes many more variables into consideration in order to increase robustness to false events. Thus, although analysis of false events within one sensor set is feasible, it is not possible to compare false events between systems from different sensor combinations. The sensitivity settings used in the analyses in this chapter for precharge and intervention braking were selected based on expert judgment and experience with the sensor systems given their current state of development.

Table 32: TTC Settings for Precharge and Intervention Braking for the Radar-Only Setup

Alert Type	Sensitivity Setting	Time to Collision (TTC) Criteria (seconds)
Precharge	Baseline	0.9
	+25% sensitivity	1.04
	+ 50% sensitivity	1.3
Intervention Braking	Baseline	0.5
	+25% sensitivity	0.6
	+50% sensitivity	0.7

As illustrated in Figure 37, the primary false precharge (“near miss”) events were associated with Curve Entry, Curve Exit, and Short Radius Turns driving scenarios. The majority of the event types examined was observed in each of the sensitivity settings. Note that in Figure 37 the Baseline + 25% and Baseline + 50% events were normalized to the total number of Baseline events, making it possible for percentage values to exceed 100%. This is can result because as the sensitivity is increased, more events are expected to occur as compared to the baseline setting.

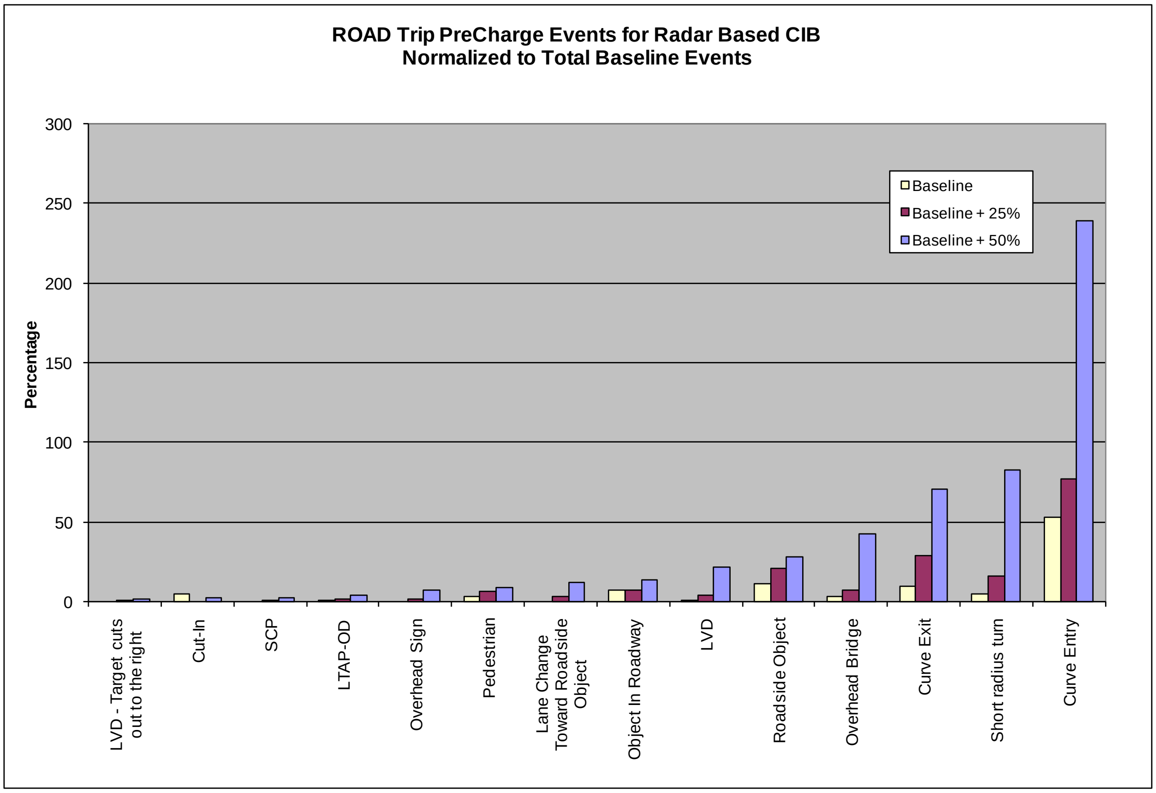


Figure 37: Radar-only Precharge Events (by Scenario)

As illustrated in Figure 38, the primary false intervention events were associated with Objects in Roadway and Curve Entry scenarios. Curve Exit, Roadside Object, Overhead Bridge, and Overhead Sign events. These event types examined were observed in each of the sensitivity settings.

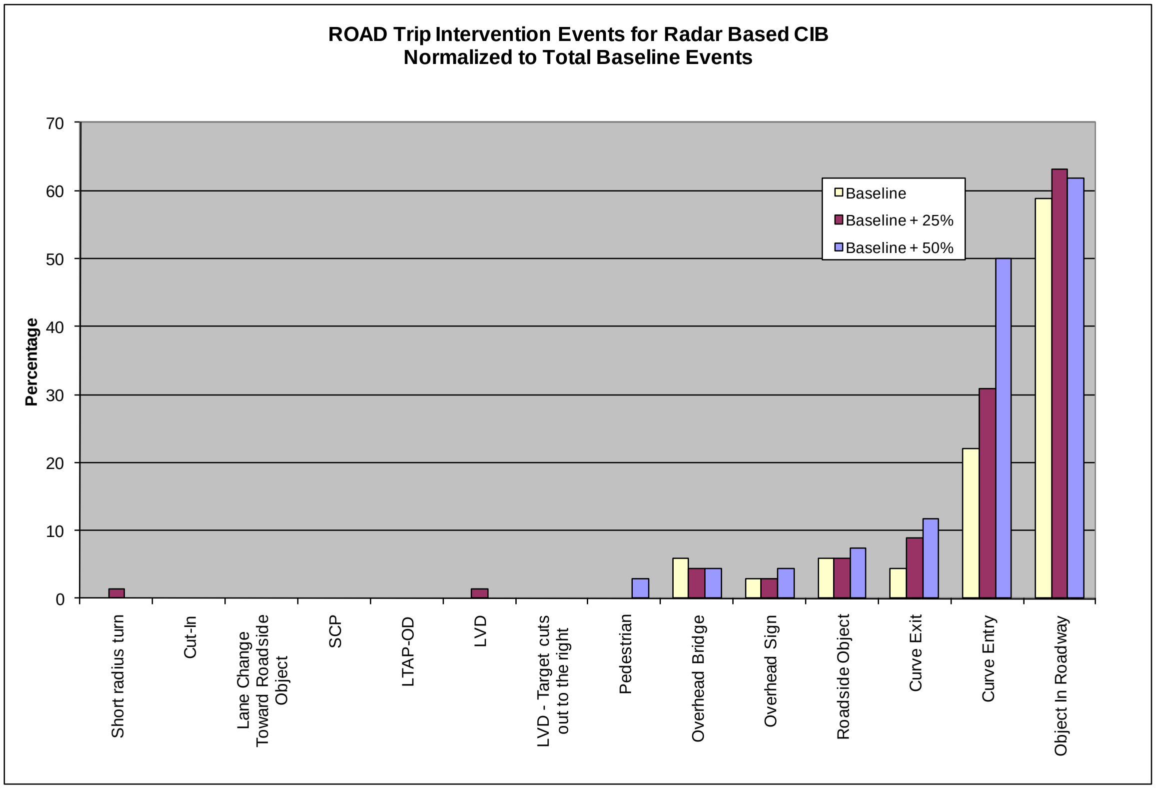


Figure 38: Radar-only Intervention Events (by Scenario)

4.5.2.1.1 Object-in-Roadway False-Event Scenario

An Object in Roadway false event can occur when the radar detects reflective objects embedded in the road, such as manhole covers, Bott's Dots, or metal grates. If the detection persists it may appear to the radar to be a stationary vehicle in the host vehicle's path, which can result in a false intervention event. Figure 39 provides illustrations of this type of scenario. While this event only accounted for a small percentage of Precharge Events, the tendency of this type of false target to persist results in it accounting for approximately 40% of false interventions at all three sensitivity settings. An analysis of the kinematics of this scenario and an illustration of the event distributions can be found in Appendix N.

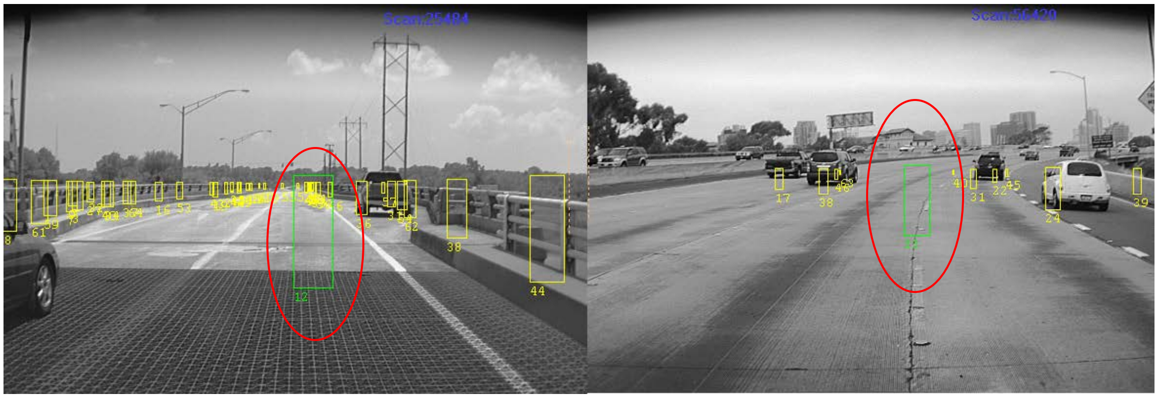


Figure 39: Objects in Roadway Detected as In-Path Targets

4.5.2.1.2 Curve-Entry False-Event Scenario

As illustrated in Figure 40, Curve-Entry false event can occur when the radar detects reflective objects on the side of the road at the entrance to a curve (i.e., before the host vehicle has actually entered the curve). This event resulted in approximately 40% of all false activations at each sensitivity setting. An analysis of the kinematics of this scenario can be found in Appendix N.

(green rectangle indicates primary target identified by radar)

Figure 40: False Activation on Stationary Object during Curve-Entry

4.5.2.1.3 Curve-Exit Scenario

Similar to the Curve-Entry scenario, a Curve-Exit event can occur when the radar detects reflective objects on the side of the road while exiting the curve. Figure 41 illustrates this type of false event. This type of event resulted in approximately 8%, 14%, and 13% of all false activations observed with the baseline threat assessment, +25% sensitivity, and +50% sensitivity setting, respectively.

(Note: this figure shows the scene exiting the first half of an S-curve)

Figure 41: False Activation on Stationary Object during Curve-Exit

4.5.2.1.4 Roadside Objects

A Roadside Object event can occur when an object that is on the side of the roadway is detected as being in the host vehicle's path. This is often the result of the host vehicle wandering within its lane or changing lanes toward a roadside object. Figure 42 illustrates this type of false event. This event resulted in approximately 9%, 10%, and 5% of all false activations observed with the baseline threat assessment, +25% sensitivity, and +50% sensitivity setting, respectively. An analysis of the kinematics of this scenario can be found in Appendix N.

Figure 42: False Events Caused by Roadside Objects

4.5.2.1.5 Overhead Signs and Bridges

An Overhead Signs and Bridges type of event can occur when the radar detects an overhead object and interprets it as being in the host vehicle's path. Figure 43 provides an illustration of this type of false event. This event resulted in approximately 5.5%, 5.5%, and 9% of all false activations observed with the baseline threat assessment, +25% sensitivity, and +50% sensitivity setting, respectively. An analysis of the kinematics of this scenario can be found in Appendix N.

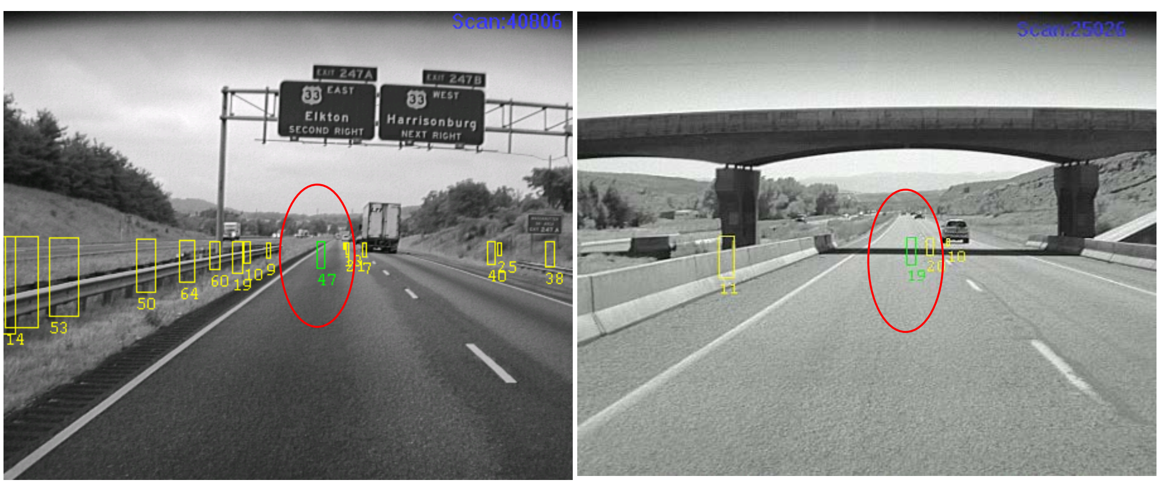


Figure 43: False Activation on Stationary Object Due to Overhead Object

4.5.2.1.6 Short Radius Turns

The Short Radius Turns event can occur when the radar detects an object while performing a low-speed turn (see Figure 44). This event resulted in approximately 3%, 7%, and 13% of all false activations observed with the baseline threat assessment, +25%

sensitivity, +50% sensitivity setting, respectively. An analysis of the kinematics of this scenario can be found in Appendix N.

Figure 44: False Activation during Short Radius Turn

4.5.2.2 Analysis of Stand-Alone Mono-Vision System

In order to evaluate the CIB data in a Mono-Vision-only configuration, the entire dataset had to be re-simulated (in order to eliminate any radar influence on the performance of the vision detection algorithms) and a new rudimentary threat assessment module was created. The baseline sensitivity of the system was set similar to that of the fusion-based system.

Since the threat assessment of the resulting system configuration was not suitably optimized for a “vision-only” sensing input, a larger number of false interventions and near misses occurred than would be anticipated in a production system. Because of the higher number of false events observed, +25% and -25% changes in system sensitivity relative to the baseline were employed (instead of using +25% and +50% as was done for the other sensing combinations). This setting approach was chosen because it was felt to provide a better indication of how false intervention performance might change with changing sensitivities, while still giving a realistic representation of potential false event scenarios.

As expected, investigation of the vision-only false events indicated that a different set of false event classification scenarios had to be defined. Mono-Vision systems do not measure range and range rate directly but instead rely on visual scene cues, such as position of the detected vehicle in the frame, and its change in size and motion from frame to frame. The majority of the observed false events appear to be the result of the perceived size or position of the detected vehicle changing abruptly across frames, usually due to other objects in the scene (e.g., shadow or road markings) being included as part of the perceived (detected) vehicle. Figure 45 shows the distribution of false precharge (“near miss”) events across sensitivity setting conditions normalized to the total number of baseline events. This was done to illustrate how the number of events changed with sensitivity settings.

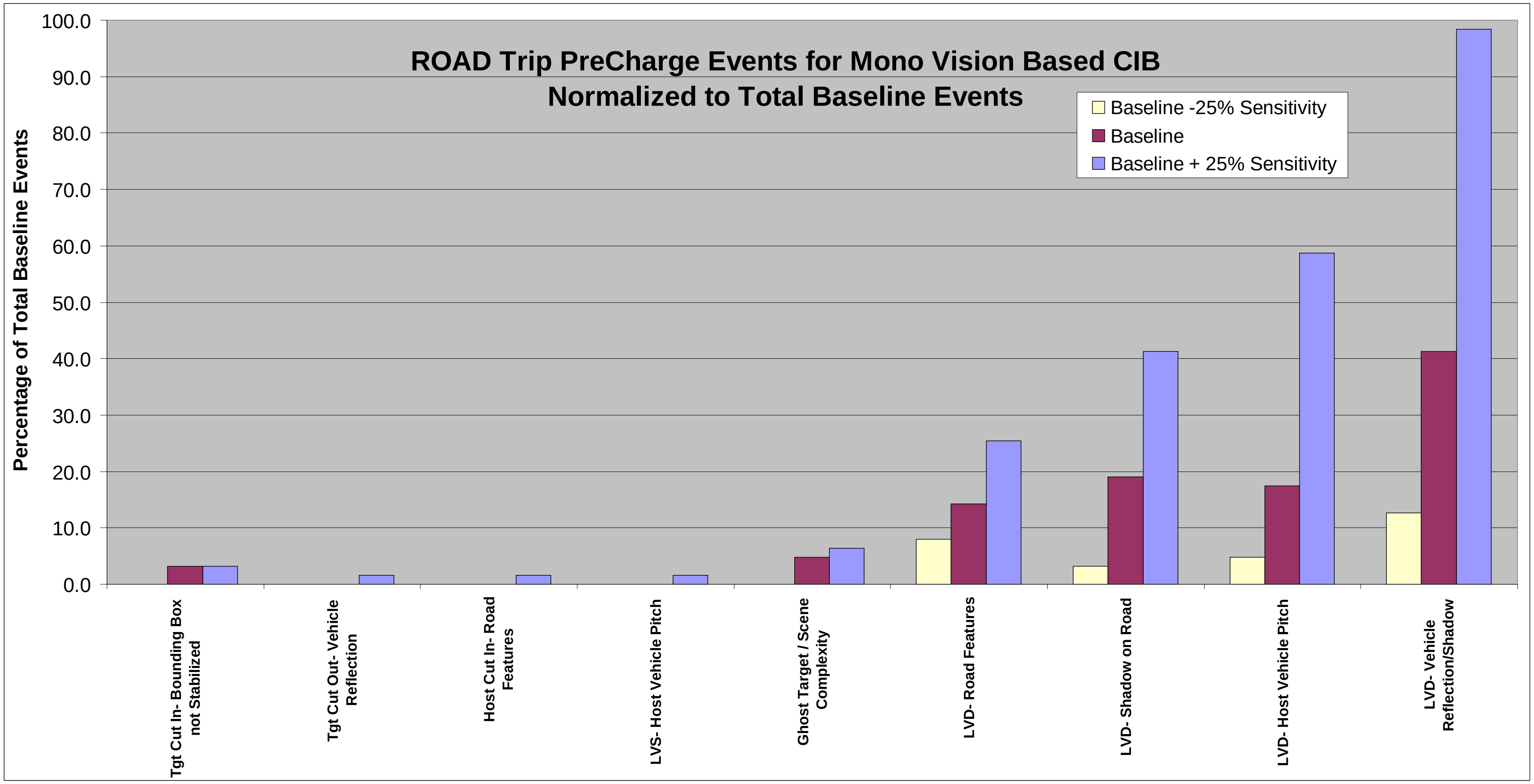


Figure 45: Scenario Classifications for Mono-Vision-Only, False, Precharge Events

Figure 45 indicates the Mono-Vision false precharge events primarily occurred during Lead Vehicle Decelerating (LVD) scenarios. These false event conditions can also be influenced and exacerbated by the deceleration profile of the lead vehicle.

An analysis of the rate of occurrence and kinematics of these false event scenarios can be found in Appendix N.

4.5.2.2.1 LVD – Road-Features

The LVD Road-Feature events occurred when the target vehicle passed over a feature on the roadway surface, such as a crosswalk marking, turn lane arrow, or discolorations on the road surface. Figure 46 shows examples of this type of false event.

Figure 46: Road Features Influencing Vision Measurement

Roadway surface features were sometimes misinterpreted as part of the target vehicle, which in turn influenced the Mono-Vision system's target size and position estimates, and hence, the threat potential of the target vehicle. Consequently, the threat assessor may falsely report the target vehicle under these conditions sooner than desired as an imminent threat.

4.5.2.2.2 LVD – Shadow-on-Road

LVD Shadow-on-Road-related events occurred when the target vehicle passed over a shadow on the roadway surface, such as those created by roadside objects like trees or buildings. Figure 47 shows an example of this type of false event.

Figure 47: Shadow-on-Road Influencing Vision Measurement

As with the LVD Road-Features events, the shadow was sometimes misinterpreted as part of the target vehicle, which in turn influenced the system's target size and position estimates, and hence, resulting in overestimating the threat potential of the target vehicle.

4.5.2.2.3 LVD – Host-Vehicle-Pitch

The LVD Host-Vehicle-Pitch events occurred when the target vehicle passed over a discontinuity on the roadway surface, such as those created by driving through intersections while going up or down a hill. Figure 48 shows an example of a large pitch change that led to this type of false event.

Figure 48: Change-in-Vehicle Pitch Influencing Vision Measurement

The resulting vehicle pitch change momentarily moves the horizon line and, thus, the position of the target vehicle in the image. This sudden movement of the target vehicle may temporarily distort the perceived size and position of the target vehicle. As a result, the threat assessor may misinterpret the target vehicle as an imminent threat.

4.5.2.2.4 LVD – Target-Vehicle-Reflection/Shadow

The LVD Target-Vehicle-Reflection/Shadow events occurred when the target vehicle casts a long, high-contrast shadow on the roadway surface, such as those created when the sun is relatively low in the sky. Figure 49 shows examples of this type of false event.

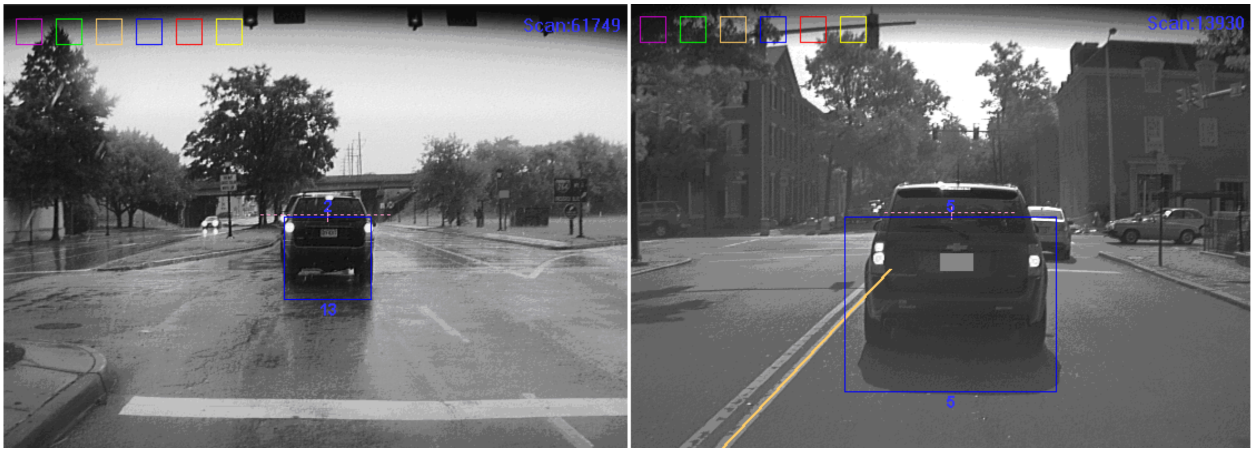


Figure 49: Vehicle Reflection/Shadow Influencing Vision Measurement

As with the LVD Road Feature events, the shadow was inadvertently associated with the target vehicle, but in these cases the shadow moved with the target vehicle. At longer ranges when the visual angle subtended by the shadow was lower, the shadow had little effect on the perceived size of the target vehicle. However, as the range to the target vehicle decreased, when the visual angle subtended by the shadow was higher, the shadow influenced the perceived size and position of the target vehicle. As a result, the threat assessor misinterpreted the target vehicle under these conditions as an imminent threat.

4.5.2.2.5 Ghost-Targets and Scene-Complexity

Ghost-Target and Scene-Complexity events occurred when the vision algorithm incorrectly interpreted non-vehicle elements in the scene as a vehicle. When this condition lasts for a sufficient amount of time, it can cause false events. Figure 50 shows examples of these types of false event.

Figure 50: Ghost Targets/Scene Complexity Influencing Vision Measurement

4.5.2.3 Analysis of Fused, Mono-Vision/Radar Sensing

The concept of “fused” sensing generally refers to using information from two or more different sensing systems (e.g., radar and vision) to obtain a more complete understanding of the environment than would be possible with each individual system. In the case of both vehicles used in the ROAD Trip, this consisted of the fusion of the Long/Mid Range radar and Mono-Vision systems. The precise advantages of this combination of sensors depend on the exact nature of the fusion implementation. Because each of these two sensing technologies have well understood strengths and weaknesses in different areas (e.g., precise range estimates versus accurate target classification) the information provided by the combination of these sensors can be used in a complementary fashion to strengthen overall system performance. In some cases, information from one of the sensing systems can be used to augment the performance of the other. For example, the fusion algorithm can use the target classification information from a vision sensing system to confirm targets identified and measured by the radar sensing system.

As the raw data collected during the ROAD Trip was “fused” (i.e., Mono-Vision and Radar), this data served as the “baseline” for the fusion analysis. As with the radar only and camera only methods, a corresponding analysis was performed at varying sensitivities in order to better understand system performance (see Figure 51). These additional sensitivities were set to +25% and +50%. The raw data was re-simulated at these sensitivity levels to produce comparative data sets.

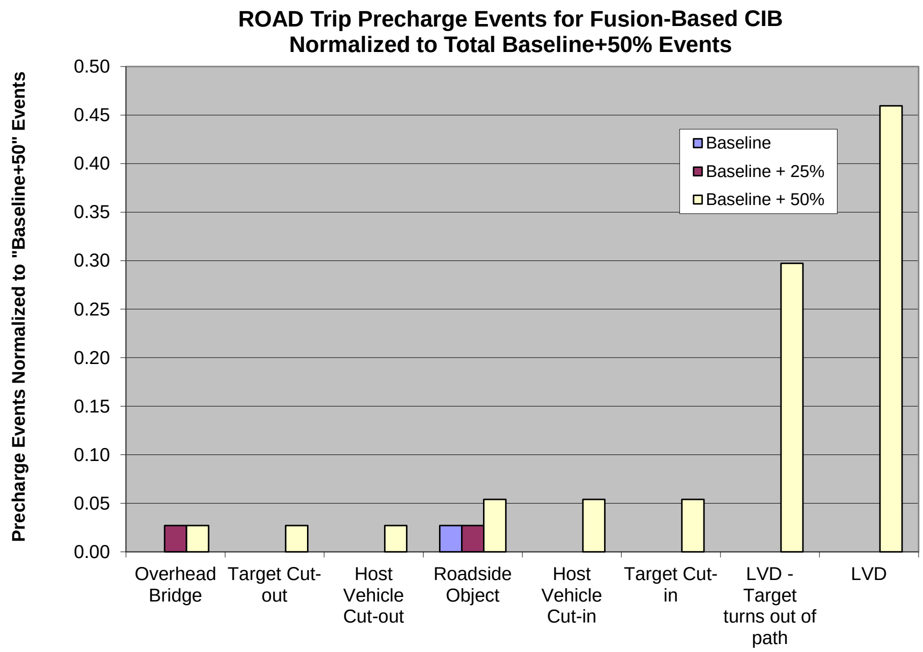


Figure 51: Scenario Classifications for Fusion False Precharge Events (Normalized)

The above results indicate that combining both radar and camera data into a fused system dramatically reduced the total number of false precharge events over the stand-alone sensors used in the current testing. At the baseline sensitivity level, false Precharge events were reduced almost completely, and False Interventions were eliminated entirely, even for the increased sensitivity settings. Only by adjusting the sensitivity level significantly did the occurrence of false Precharge events increase. Results from the +50% sensitivity level event distribution shows the prominence of LVD and LVD–Target Turns Out of Path events. An analysis of the kinematics of these scenarios can be found in Appendix N.

4.5.2.3.1 Roadside Object

The only Roadway Object event at the baseline sensitivity level was a "Roadside-Object" Precharge event. Figure 52 depicts this event in which the radar picks up a row of concrete posts along the lane edge as a stationary target. This information may have been fused with "moving" vision data, which in turn created a false valid target to which the system then reacted.

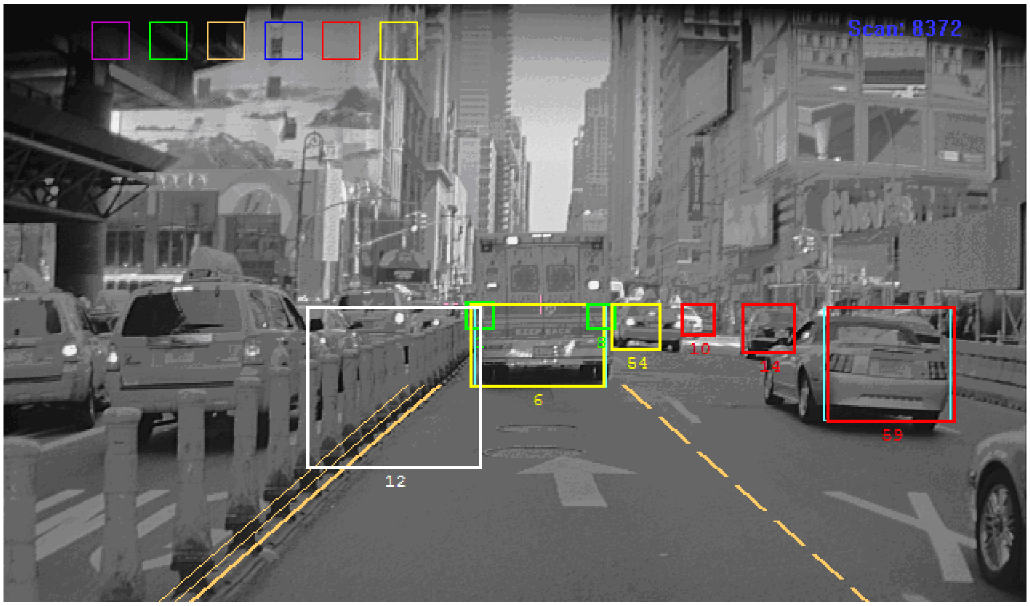


Figure 52: False Precharge Event at Baseline Sensitivity Due to Roadside Object

4.5.2.3.2 Lead Vehicle Decelerating (LVD)

Upon reviewing the LVD events, it was observed that most of the occurrences were a direct result of the increased sensitivity level rather than a misinterpretation of the sensor data or detection of a false target. Both the range and range-rate information recorded during these events support that under baseline sensitivity levels, a Precharge event would not occur.

Figure 53 illustrates a case during normal highway driving where traffic was forced to reduce speed at a moderate deceleration level, and a legitimate system Precharge event was triggered (but only at the + 50% sensitivity level).

Figure 53: "LVD" Precharge Event at Baseline + 50%

4.5.2.3.3 LVD – Target Turns Out-of-Path

Reviewing the "LVD – Target Turns Out-of-Path" subset of events produced a similar set of results as was found in the LVD analysis. In general, these events were deemed to be strictly a result of the increased sensitivity level, and judged as either unnecessary or "unwanted" from the driver perspective.

Figure 54 illustrates the case in which the target vehicle decelerates before turning out of the path of the host vehicle. The host vehicle's range and range-rate information supported the trigger of early Precharge event.

Figure 54: "LVD - Target Turns Out-of-Path" Precharge Event at Baseline + 50%

4.5.2.4 Analysis of Stereo-Vision Based System and Supplier-Recommended Operational Test Scenarios for Stereo-Vision:

The data collected from the Stereo-Vision system installed in Vehicle E required developing a different analysis approach than was used for the other sensor configurations. First, the Stereo-Vision sensing system generated extremely large video file sizes, which prohibited continuous video data collection. Instead, target report data was transmitted from the sensors to the vehicle CAN where it was recorded continuously to the high-capacity data drive used for the other CIB system installed on the vehicle. Additionally, trigger points were established which initiated video data recordings surrounding CIB activation events identified by the Stereo-Vision system. These data recordings were triggered at both 0.6 sec and 0.3 sec simple TTC thresholds. Event data, including vehicle CAN, GPS, and target identifier information was recorded with these videos 16 seconds before and 4 seconds after the trigger event.

Data from 258 event triggers were recorded over the ROAD Trip. An initial, post-trip, data review revealed that a large number of these recorded events were corrupted by malfunctions within the control module. These malfunctions were primarily traced to the early development level of the Stereo-Vision system algorithms. The recordings were reviewed and re-simulated by the supplier to determine whether the events related to actual system false activation or were caused by the control module malfunctions. Based on the re-simulation of the recorded video files, none of the false positive conditions observed lead to specific tests to verify against potential core systemic Stereo-Vision system issues. However, the system supplier recommended a few situational scenarios that tend to be generally challenging for vision-based sensing systems, including inclement weather and low-light conditions (which are shown in Figure 55).

These conditions could be addressed as an adaptation to the operational scenarios for Mono-Vision systems outlined in Section 4.5.2.2, incorporating low light or simulated rain conditions using, for example, an overhead sprinkler system.

Furthermore, visually repeating patterns (e.g., trees, bushes, and fences) are especially challenging for Stereo-Vision systems. In addition, to verify the performance of a vision systems “Horizon Line Estimator,” the supplier suggests that roadway inclines and/or declines may be considered within operational test scenarios. This type of test is consistent with the Host Vehicle Pitch Change and Shadow-on-Road tests described for the Mono-Vision-based system in Sections 4.5.2.2.3 and 4.5.2.2.4.

Figure 55: Example Image from an Event Recording Obstructed by Rain, and Event Recorded in Low-Light Conditions

4.5.3 Environmental Conditions Not Assessed by the ROAD Trip

Due to program timing limitations, it was not possible to expose the vehicles driven on the ROAD Trip to winter driving conditions. Therefore, it is likely that there are winter driving scenarios that could cause false events that were not captured on this trip. Detailed information regarding potential winter weather-related issues found through OEM development can be found in Appendix N.

4.5.4 Operational Test Scenarios

Operational scenarios are the set of tests defined to evaluate CIB system performance in the presence of targets that do not represent an actual vehicle threat. The operational tests examine the propensity of a CIB system for undesirable false CIB activations. The operational test methods developed and evaluated throughout the object were based on data acquired during on-road driving in actual traffic conditions (e.g., the ROAD Trip). These tests assess the robustness of a CIB system to reject a variety of non-threatening targets that appear to be a threat due to environmental circumstances.

The Operational test scenarios developed were not deemed validated since there was not sufficient data to categorize them as “Validated” (see definition provided in Section 4.2.1) due to the observed lack of repeatability and inability to discriminate the differences between varying levels of CIB performance.

In order to evaluate the propensity of CIB systems to inappropriately engage due to the types of false event scenarios observed during the ROAD Trip, a set of operational (false event) “on track” tests were devised that are intended to provide a first-order check for these false activation scenarios. It is important to stress that these tests are a useful part of assessing CIB system performance but are not considered a substitute for real-world evaluations. In real-world driving, false activations are typically rare and are not always repeatable. Unlike the Functional test scenarios, the test requirements below have been specified with the intent to replicate the range of values observed in the field. Furthermore, it is recommended that the tests described below be run as a series of repeated tests that exercise system performance over the wide ranges provided (i.e., rather than repeating the tests at a single speed condition).

4.5.4.1 Operational Test Procedure for Objects-in-Roadway

The Object-in-Roadway event can be replicated on a test-track environment with the test arrangement illustrated in Figure 56. In-Road objects may be represented by placing radar reflective objects (e.g., Bott’s dots or corner cubes) on the ground in the vehicle’s path. Although reflectivity data for the in-roadway objects were not readily available from the ROAD Trip results, many of these events were caused by reflectors embedded in the roadway (e.g., Bott’s dots). Therefore, the object recommended for this event is either a commercially available in-road reflector, or alternatively, to characterize the radar reflectivity of such a reflector and substitute an appropriately-sized corner cube.

To test the operational capability of the test vehicle CIB system in an Objects-in-Roadway Operational Scenario, the test vehicle is driven in a straight and level lane over a small stationary target at a constant forward velocity.

The proposed test procedure is described in detail in Appendix O.

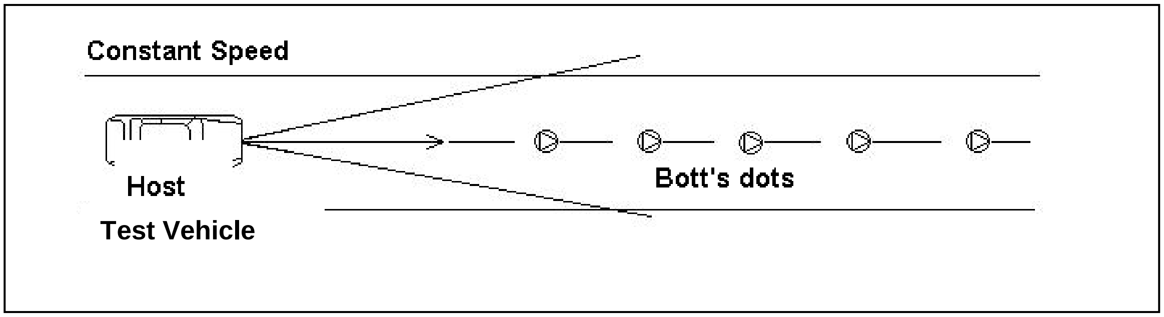


Figure 56: Test Vehicle with Objects-in-Roadway

4.5.4.2 Operational Test Procedure for Stationary Object at Curve-Entrance

In order to replicate the Curve-Entry false event scenario (See Figure 57), the test vehicle shall drive on a straight section of roadway approaching a curve. Target placement at the entrance shall be on the side of the roadway after the curve begins, such that continuation of the straight-line path would intersect the target. Since this type of event can also effect fusion-based systems, it is suggested that the stationary target used for this test be a mid-size passenger sedan rather than a corner cube or other radar reflective device. Using a mid-sized sedan will make the same test method valid for both radar and fusion systems.

The proposed test procedure is described in detail in Appendix O.

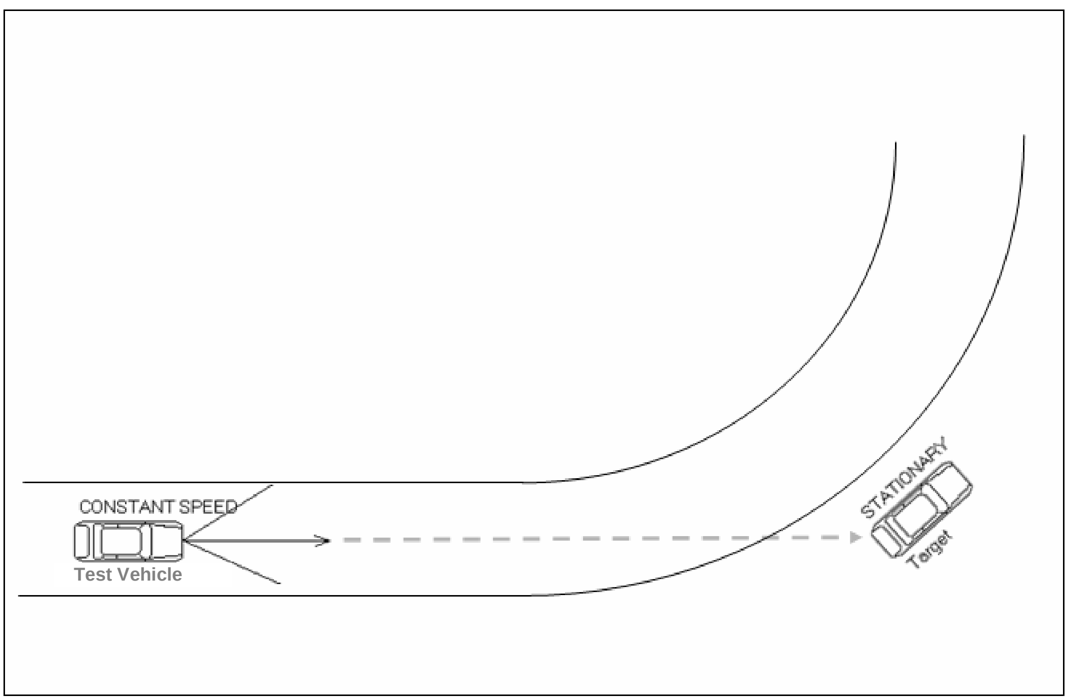


Figure 57: Stationary Vehicle Located at Curve Entrance

4.5.4.3 Operational Test Procedure for Stationary Object at Curve-Exit

In order to replicate the Curve-Exit false event scenario, the test vehicle shall drive on a section of roadway of constant curvature and approach the end of the curve as illustrated in Figure 58. A stationary target vehicle shall be placed just past the curve exit on the inside of the curve.

Target placement at the curve exit shall be on the side of the roadway after it becomes straight, such that continuation of the curve would intersect the target. Since this type of event can also effect fusion-based systems, it is suggested that the stationary target used for this test be mid-size passenger sedan rather than a corner cube or other radar reflective device. This will make the same test method valid for both radar and fusion systems.

The proposed test procedure is described in detail in Appendix O.

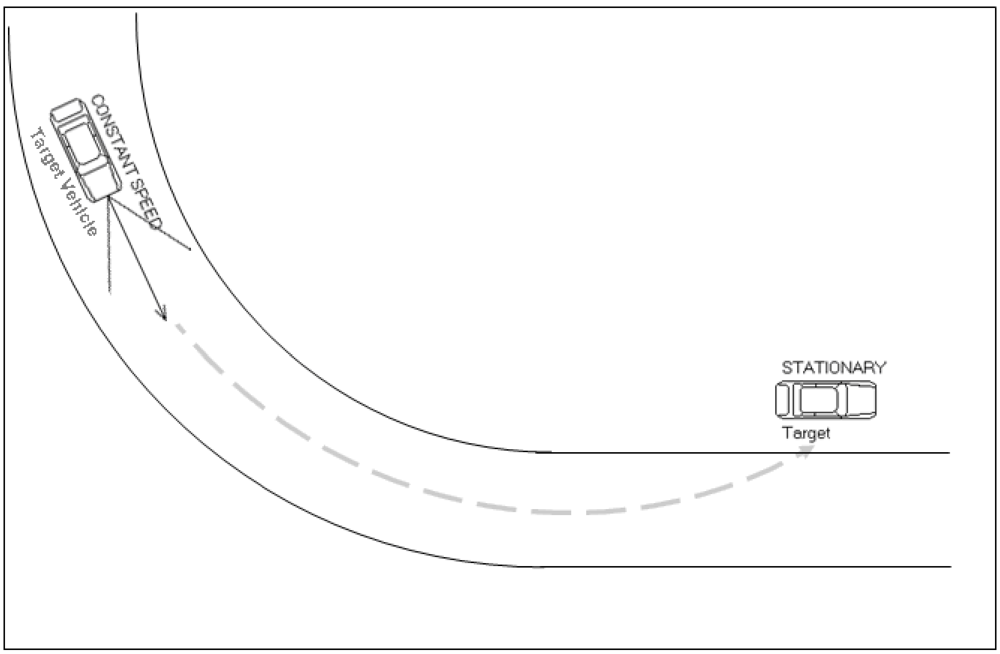


Figure 58: Stationary Vehicle at Curve Exit

4.5.4.4 Operational Test Procedure for Roadside Stationary Objects

In order to replicate the Roadside-Object false event scenario, the test vehicle shall drive on a straight section of roadway and approach a row of stationary objects as illustrated in Figure 59. As it approaches the stationary objects, the test vehicle would perform a mild lane change towards them (see test parameters in Appendix O).

Target placement shall be on the side of the roadway with an open lane between the test vehicle's starting lane and the stationary targets. Since this type of event can also effect fusion-based systems, it is suggested that the stationary targets used for this test be mid-size passenger sedans rather than corner cubes or other radar reflective devices. Use of actual cars will allow the test method to be valid for both radar and fusion systems.

The proposed test procedure is described in detail in Appendix O.

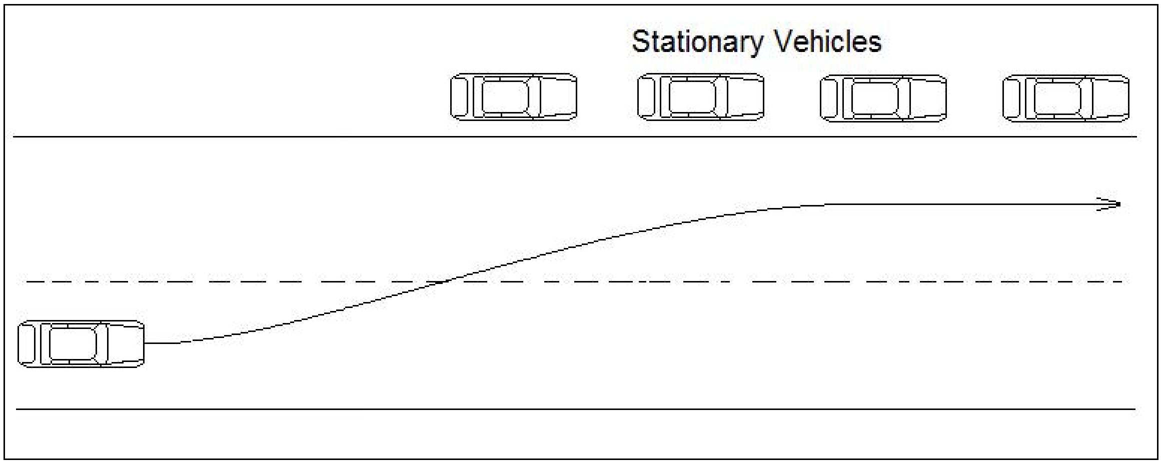


Figure 59: Roadside Stationary Vehicles

4.5.4.5 Operational Test Procedure for Overhead Signs and Bridges

In order to replicate the Overhead Signs and Bridges false event scenario, the test vehicle shall drive on a straight section of roadway and approach a bridge underpass or an overhead sign, as illustrated in Figure 60. The bridge or sign shall have a metallic structure.

The proposed test procedure is described in detail in Appendix O.

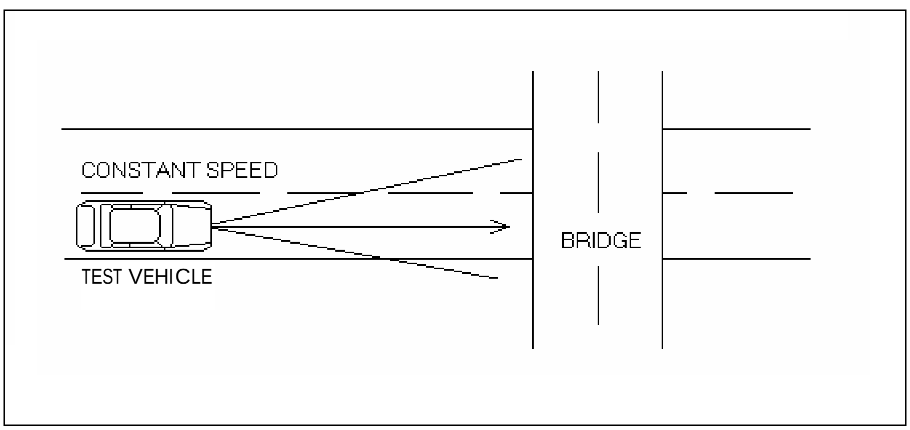


Figure 60: Overhead Sign/Bridge

4.5.4.6 Operational Test Procedure for Short-Radius-Turns

In order to replicate the Short-Radius-Turn false event scenario, the test vehicle shall perform a short-radius, low-speed turn next to a row of stationary vehicles (as illustrated in Figure 61). Target placement shall be on the side of the roadway and out of the actual path of the turning test vehicle. Since this type of event can also effect fusion-based systems, it is suggested that the stationary targets used for this test be mid-sized passenger sedans rather than corner cubes or other radar reflective devices. Use of mid-sized passenger cars will allow the same test method to be valid for both radar and fusion systems.

The proposed test procedure is described in detail in Appendix O.

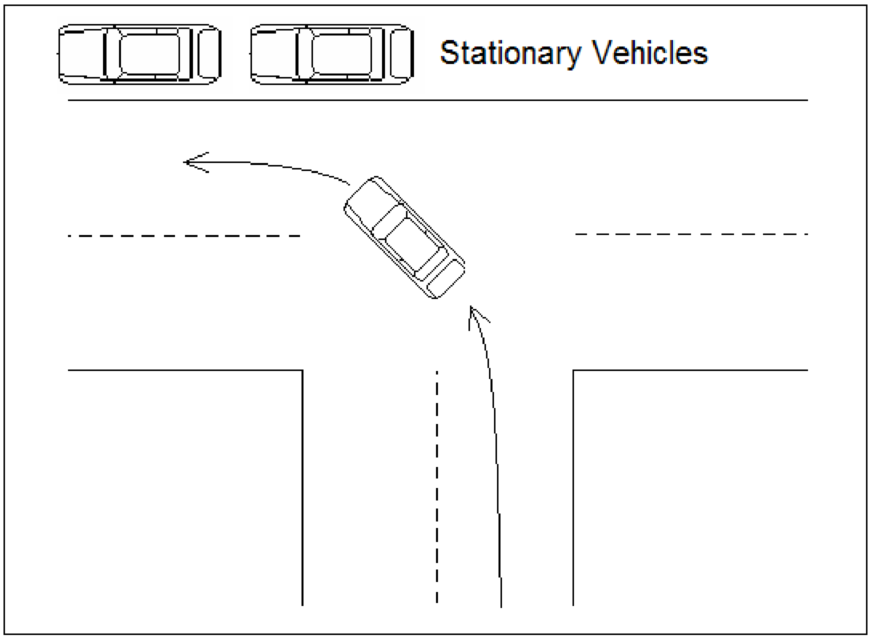


Figure 61: Short-Radius Turn

4.5.4.7 Operational Test Procedure for Lead Vehicle Deceleration (LVD)

The majority of vision-related false events from the systems evaluated were found to be due to various visual cues interfering with system performance. In order to replicate these false event scenarios, a test similar to the LVD positive performance test can be used, while introducing representations of the various visual cues that have been observed to be potentially problematic.

The test vehicle shall be driven on a straight section of roadway while following the target vehicle as described in Section 4.2.1.3. The target vehicle shall then decelerate at a rate that falls within the values specified for the test, while encountering one of the visual cues described in Section 4.5.2.2.

The proposed test procedures are described in detail in Appendix O.

These test scenarios assess performance during Lead Vehicle Decelerating scenarios and are designed such that a collision does not take place, thus allowing the use of a real vehicle for the leading target. These four tests involve variations on the test scenario for

LVD. The test procedures for these are the same for all four with differences in visual cues represented in each test.

4.5.4.7.1 Operational Test for LVD On-Road Features

As illustrated in Figure 62 for the LVD On-Road Features operational test scenario, the lead vehicle shall start its deceleration just prior to traversing over a series of on-road markings that were observed to be challenging for the Mono-Vision systems evaluated.

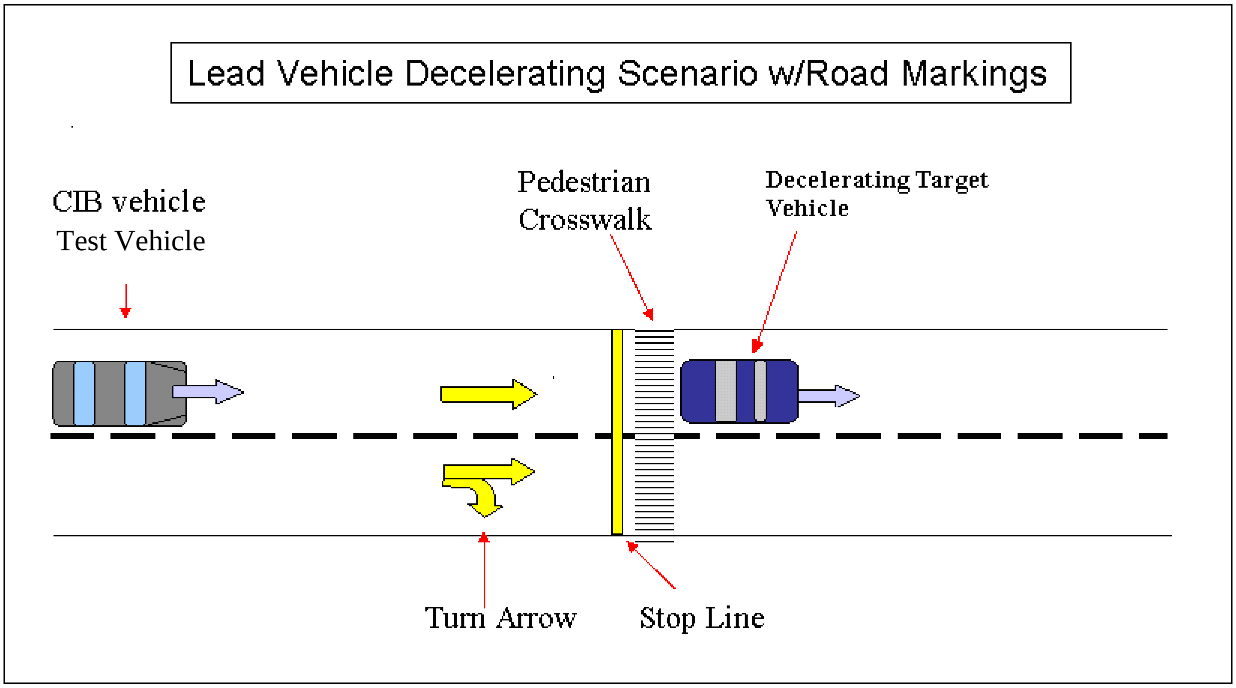


Figure 62: Operational Test for LVD On-Road Features

4.5.4.7.2 Operational Test for LVD Over Shadows-On-Road

As illustrated in Figure 63, for the LVD Over Shadows-on-Road operational test scenario, the lead vehicle shall start its deceleration just before driving over a series of shadows cast onto the road.

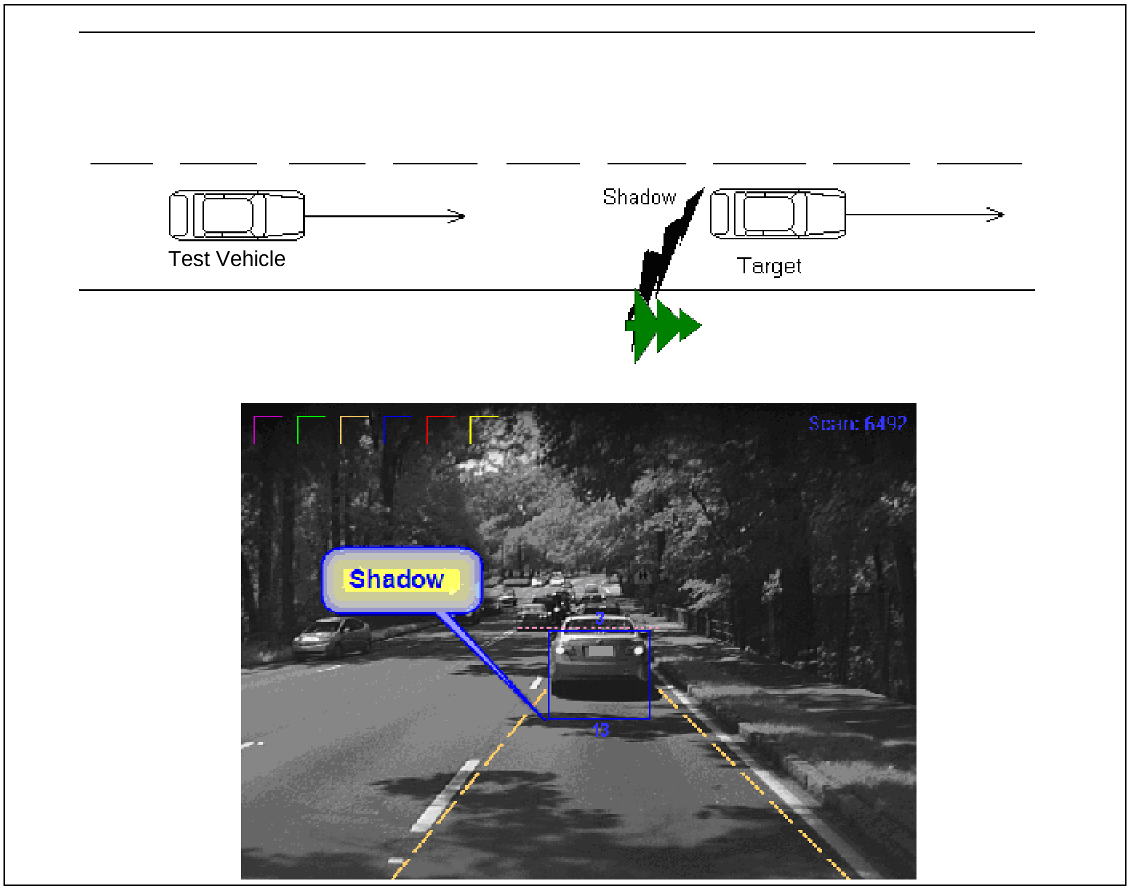


Figure 63: Operational Test for LVD Over Shadows-on-Road

4.5.4.7.3 Operational Test for LVD during CIB-Vehicle-Pitch-Change

As illustrated in Figure 64, for the LVD During CIB-Vehicle-Pitch-Change operational test scenario, the lead vehicle shall start its deceleration as the test vehicle is about to undergo a change in pitch. The designated pitch change for this test is presented in the table of LVD Scenario Physical Conditions found in Appendix O, Section O.7.4.

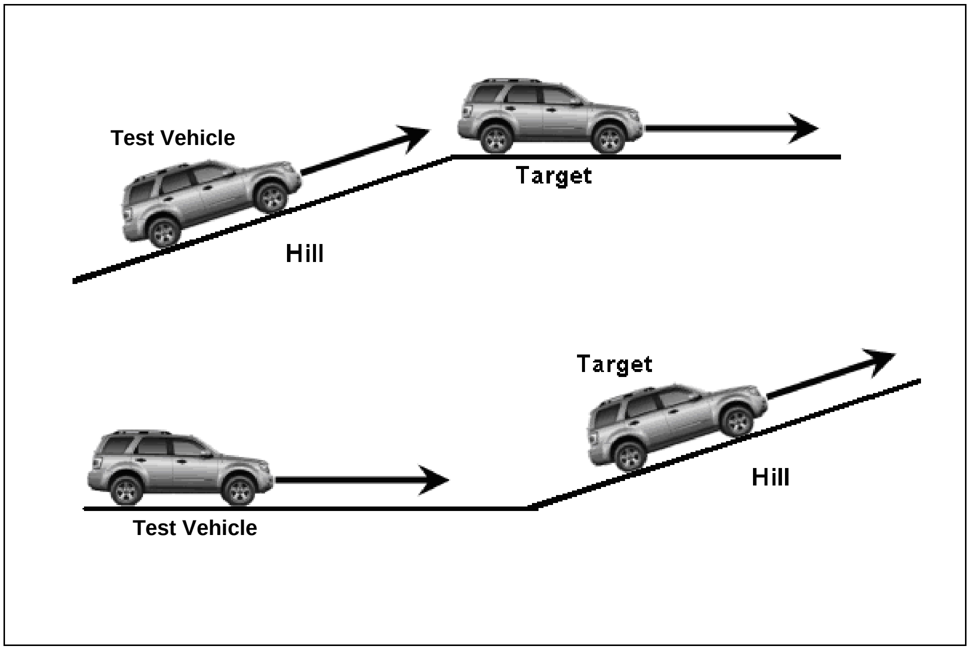


Figure 64: Operational Test for LVD during CIB-Vehicle-Pitch-Change

4.5.4.7.4 Operational Test for LVD with Target-Vehicle-Shadow

As illustrated in Figure 65, for the LVD with Target-Vehicle-Shadow operational test scenario, the test shall be run during low-sun angle conditions such that a shadow is cast extending more than 3m behind the rear of the target vehicle.

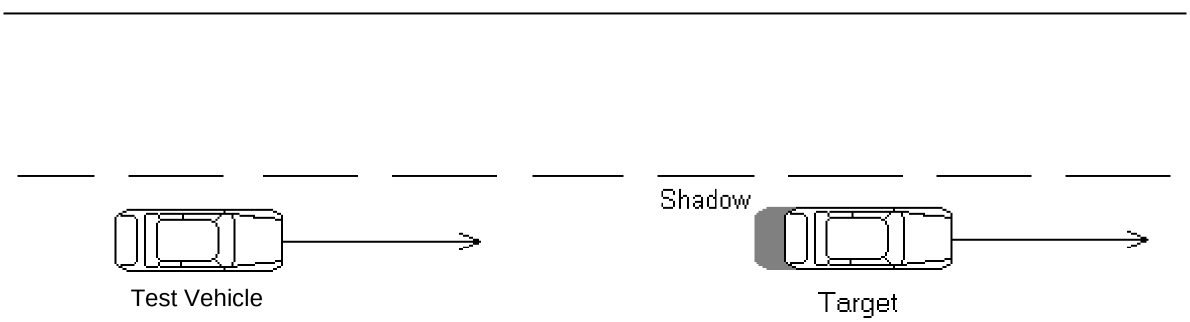


Figure 65: Operational Test for LVD with Target-Vehicle-Shadow

4.5.4.7.5 Operational Test for LVD and Target Turns Out-of-Path

The events that were observed for the “LVD and Target Turns Out-of-Path” scenario had very similar kinematic values to those found in the other LVD false events. As such, these events could be replicated by using the operational test procedures as described in this section, with the modification that the lead vehicle turns “Out-of-Path” (e.g., makes a right turn) while decelerating, as is illustrated in Figure 66.

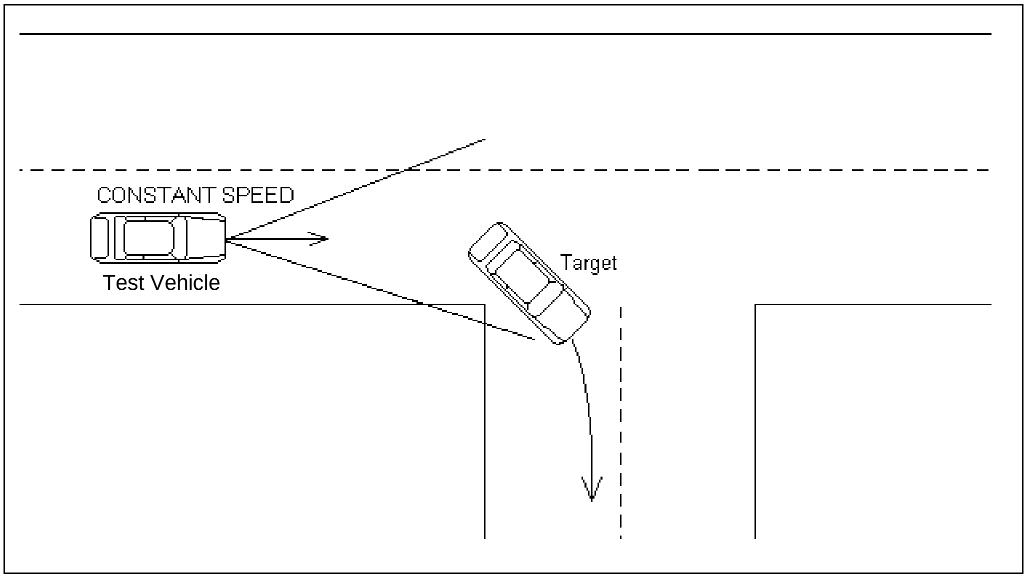


Figure 66: LVD Target Turns Out-of-Path Operational Test

5 Finalization of Minimum Performance Specifications and Development of Benefits Estimation Methodology

This chapter documents the final stages of the CIB Project, including recommendations for minimum performance metrics and development of a benefits estimation methodology. For the functional test method minimum performance metrics, three measures are presented as both a means for establishing minimum performance values and as a means for differentiating between CIB systems. These measures included the ability of a CIB system to respond to the functional test scenarios (i.e., percent activations) and the average speed reduction achieved by the CIB system

The final task of the project was to attempt to work toward developing a methodology for estimating the potential benefits of CIB systems. The proposed benefits estimation methodology was developed by NHTSA and Volpe. Volpe's methodology is expected to be documented separately in a report to NHTSA. Volpe's proposed methodology attempts to link measured CIB system performance to the existing United States crash data. CIB Consortium participation within this process consisted of providing feedback on the benefits estimation methodology developed by Volpe and providing sample test data for Volpe to use to exercise their proposed methodology. This chapter summarizes the feedback provided by the CIB Consortium and recommends further work and data that is required in order to attain CIB benefit estimates.

5.1 Finalize Performance Specifications for Desired Function

The performance specifications documented in this section represent a refinement of the preliminary specifications documented earlier in the CIB Project. The preliminary functional requirements described an initial set of CIB system and component capabilities which would be required for the project test vehicles. These preliminary requirements were further refined and used for selecting the sensing and brake technologies employed in the project test vehicles. This selection process was described in Chapter 3, along with the detailed specifications for the development of test methods motivated by the priority crash scenarios identified in Chapter 2. Following completion of the test vehicle builds and the test method development and validation, the remaining work was undertaken to develop the overall system performance specifications estimated to provide a measureable level of expected CIB system benefit in the final set of validated test procedures.

5.1.1 Crash Energy Versus Vehicle Speed

Vehicle speed and closing speed to an object or another vehicle are critical to the crash harm or severity. The relative speed between the vehicle and the collision partner immediately prior to impact is also a critical factor for the pre-crash sensing technology. In order to reduce crash energy and ultimately crash injury, an impact speed reduction between striking and struck vehicle or struck object is necessary.

For a CIB-equipped vehicle, the impact speed reduction in this case can be expressed as the projected impact speed without CIB activation minus the actual impact speed with CIB activation. The decrease in vehicle speed due to autonomous braking represents a change in velocity that is referred to here as delta impact speed (or ΔIS). It should be stressed that ΔIS, is *not* the same as the crash ΔV measured by an event data recorder or the crash ΔV estimated via post-hoc crash reconstruction techniques using vehicle crush. Instead, ΔIS represents a method of estimating a reduction in crash energy using the following kinetic energy (KE) equation:

$$KE = (1/2)*(mV^2) \quad (1)$$

Where:

KE = Kinetic Energy
m = Mass
V = Velocity

The intent of a CIB system is to reduce the relative speed between a CIB-equipped vehicle and another vehicle or object prior to impact and, as a result, reduce the crash energy. Figure 67 contains an example set of test measurements for a LVM scenario. As shown in the figure, the test vehicle achieved a 10.5 km/h speed reduction from the time the test vehicle begins to brake until impact with the target. There is a corresponding reduction in crash energy related to that speed reduction.

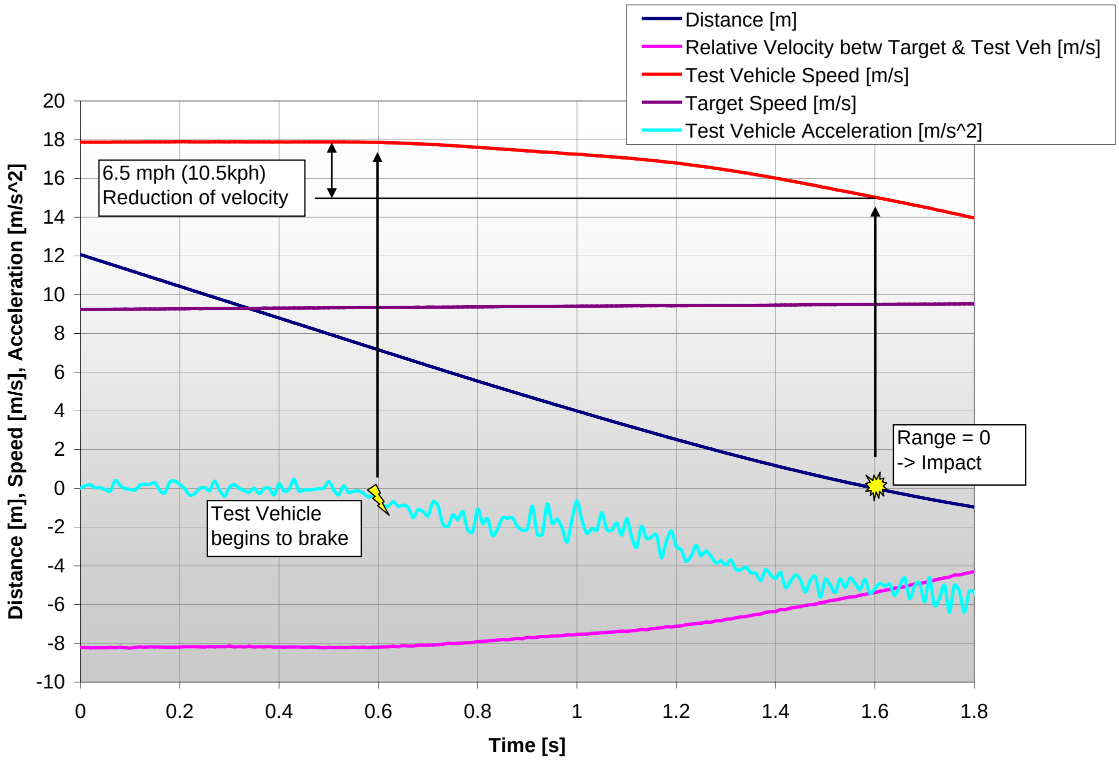


Figure 67: Test Data from Lead Vehicle Moving Scenario

For evaluating minimum performance specifications for CIB systems within this project, crash energy assessments for vehicle-to-vehicle crashes assume impacts between vehicles having identical size, mass, and stiffness. Under this assumption, the crash energy is distributed evenly between the two vehicles.

The minimum performance specifications recommended here represent a minimum level of crash energy reduction needed to measure potential safety benefits rather than a specific level of energy reduction needed to obtain a particular reduction in injury risk. The change in crash energy with CIB activation compared to the same case without CIB activation is defined as follows:

$$\Delta KE(\%) = 100 * \frac{KE1 - KE2}{KE1} \qquad (2)$$

Where:

KE1 = crash energy prior to application of the CIB system

KE2 = crash energy related to impact speed reduced by activation of the CIB system

Since mass does not change in these events (based on assumptions made above), the relationship in crash energy as impact speed changes can be shown in the following equation:

$$\Delta KE(\%) = 100 * \frac{V_1^2 - V_2^2}{V_1^2} \quad (3)$$

Where:

V1 = relative vehicle speed prior to CIB system activation

V2 = relative vehicle speed after CIB system activation

This relationship is used later in the report to demonstrate the relative effect on crash energy of the minimum specifications of impact speed reduction (ΔIS) compared to the crash energy reductions achieved through the CIB test data. See Section 5.1.5 for an additional discussion of the reduction in crash energy resulting from impact speed reductions.

5.1.2 Resolution of Available U.S. NASS ΔV Data

Volpe obtained NASS data and subsequently sorted the cases into bins of 5 km/h. Given this bin size, the smallest measure of change to ΔV that could potentially result in a notable shift from one bin to another would be half of this 5 km/h bin size, or 2.5 km/h. However, since ΔV data are presented in integer values, changes in ΔV of 3 km/h or more would be needed to potentially see a notable shift from one bin to another. Vehicle impact speed reductions (ΔIS) which lead to shifts in crash data from one ΔV bin are used by NHTSA/Volpe in the CIB Benefits Estimation Method. The method is expected to be documented in a separate report prepared by Volpe. Minimum measures of change will be used in this report to establish the lowest level of ΔIS required in order to detect a change in ΔV and, therefore, a potential measure of system benefit. As stated earlier, given the assumption that crash energy is evenly distributed between impacting vehicles of equal size, mass, and stiffness, a reduction of 3 km/h ΔV in either vehicle would require an impact speed reduction (ΔIS) of at least 6 km/h. Therefore, the minimum ΔIS required to provide a measureable level of CIB system benefit was estimated to be approximately 6 km/h. Again, the reader should be reminded that there is a distinct difference between ΔV (i.e., the change in a vehicle's speed after impact) and the measure used in this analysis, ΔIS (i.e., the projected change in a vehicle's impact speed with and without CIB activation).

5.1.3 Priority of Validated Functional Test Procedures

As discussed in Chapter 4, test methods representing three of the original priority crash scenarios were successfully validated. The three validated crash scenarios were:

- Lead Vehicle Stopped (LVS)
- Lead Vehicle Moving (LVM)
- Lead Vehicle Decelerating (LVD)

Table 33 displays the sample counts, sample weights and FYL associated with these three scenarios based on the top-down analysis discussed in Chapter 2.

Table 33: Vehicle-to-Vehicle Front-to-Back Crashes by Pre-Crash Scenario and Impact Combinations (CDS)

Pre-Crash Scenario	AV CT	AV WT	FYL
LVS – no vehicle maneuver	3,574	2,472,887	252,022
LVD – no vehicle maneuver	1,159	842,462	61,707
LVM – no vehicle maneuver	700	304,127	53,354

AV CT: CDS Count of All Vehicles Involved
AV WT: CDS Weight of All Vehicles Involved
FYL: Functional Years Lost

Several studies have indicated that LVS crashes often evolve from and are closely related to the LVD scenario, in which the leading vehicle in a car following (coupled) situation subsequently stops and is then struck by the following vehicle. For example, Najm and Smith (2007) noted, regarding LVS crashes, that:

> "In 50% of these crashes, the lead vehicle first decelerates to a stop and is then struck by the following vehicle. This typically happens in the presence of a traffic control device or the lead vehicle is slowing down to make a turn. This particular scenario is closely related to, but distinct from, the lead-vehicle-decelerating scenario."

In addition, analysis of the data from the Automotive Collision Avoidance Systems Field Operation Test (Automotive Collision Avoidance System Field Operational Test Final Program Report, 2005; Automotive Collision Avoidance System Field Operational Test Report: Methodology and Results, 2005) also suggests that the percentage of LVD relative to LVS cased could be potentially substantially higher.

The resulting redistribution of LVS cases, based on the Najm and Smith (2007) findings produce the case counts, case weights, and FYL displayed in Table 34. For CIB purposes, LVS cases that involve deceleration of the lead vehicle are better represented by the LVD test scenario. This is because CIB systems will typically respond to stopped vehicles if the CIB systems have previously detected and tracked that vehicle as a moving target prior to the target decelerating to a stop. Although CIB systems typically react to stopped vehicles that were previously detected and tracked as a moving target, CIB systems may have difficulty distinguishing these "Never-Before-Seen-Moving" (NBSM) stopped vehicles from other non-threatening objects. Indeed, to help prevent false activations to non-threatening objects, some CIB systems are designed not to respond to NBSM objects. Crash data suggests that systems without NBSM capability will still provide substantial field benefit. Consequently, CAMP-CIB recommends accumulation of further CIB system field data is recommended before encouraging or requiring NBSM capability.

Table 34: Adjusted Vehicle-to-Vehicle Front-to-Back Crashes by Pre-Crash Scenario and Impact Combinations (CDS)

Pre-Crash Scenario	AV CT	AV WT	FYL
LVD – no vehicle maneuver	2,946	2,078,906	187,718
LVS – no vehicle maneuver	1,787	1,236,444	126,011
LVM – no vehicle maneuver	700	304,127	53,354

Note: Data are values from Table 33 adjusted to account for an estimated 50% of LVS cases involving Lead Vehicle Deceleration prior to stopping.

AV CT: CDS Count of All Vehicles Involved
AV WT: CDS Weight of All Vehicles Involved
FYL: Functional Years Lost

Given this redistribution of LVD and LVS cases, and the anticipated field benefits of CIB systems without NBSM capability, the recommended order of priority for the validated set of CIB test methods (in order of importance) is as follows:

- Lead Vehicle Decelerating (LVD)
- Lead Vehicle Moving (LVM)
- Lead Vehicle Stopped (LVS) -- used as a potential future differentiator of CIB systems

5.1.4 CIB Activation Rates

Another important factor influencing the minimum performance specifications of CIB systems is the consistency and reliability of system performance, as measured by missed activations and variations in distance/time when activations occur. As shown in Figure 68 for two hypothetical systems, considering only the average speed reduction recorded from all test runs fails to fully characterize overall CIB performance. In the depicted example, System A and System B both yield an average speed reduction of 5 km/h recorded across the test series. Although System A activates in only 50 percent of the tests performed, this system achieves a speed reduction of 10 km/h when it does activate. In contrast, System B activates in 100% percent of the same tests and yields a consistent 5 km/h speed reduction across the test series. Consequently, while the speed reduction value of System B is half of that provided from System A when it is activated, System B delivers a much more consistent performance and provides benefit in a much higher percentage of crash cases. This trade-off issue will be discussed further in the context of the benefits estimation methodology.

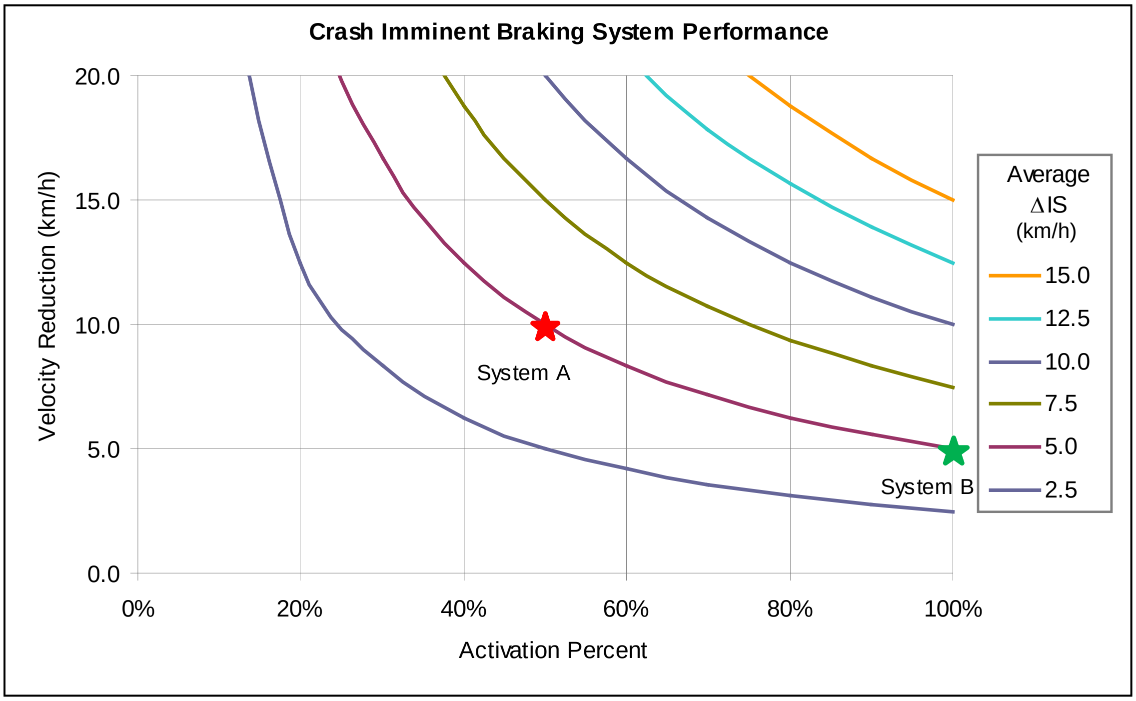


Figure 68: Hypothetical Example of CIB System Performance Relative to Probability of Activation

5.1.5 Recommended Minimum Performance Specifications for Validated CIB Functional Test Methods

Based on the rationale in the previous sections, Table 35 presents CAMP-CIB recommended minimum performance specifications for the validated CIB functional test methods. These metrics represent the lowest level of performance that is likely needed to provide a measureable level of system benefit. From these minimum metrics, higher levels of system performance can be used to differentiate between various CIB system technologies and configurations, as illustrated in Table 36.

Table 35: Recommended Minimum Performance Specifications for Validated CIB Functional Tests

Test Conditions: LVD, LVM (See Note 1)	
Measure	**Minimum Value**
Activation Rate	80% of 10 tests
Average Speed Reduction	6 km/h (See Note 2)

Notes:

(1) As specified in Chapter 4 and Appendix L, Section L.10

(2) Calculated only from those tests in which system activation occurred

Table 36: Functional Test Performance for Possible Future Differentiation Between CIB System Configurations

Test Condition: LVS (See Note 1)	
Measure	**Differentiating Value**
Activation Rate	≥80% of 10 tests
Average Speed Reduction	≥6 km/h (See Note 2)

Notes:
(1) As specified in Chapter 4 and Appendix L, Section L.10
(2) Calculated only from those tests in which system activation occurred

The future differentiation proposed could be comprised of three factors:

1. A sensing system that would handle an LVS scenario generally requires a higher level of sensing technology relative to a system that addressed LVD/LVM scenarios
2. Greater than 8 activations out of 10 trials
3. Greater than 6 km/h average speed reduction

All three of these factors could be used to discriminate or differentiate between alternative CIB systems. This will be further explored within the Benefits Estimation Methodology comments documented later in this chapter. These system differentiators should also be balanced against relative system affordability, as it potentially affects the market penetration and benefit opportunities in the field. Test data from the baseline (production) vehicles and the project test vehicles support the minimum performance specifications shown in Table 35.

Figure 69 shows a graphical representation of the percentage of crash energy reduced as a function of relative vehicle speed (see Equation 3 presented earlier in Section 5.1.1) for the LVM scenario. This graph includes a curve representing the crash energy reduction associated with the recommended minimum speed reduction metric of 6 km/h, as shown by a dashed green line. As shown in Figure 69, each of the baseline vehicles and CIB test vehicles evaluated exceeded this minimum speed reduction value except CIB Test Vehicle E. This system, which was set to achieve a peak deceleration of 9 m/sec^2, only achieved approximately 2 km/h in average speed reduction for the LVM scenario during the validation tests. Brake system lag affected the overall performance of this system. For the particular test targets selected for the examples shown in Figure 69, CIB activation occurred in 100% of the tests conducted with the exception of CIB Test Vehicle G. This system demonstrated activations in 90% of the validation tests. One other notable result is that with the exception of Baseline Vehicle C, all of the other CIB system configurations tested demonstrated a relatively consistent value of speed reduction measured during the tests. Baseline Vehicle C showed a trend of producing less absolute speed reduction as relative initial speeds between the test vehicle and target increased, which results in a more rapidly declining percentage in crash energy reduction as differential speeds increased.

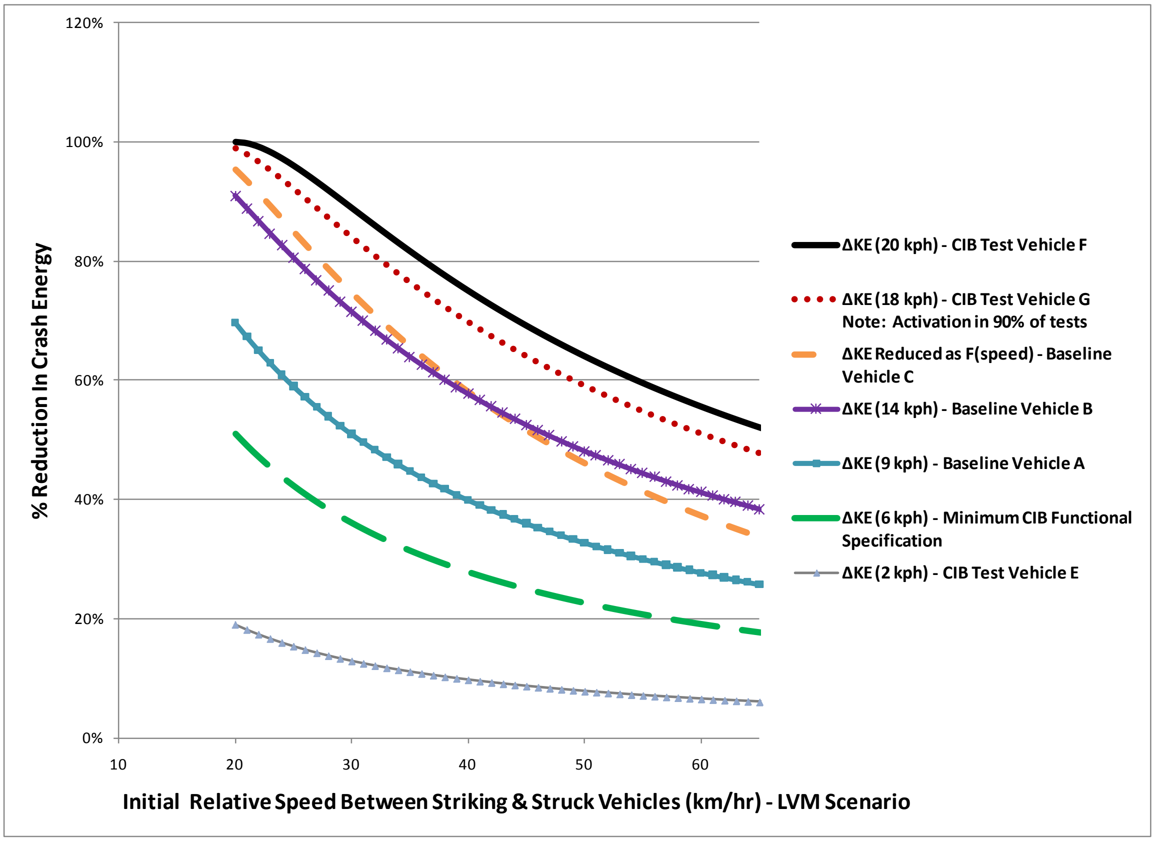


Figure 69: Percent of Crash Energy Reduced as a Function of Relative Impact Speed

As previously mentioned, because of the lag in the Vehicle E brake system between the time the CIB brake commands were sent (based on the low Time to Collision (or TTC) system setting) until the time deceleration started, the target was consistently struck before peak deceleration could be achieved. This significantly reduced the overall effectiveness of Vehicle E's CIB system.

Figure 70 shows examples of different delays in deceleration for three CIB systems tested. The CIB trigger on Vehicle E (upper graph in Figure 70) occurred 0.59 seconds prior to impact. However, vehicle deceleration did not begin until 0.22 seconds prior to impact, due to a system lag of 0.37 seconds. Vehicles F and G, (middle and lower graphs in Figure 70, respectively), used lower CIB system deceleration settings but a combination of longer TTC settings coupled with less system lag. Higher overall vehicle speed reductions were observed for these vehicles. Vehicle F achieved the highest speed reduction in this example of approximately 14 mph with a CIB trigger at 1.38 seconds prior to impact and vehicle deceleration starting at 1.26 seconds before (with a system lag of 0.12 seconds). This was achieved in part through the brake system pre-charging feature included with this vehicle. Vehicle G had the next highest system lag of 0.28 seconds but achieved a reduction of approximately 7 mph in impact speed by triggering the CIB system 0.88 seconds prior to impact. This gave the Vehicle G system 0.6 seconds to achieve its impact speed reduction.

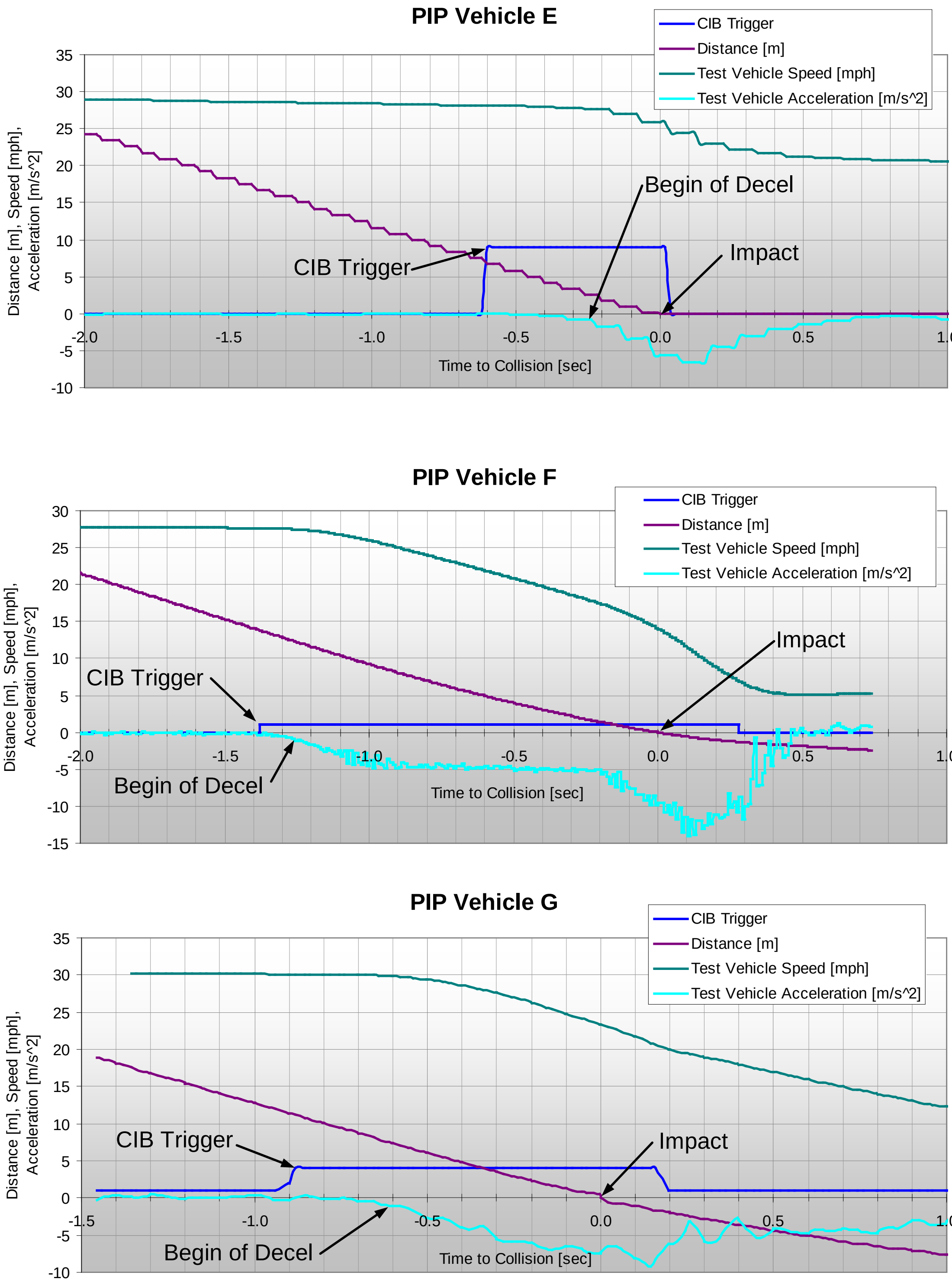


Figure 70: Examples Showing Influence of CIB Brake System Lag Time on the PIP Vehicle Deceleration

5.2 Overview of the Process Used to Develop the Proposed Benefits Estimation Methodology

5.2.1 CIB Consortium Role

CIB Consortium involvement in the benefits estimation methodology for CIB systems consisted of the following:

- Collaborated with Volpe to identify the target crash scenarios for CIB systems
- Reviewed the proposed benefits estimation methodology and provided feedback
- Provided sample CIB system results for Volpe to use in exercising their proposed methodology
- Identified additional work and data required to address concerns surrounding the level of confidence of the benefit estimates

To facilitate this collaboration, a Benefits Estimation Working Group was established consisting of NHTSA/Volpe representatives, the CIB TMT and additional technical experts from CIB partner companies. These technical experts provided knowledge in crash databases, crash injury risk estimation, statistics and vehicle safety system benefits analysis. Volpe used the priority crash scenarios and National Automotive Sampling System (NASS) data filters discussed in Chapter 2 as a starting point for defining the crashes potentially addressed by CIB systems. The results from the CIB testing conducted during the project were used by Volpe to refine the crash population of interest and evaluate their proposed benefits estimation methodology.

5.2.2 Summary of Benefit Estimation Method

Consistent with the NASS data filters used to establish the project priority crash scenarios documented in Chapter 2, Volpe started with the following target crash scenario definition for the proposed benefits estimation methodology:

Host Vehicle (Following Vehicle)

- Light vehicle less than or equal to 10,000 lbs. Gross Vehicle Weight Rating
- Model year 1998 or newer
- Towed due to damage
- No rollover
- Frontal impact is first and most harmful event
- Not stopped, disabled, parked, or backing
- Did not brake and maintained control

Other Vehicle (Vehicle Being Struck by Host Vehicle)

- Light vehicle less than or equal to 10,000 lbs. Gross Vehicle Weight Rating
- Model year 1998 or newer
- Towed due to damage
- No rollover
- Back, left, or right impact is first and most harmful event
- Involved in first event with host vehicle

Within this set of crashes defined as CIB-applicable, Volpe included the following occupant types for evaluating injuries in the host vehicle and "other" categories:

Host Vehicle (Following Vehicle)

- Belted driver
- Non-belted driver
- All belted occupants
- All non-belted occupants

Other (Vehicle or Pedestrian Being Struck by Host Vehicle)

- All belted occupants
- All non-belted occupants
- Pedestrian

Volpe defined a general benefits estimation equation as follows:

Annual Safety Benefits = Annual Societal Cost X System Effectiveness

At the highest level, for crashes deemed CIB-applicable, the estimated Annual Safety Benefits was calculated by using the estimated reduction in velocity (or ΔV) at impact due to CIB intervention to estimate a reduction in various societal "cost" (or "harm") measures. The four societal cost measures estimated included the number of occupants with a Maximum Abbreviated Injury Scale (MAIS) value of two or higher (MAIS 2+), the number of occupants with a MAIS value of three or higher (MAIS 3+), the Value of Statistical Lives Lost, and the Functional Years Lost.

These measures were estimated within each of the various occupant type categories (as indicated above) by crash scenario (e.g., lead vehicle stopped) combinations. In order to estimate CIB benefits for each of these combinations, Volpe developed assumed relationships between ΔV and the various societal cost measures (i.e., injury risk curves). That is, assumptions were developed with respect to the proportion of occupants within each ΔV bin and the societal cost value per occupant within each ΔV bin. Based on these assumed relationships, societal benefits were estimated by comparing the value of a "baseline" vehicle (i.e., without CIB intervention) to that obtained with a CIB-equipped host vehicle that provides an assumed reduction in ΔV.

Monte Carlo simulation was then conducted to evaluate the proposed benefits estimation methodology using selected samples of CIB system test data provided from the aforementioned validation tests conducted by the CIB TMT. Confidence intervals, sensitivity studies on various methodology parameters and other factors affecting the robustness of the proposal were also evaluated. Details of each of these steps are anticipated to be documented in Najm et al. (in preparation).

Although Volpe's general concept and framework of the proposed methodology appear logical, the complexities of, and the limitations in, the real-world data necessary to populate the proposed model inherently lead to concerns (discussed below) surrounding the benefits estimations generated by this methodology.

5.3 Discussion of Volpe's Proposed Benefit Estimation Method

5.3.1 Factors Affecting Estimation of Annual Societal Cost

As outlined earlier, Volpe has proposed to estimate the overall safety benefit of CIB systems by using the magnitude of "Annual Societal Costs" resulting from crashes in which CIB technology may be applicable (referred to as the "crash opportunity pool") combined with the assumed CIB effectiveness in reducing the vehicle speed at collision. Several issues have been identified with the proposed Benefits Estimation Methodology that raises concerns with accurately estimating the crash opportunity pool. These issues fall into three categories that are described below.

5.3.1.1 Estimating the Size of the Crash Opportunity Pool

The first category consists of those factors that affect estimating the size of the crash opportunity pool. These factors may result in under- or over-estimation of this pool and, thus, affect the overall estimated Annual Safety Benefit of a CIB system.

First, consistent with the scope defined for this project, the current approach does not attempt to account for other crash avoidance/mitigation systems that may overlap with or complement a CIB system in avoiding/mitigating crashes within the CIB crash opportunity pool. These include FCW and PBA systems, which are often integrated with CIB systems in today's production vehicles. Further work should investigate methods to assess the relative societal benefits of CIB versus these related crash avoidance/mitigation systems.

Second, the police accident reports and crash investigation data used for determining CIB benefits have inherent "quality" limitations. For example, consider the difficulty and subjective nature in assessing post-crash whether or not a "driver braked" in a pre-crash event without on-board data collection. (Note: This assessment played a large role in determining the size of the crash opportunity pool.) Similarly, errors may occur in estimating the vehicle speed at time of impact and the pre-crash maneuver of the striking vehicle before the impact. These police accident report and crash investigation limitations could potentially be addressed via cases in which vehicle EDR data are available (provided the EDR records the relevant variables). Such data is likely to be more readily available in the future due to NHTSA's EDR ruling (Part 563 – Event Data Recorders), which goes into effect on September 1, 2012.

Overall, the potential for these issues to affect the size of the CIB crash opportunity pool is considered very significant. For example, including cases where FCW alone would have helped avoid or at least mitigate the crash results in over estimating CIB benefits. On the other hand, excluding cases where the vehicle was braking (e.g., where the braking may have occurred just prior to impact) results in under estimating CIB benefits. A CIB system may apply the brakes well before the driver prior to an impact, and independently of whether or not the brakes are already applied. Unfortunately, there is no clear manner in which to weight these over- and under-estimation of CIB benefit factors. Consequently, the approach taken per the scope of this project to establish the size of CIB crash opportunity pool creates problematic issues for determining CIB benefits.

5.3.1.2 Uncertainty Associated with NASS Base Estimates

The second category of factors which affect estimating the CIB crash opportunity pool are related to the uncertainty associated with NASS "base" estimates. These "base" estimates, which involve applying weightings to each CIB-applicable crash, play an important role in determining the size of the crash opportunity pool. These NASS estimates have large statistical confidence intervals, which creates uncertainty and a lack of confidence in the underlying dataset used to estimate CIB benefits.

With respected to estimating potential CIB benefits in pedestrian-related crashes, the Pedestrian Crash Data System (PCDS) dataset used to assess CIB benefits in pedestrian-related crashes in the current effort is not a nationally representative sample of vehicle-to-pedestrian crashes. This dataset was used in the current effort since detailed crash event data was available for over 600 vehicle-to-pedestrian crashes. Consequently, any CIB benefits data derived from the PCDS data may not be representative of the pedestrian crashes in the U.S. Future work could consider developing techniques for exploring the relationship between PCDS and GES data to potentially generate national CIB benefit estimates. It should also be noted that the pedestrian impact speed values contained in the PCDS database are estimated. Furthermore, using the posted speed limit as a surrogate for impact speed is problematic since many pedestrian crashes occur near intersections where vehicle travel speeds may be well below posted speed limits.

In summary, the potential for these crash data base limitations to introduce error into establishing the CIB crash opportunity pool is considered significant. The large confidence intervals associated with the NASS estimates coupled with the relatively small number of CDS cases available may lead to overly influential cases driving unstable estimates. This issue is exacerbated even further when more detailed breakdowns of the data are employed to address more specific crash scenarios.

5.3.1.3 Availability of Data after Application of Filters

The third category of factors affecting the crash opportunity pool is related to the limited amount of data that is available for determining CIB benefits after the CIB "filters" used to establish this pool (e.g., "driver did not brake") were applied. Figure 3, previously discussed in Section 2.4, illustrates the list of filters and filter logic used by the CIB

Project in the development of test procedures and serves to illustrate the effect of using various filters when establishing CIB benefits. With the exception of the first filter shown in Figure 3 in Section 2.4 (i.e., AIS+2), all of the remaining filters were used in estimating CIB benefits. Consequently, in the benefit estimation process, property-damage-only and lower-injury-severity cases were included.

The application of these filters reduced the "opportunity pool" of cases used to develop the test conditions to approximately 10% of the original size. Although the AIS2+ filter is not being used in the proposed CIB Benefits Estimation Methodology, this example illustrates the limitation in the amount of data available, particularly when considering that this data is further broken down into various ΔV speed bins for each of the various vehicle-to-vehicle, vehicle-to-object and vehicle-to-pedestrian crash types examined. For example, in the case of the vehicle-to-object crash scenario, application of the filters reduced the number of available cases from 1,903 to 121. The vehicle-to-object cases are further broken down in the lower part of Figure 3 in Section 2.4 where the classification by the type of object struck is provided along with the weights associated with each of these categories. This raises concern that a small number of unique crash cases (which are in turn weighted to project national estimates) may have an undue influence on the CIB Benefits analysis.

5.3.2 Factors Affecting Estimates of CIB Effectiveness

Although the current CIB Project produced a large set of tests and test results that can be used to discern the performance of various CIB systems, there are limitations on these results that should be well understood. Future related research should address these limitations.

5.3.2.1 Test System Performance Limitations

The PIP vehicles that were employed to evaluate the test procedures documented in Chapter 4 were not production systems. Rather, these systems were configured specifically to allow varying levels of CIB system functionality in order to evaluate the ability of the tests developed to differentiate CIB performance levels. Therefore, while the test results shown in Chapter 4 are appropriate for evaluating the proposed test methods, these same test results are not considered appropriate for establishing CIB effectiveness estimates.

For example, production CIB systems typically employ a variety of techniques to suppress false events (i.e., inappropriate CIB autonomous brake activations) in real-world situations. Inappropriate, brake-activation events have great potential to adversely affect driver usage and acceptance of CIB systems. The CIB systems deployed on the ROAD Trip documented in Chapter 4 did not have false event countermeasures implemented in order to more effectively assess the types of scenarios that could potentially cause false events for the various sensor combinations. Additionally, the post-processing methods required to evaluate single sensor (i.e., radar-only or vision-only) system performance were different by necessity. Therefore, while the data obtained during the ROAD Trip was appropriate for the evaluation of the various sensor combinations and different sensitivity settings within each combination, this data is not appropriate for the evaluation of false-event performance of CIB systems in general (or the relative false-event performance across different sensor combinations).

In addition, the recommended functional performance tests are intended to represent the primary crash scenarios that CIB systems are intended to address. However, for practical reasons, these tests only directly address basic CIB system functionality. Future work may consider employing a wider variety of test method approaches, particularly as CIB technologies mature and expand their capabilities (e.g., the types of crashes they are intended to address).

As previously described in Chapter 3, it should also be stressed that vehicle (balloon car) and pedestrian (mannequin) targets used in testing were relatively early prototypes, and consequently, did not always accurately represent the radar and vision characteristics of real-world targets. Thus, additional development of targets (especially pedestrian targets) is recommended for future work. While the validated test methods and targets developed during this project will be capable of providing data for measuring the performance of a particular CIB system, the data taken during the course of this project should not be used for the purpose of estimating overall CIB technology benefits.

The inflatable balloon car targets used early in testing exhibited very poor radar reflectivity. These targets had to be modified to give even moderately acceptable radar performance. However, the inflatable target developed by NHTSA later in the project exhibited improved radar reflectivity. Testing showed this target to be comparable to the reflectivity of a typical automobile when viewed from the rear. However, when this target was tested from angles other than the rear, it was found that further target enhancements are needed in order for this target to be fully representative. Although the visual characteristics of this target were good enough for the vision systems employed in the PIP vehicles to identify the target from the rear, it should be pointed out that the visual characteristics were not evaluated thoroughly. Similarly, the reflectivity of these targets was not evaluated for CIB sensing systems based on LIDAR sensors. Note that these comparisons were made to one real vehicle. Additional work should be performed to compare the radar reflectivity of a wider range of vehicles with the balloon car to validate the balloon test target.

With respect to the pedestrian target (mannequin), the radar return variability as a function of azimuth angle and target rotation was evaluated and a configuration was established that correlated roughly to a 50^{th} percentile human. However, it should be noted that other (non radar-return) characteristics of the pedestrian target, such as the visual, motion and thermal characteristics, were not evaluated in this project.

5.3.2.2 Repeatability of Functional Tests

The proposed benefits estimation methodology must also take into consideration the consistency and reliability of CIB system performance, accounting for cases where the system does not respond to a valid target (i.e., a missed event) and the variability in CIB activation performance to valid targets. For example, it could be argued that the hypothetical System A and System B shown earlier in Figure 68 should not be rated equally, even though their average change in impact speed (ΔIS) is the same. In this example, average ΔIS is the velocity reduction multiplied by the activation rate. The driver who experienced activation with System A would benefit from a higher ΔIS but with only a 50% activation rate. System B, on the other hand, would have activated for 100% of events and provided a consistent 5 km/h ΔIS. As a result, System B would have delivered a higher probability of a benefit because it provides a more consistent performance than System A.

5.3.2.3 "Harm" Functions (and the Desire for Small ΔV Bins)

Limitations in the amount of available CDS and PCDS data are problematic with respect to supporting the desire for small ΔV bins for estimating injury risk and establishing the "harm functions" as a function of ΔV used in the proposed benefit estimation process and for discriminating performance between different CIB system configurations. In general, as noted above, very limited data was available to estimate the current injury rates by ΔV used in the CIB benefits analysis. Furthermore, those "harm" functions were generated using averaged rather than raw data. The use of averaged data can be problematic with respect to leaving an impression of better resolution than the actual statistical fit of the available data can support.

5.3.2.4 Effect of Potential Unintended Consequences

CIB systems have the potential to lead to unintended consequences. For example, a CIB system designed to activate "early" during a valid event can lead to the negative consequence of increased probability of CIB false activation events. A potential unintended consequence of a CIB false event is that the CIB-equipped vehicle is struck from behind by a following vehicle. Furthermore, even if the effect of the false event turns out to be benign (e.g., there is no following traffic), false events could lead drivers to disable their CIB system or avoid driving or purchasing vehicles with such systems. Consequently, since CIB false events have great potential to negatively influence the usage and market penetration of CIB systems, great care must be taken to minimize the occurrence of such events. The current proposed CIB benefits estimate methodology does not address this important, and admittedly challenging, false event issue.

5.3.2.5 Market Penetration Assumptions

The proposed CIB benefits approach also does not examine the effect of various realistic market penetration assumptions. These assumptions can be affected profoundly by a variety of factors, including assumed system price and performance (including false event issues). These assumptions are further complicated by the "overlap" of benefits provided by related systems, such as FCW and PBA.

6 Summary

This project focused on the development and validation of performance requirements and objective test procedures for CIB systems and the assessment of the injury reduction potential of various CIB system configurations with differing performance capabilities. The first phase of the project focused on the identification of CIB-applicable, target crash scenarios and the development of preliminary functional requirements for pre-crash sensing and braking systems.

The second phase of the project involved identifying forward-looking sensors and systems that could potentially be used in future CIB systems. Initial minimum performance specifications for the project prototype CIB systems were determined and candidate CIB systems were identified. Next, preliminary evaluations and ranking of technology candidates were conducted in order to select CIB systems to build into the CIB PIP development vehicles. Finally, the selected CIB system combinations were sourced and built into the PIP vehicles and test target systems for evaluating these systems (e.g., balloon cars with a towing system) were developed.

The third phase of the project involved developing objective test procedures and evaluating their capability to differentiate the relative performance and potential benefits of the selected CIB systems. These test procedures assess both desired activations as well as operational scenarios included in the performance specifications. During this phase, additional development and confirmation of the test methods were conducted, the test methods were verified to be capable of differentiating the relative performance of the selected CIB systems, and the validated test methods were finalized. Real-world data was also gathered for the purposes of developing operational assessment tests to evaluate CIB system robustness against false activations.

The fourth and final phase of the project involved finalization of the CIB performance specifications and development of the benefits estimation methodology. For the functional test method minimum performance metrics, three measures were presented as both a means for establishing minimum performance values and as a means for differentiating between CIB systems. These measures include the percent activation in each of the three functional test scenarios and the average speed reduction achieved by the CIB system in each of these scenarios. These performance metrics for the operational test scenarios represent a minimum set of real-world conditions for which any given CIB system could reasonably be expected to execute some level of automatic braking.

The Benefit Estimation Methodology explored for assessing CIB benefits was developed by researchers at the Volpe Center. This methodology employs a conceptual framework which is currently dependent, in many cases, on data that is either of limited quantity and/or quality, or on data that does not exist (which requires assumptions). In order to exercise the proposed methodology to estimate CIB benefits, numerous approximations, substitutions and simplifying assumptions were necessarily required. Overall, despite earnest attempts to make use of all available crash data, the estimates produced by the proposed Benefit Estimation Methodology, as applied to CIB in this project, are not considered robust or sufficiently accurate. However, it is important to stress that the crash data mining conducted under this project was felt to be valuable for establishing CIB test scenarios.

Despite the concerns that have been raised with efforts to establish CIB benefits with the proposed Benefits Estimation Methodology, there are a number of important "lessons learned" that may prove valuable in future related research. Estimating the CIB-applicable "crash opportunity pool" and the associated benefits of a CIB system reducing the impact speed proved challenging as a result of many factors. Examples of these factors included lack of precise knowledge (via police accident reports and crash investigations) with respect to if, when, and the extent to which the driver braked prior to a crash and the extent to which other related crash countermeasures (e.g., FCW or PBA) may reduce projected CIB benefits. In addition, it should be stressed that the impact of CIB false events and various market penetration assumptions were not addressed under the current project.

More generally, limited data was available to exercise the proposed Benefits Estimation Methodology. As a result, in some cases, significant data were explored as substitutions (e.g., using PCDS data to establish national benefit estimates). Furthermore, the data available were characteristically associated with large confidence intervals where there is a significant risk of highly unstable estimates from a small number of cases that may be highly influential in the resultant benefit estimations. Thus, the ability to estimate confidence intervals surrounding a CIB Annual Benefit Estimate is problematic given the level of uncertainty surrounding the various inputs required in the benefit estimation process.

7 Recommendations and Future Work

The following provides some recommendations and suggested future investigations to assist in the reconciliation of issues with the proposed benefits estimation process for CIB systems.

As production CIB systems become increasingly available, future research could be conducted to better understand the circumstances leading up to and the effectiveness of CIB activations. These investigations may also be able to further explore the use of EDR data, which may provide important data such as vehicle speed and driver brake applications. Furthermore, field crash analysis should be undertaken to begin to understand the real-world effects of emerging CIB production systems. This analysis could help explore the extent to which CIB will offer additional benefits beyond those offered by other related (e.g., FCW) systems, already offered in production vehicles.

From a CIB test procedure perspective, production representative CIB systems could be evaluated under a wider range of dynamic approach conditions than were possible under the current effort. In addition, a number of crash scenarios (e.g., those involving pedestrians) merit evaluating additional test procedures development.

From a crash data perspective, establishing national CIB benefit estimates is particularly problematic for pedestrian crashes given the lack of detailed PCDS data. Hence, efforts are recommended to review the sample size and necessary elements (e.g., impact speed) of pedestrian crash databases required to work toward establishing a nationally representative pedestrian crash database sample.

Future efforts intended to incorporate the proposed Benefit Estimation Methodology developed by Volpe should employ improved statistical modeling approaches for developing injury risk estimates, more fully address the influence of potentially overly influential CDS cases, and identify ways of more directly using the GES database (rather than extrapolating from CDS and PCDS data to annual estimates).

Future work should be performed to evaluate CIB systems triggered by the braking of the driver. Such systems could supplement autonomous braking systems and could potentially have greater benefits than autonomous braking systems alone. As demonstrated in Figure 3, a significant number of crash cases were filtered out from further consideration which involved driver braking.

Work should be performed to develop a methodology for validating and quantifying test target characteristics (e.g., the optical, radar return, LIDAR return) from a range of typical U.S. vehicles.

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DOT HS 811 521
September 2011

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