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A Methodology for Estimating Potential Safety Benefits for Pre-Production Driver Assistance Systems

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16. Abstract

This report develops and demonstrates a methodology for estimating the potential safety benefits of pre-production driver assistance systems. The methodology uses an engineering description of system performance in conjunction with a detailed analysis of crash data to establish objective tests for the system. The results from these tests are combined with additional analysis of crash data files and naturalistic driving data to estimate measures of effectiveness for the system. The two measures of effectiveness used in this report are the Exposure Ratio and the Prevention Ratio.

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Glossary

B	Benefits
BA	Brake Assist
CPB	Crash Prevention Boundary
DAS	Driver Assistance Systems
E	Effectiveness (For a Specific Crash-Related Scenario)
ECA	Estimated Closest Approach
ER	Exposure Ratio
FARS	Fatality Analysis Reporting System
FOT	Field Operation Tests
GES	General Estimate System
KME	Kinetic Motion Event
MOE	Measure of Effectiveness
MOP	Measure of Performance
N_w	Number of Measure With System Deployment;
Nwo	Number of Measure Without the System; Example Number of Crashes
OR	Odds Ratio
P	Probability. Example: Probability of Crash
PR	Prevention Ratio
SE	System Effectiveness
S_W	Number of Scenarios With System Deployed
S_{WO}	Number of Scenarios Without System Deployed
TTC	Time to Collision
VMT	Vehicle Miles Traveled
X	Measure of Exposure
Critical Event	GES Pre-Crash Variable
First Harmful Event	GES Pre-Crash Variable

Executive Summary

This report develops and demonstrates a methodology for estimating the potential safety benefits of pre-production driver assistance systems. The methodology uses an engineering description of system performance in conjunction with a detailed analysis of crash data to establish objective tests for the system. The results from these tests are combined with additional analysis of crash data files and naturalistic driving data to estimate measures of effectiveness for the system. The two measures of effectiveness used in this report are the Exposure Ratio and the Prevention Ratio. The report is organized into seven chapters that describe and demonstrate the methodology, plus a summary chapter. The first chapter describes the methodology and outlines relationships between elements of the methodology. Each of the following chapters focuses on a specific element of the methodology.

Analyses of data from crash data files form a fundamental part of several elements of the methodology. One innovation in this report is the introduction of a new framework for analysis of crash data. This framework, called the Universal Description, is a set of mutually exclusive combinations of Critical Event, Avoidance Maneuver, and First Harmful Event. This set of mutually exclusive combinations forms a common starting point for evaluation of any technology or system. Thus, overlaps in coverage by different technologies are easily identified. Likewise, identification of gaps in anticipated coverage for a specific system is simplified.

The report includes a section that describes the basic definition of benefits (which can be, for example, the reduction in number of crashes or the number of injuries experienced by victims of crashes that do occur) and develops three formulations that can be used for estimating benefits. These formulations provide a means of comparing results from this methodology with other evaluations and assessments of benefits. This section includes an appendix in which a select sample of previous evaluations is reviewed.

As a demonstration of using crash data to develop test conditions for a system, the report includes a detailed development of test conditions for lane-keeping/road departure assistance systems. The analysis is based on 2004 GES and FARS data and concludes with a set of five tests for these systems. The tests are summarized in the following Table ES-1.

The report develops a novel approach to the experimental design of objective tests. The method accomplishes the dual needs of incorporating driver variability and being objective. The approach addresses the seemingly incompatible nature of these two needs by using volunteer drivers to perform baseline tests while high-fidelity recordings are made of the details of their performance. These recordings are used as input to pre-programmed controllers for the tests with the DAS active. The selection of volunteer drivers is based on the distribution of age and gender of crash-involved drivers.

Type	Roadway	Specifics	Speed (80% of all crashes)	Speed (80% of fatal crashes)
Two vehicles; opposite direction	- Two-lane - Undivided - Curve	- 350 ft separation (485 ft at 55 mph) - 3 degree approach angle	40 mph, both vehicles	55 mph, both vehicles
Two vehicle; opposite direction	- Two-lane - Undivided - Straight	- 350 ft separation (485 ft at 55 mph) - 3 degree approach angle	40 mph, both vehicles	55 mph, both vehicles
Two vehicle; same direction	- Multilane - Straight	- 3 degree approach angle	40 mph, lead vehicle 45 mph, Following vehicle	65 mph, lead vehicle 70 mph, Following vehicle
Single vehicle	- Two-lane - Undivided - Curve	- Narrow shoulder - 3 degree approach angle	50 mph	75 mph
Single vehicle	- Multilane - Straight	- Shoulder with parked vehicle - 3 degree approach angle	30 mph	70 mph

Table ES-1 Test conditions for lane-keeping/road departure driver assistance systems

An important element of the methodology is the use of naturalistic driving data. One chapter in the report demonstrates the use of naturalistic driving data for estimating how a DAS might help drivers avoid imminent crashes. One source of information for estimating the Exposure Ratio is naturalistic driving data. The chapter includes an extensive example using data from a recently completed field operational test.

The report also includes an example of the data processing needed to convert test outcomes to estimates of the number of crashes that would be prevented by the system. A hypothetical brake assist system is used for this example.

A final chapter summarizes the report and discusses relevant issues.
Some suggestions for future work include:

- More detailed consideration of driver characteristics such as distraction and state of alertness;
- Extension of the crash avoidance focus of this report to include crash severity mitigation;
- Extensions of the methodology to support future provisions of the New Car Assessment Program (NCAP); and
- Validation and calibration of the methodology.

CHAPTER I
Introduction

In 2004, more than 10 million drivers were involved in police-reported crashes. Each of these crashes began with a critical event. The drivers who were confronted with these events responded by braking, steering or both; or by taking no action. The purpose of Driver Assistance Systems (DAS) is to intervene in this chain of events in such a way that the criticality of the event is changed and/or the efficacy of the driver response is improved. This report describes a methodology that can be used to estimate the potential number of crashes that could be prevented. The methodology focuses on pre-production driver assistance systems by combining the engineering description of system performance, statistical descriptions from representative data files (both crash files and naturalistic driving files) and results from objective tests to estimate the safety impact of the technology. For each system that is studied, there will be a series of activities. The diagram in Figure I-1 depicts this process.

Each of the rectangles in this diagram represents an activity and each parallelogram represents an output. The overall process begins with the identification of a candidate system or technology. This is the uppermost rectangle in the diagram. The intermediate steps or activities create a database that is then used in the final activity to estimate the potential safety benefits (reductions in the number of crashes, injuries, and fatalities).

Activity 1. Describe the system design and performance

The output of the countermeasure system design activity is a detailed engineering description of the system and its performance. The performance description from this activity is the starting point for the remainder of the process. This activity is not the focus of this report. So, even though it is an important step in the process, it is not emphasized here.

Activity 2. Analyze GES and other crash data files

In this activity, variables and data elements from GES and other files, based on the performance description from Activity 1, are identified. The analyses in this activity begin with the complete description of the crash problem. These analyses are the foundation for development of objective tests in Activity 5 as well as most of the other activities. Chapter IV provides a guided tour through analysis of GES and FARS data to identify scenarios that could be used as the foundation for tests on lane-keeping/road departure systems. The conclusion of Chapter IV is a set of five test conditions that lay the foundation for testing lane change/road departure systems.

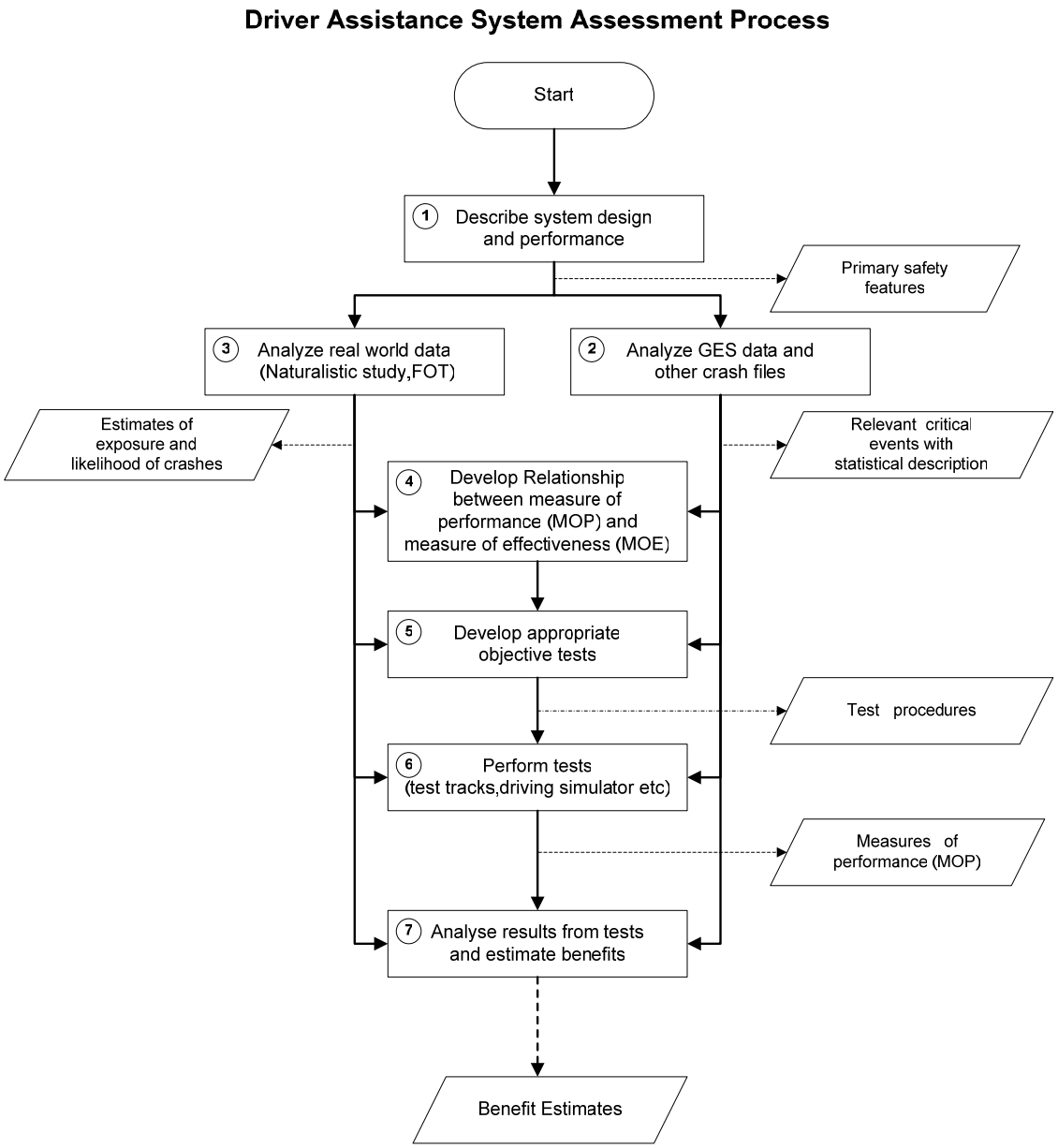


Figure I-1: Process for assessing the safety impact of driver assistance systems

<u>Activity 3. Analyze real-world data such as naturalistic driving and field operational tests.</u>

In this activity data from naturalistic driving studies are analyzed to determine the level of exposure of critical events. The level of exposure from naturalistic driving data complements the results from analysis of the crash data files. These results are used for refining test conditions and for providing the baseline for estimating any reduction to the exposure rate that are provided by the system. As seen in Chapter III on the benefits estimation process, the Exposure Ratio is a key component of the benefits estimation process. A detailed example of use of existing naturalistic driving data for this purpose is provided in Chapter V. This chapter also includes a short discussion of how naturalistic data can be used to provide anecdotal insights in the details of how a technology would

intervene in a specific situation. There is also a discussion in Chapter IV about the use of naturalistic driving data to determine appropriate test conditions.

Activity 4. Develop relationships between measures of performance and measures of effectiveness.

The underlying principle of a crash avoidance system is that it assists the driver in avoiding crashes that would otherwise occur. This principle is intimately intertwined with driver crash avoidance performance; and the concept that, for each scenario that a driver faces, the driver can perform in a manner that avoids a crash or that results in a crash. The corollary is that the purpose of a crash avoidance system is to assist the driver in a way that improves the likelihood of successfully avoiding a crash in scenario that may lead to a crash. The linkage between measures of performance (MOPs) and measures of effectiveness (MOEs) is the embodiment of the corollary, i.e. the relationship between MOPs from objective tests and MOEs quantifies how the system will assist the driver in a way that improves crash avoidance performance.

The basic MOEs, as developed in Chapter III, are the Exposure Ratio and the Prevention Ratio. The Exposure Ratio is the ratio between rate of exposure (i.e., the rate at which drivers encounter an imminent crash) with the system and the rate of exposure without the system. Similarly, the Prevention Ratio is the ratio between the probability of having a crash with the system and the probability of having a crash without the system. Here the scenario has progressed through the imminent crash phase. A major link in the benefits estimation process is the connection of test results from the tests described in Chapter VI and estimates of Prevention Ratio or Exposure Ratio. As seen in Chapter III, the process of estimating benefits involves estimating prevention ratio and exposure ratio for a number of technology-relevant scenarios. Part of the input to this process comes from testing of the technology. Prescriptions of specific test measurements and outcomes, i.e. measures of performance, are part of the development of tests. This technology-specific development is not emphasized in this report.

Activity 5. Develop appropriate objective tests

In this activity, tests for the system are developed. This activity is tightly coupled with Activity 2. Due to the nature of this technology-specific step in the methodology, it is not emphasized in this report. Chapter VI outlines a six step process that leads to tests that are objective and that address driver variability.

Activity 6. Perform tests

In this activity, the tests developed in Activity 5 will be performed. These tests will probably be run on test tracks, but there may be some elements of the testing that will be done on driving simulators or in other laboratory environments. The outcomes from these tests will include the Measures of Performance that are identified in Activity 4. Chapter VI describes a process that has the potential for being the foundation of tests for assessing the

performance of relevant technologies. The process outlined in this chapter addresses the need for tests to be both objective and to meet the need for capturing the variability of driver performance.

Activity 7. Analyze results from tests and estimate benefits

The final stage of the process is the estimation of benefits activity. In this activity, the calculation process described in Chapter III is combined with the problem size from Activity 2 and results of analyses and tests in Activities 4 and 6 to obtain estimates of the safety impact of the system. Chapter VII discusses a hypothetical example of setting up and using the results of a test for one specific scenario. The complete analysis of benefits would include additional tests as well as analysis of data files. Because of the technology-specific nature of this activity, it is not emphasized in this report.

Chapter II
Underlying Foundation for Analysis

The methodology described in this report is based on the timeline of events that precede each crash. The timeline is a sequence of phases during which the likelihood of a crash increases. A DAS can intervene at any point prior to the crash in this sequence of phases. A description of this generic timeline of pre-crash events is shown in Figure II-1. The three phases represent opportunities for drivers, either without or with help from a DAS, to intervene before a potential crash becomes a crash.

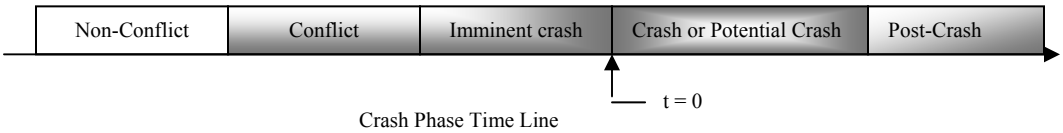


Figure II-1 Crash sequence

The chain of events that leads from a non-conflict condition to a crash begins with a Critical Event. Depending on the circumstances, the transition may go directly from a non-conflict condition to an Imminent Crash or it may go more gradually through a Conflict stage followed by an Imminent Crash phase. The challenge for drivers, whether aided by a DAS or not, is to use the time after the Critical Event to take action to prevent a crash. Drivers usually take appropriate action and avoid a crash. However, a critical event occasionally (one crash for every 450,000 miles of travel[1]) results in a crash. The assessment methodology in this report takes into account this fact that drivers without help from a DAS usually avoid crashes after a critical event. The terminology in this figure is used throughout this report to describe the driving circumstances that precede crashes or potential crashes.

Each Critical Event can lead to multiple types of crashes, or to no crash. This picture of possibilities is shown simplistically in Figure II-2. The circles on the left correspond to the 54 possible Critical Events that may lead to a crash and the circles on the right correspond to the 38 possible First Harmful Events that may occur. Each line in the diagram can be represented by a timeline such as shown in Figure II-1.

* Superscript numbers identify references

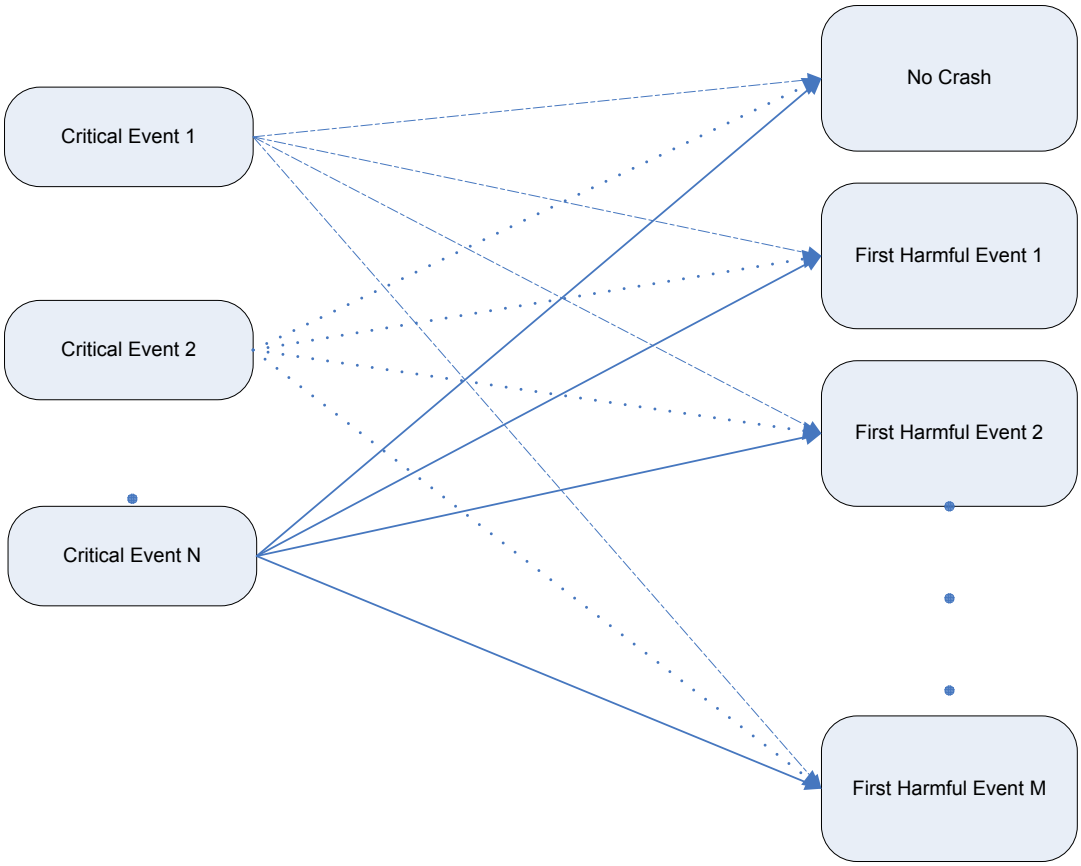


Figure II-2 Schematic diagram of interrelated Critical Events and First Harmful Events

When seen through the eyes of an accident investigator, the timeline of Figure II-1 looks like the diagram shown in Figure II-3. This figure is taken from the GES Coding Manual,[1] where the top row gives GES code for the variables described in the second row. In this figure it can be seen that there are six pre-crash variables that play a role in determining the First Harmful Event in a crash.

V21	V26	V27	V28	V29	A06
Movement Prior To Critical Event	**Critical Event**	**Corrective Action Attempted**	**Pre-Crash Vehicle Control**	**Pre-Crash Location**	**First Harmful Event**

Figure II-3 Description of pre-crash variables and respective GES[1] codes.

Assessment of the safety impact of a DAS begins with an analysis of the variables on this timeline. To simplify the description of events and conditions that precede crashes, only the Critical Event, the driver response and the resulting First Harmful Event are used in Table II-1 to describe the chain of events for each crash-involved vehicle. This description is called the Universal Description. It provides a high-level set of 90 mutually-exclusive

subsets that describe the circumstances for the individual crash-involved vehicles in the GES files.

This Universal Description provides a high-level, but complete, picture of crashes, the critical events that precede crashes, and how drivers try to prevent the crash.

As seen in subsequent chapters, the Universal Description is a common starting point for every assessment, but each assessment is a customized scrutiny of all relevant data elements.[1]

The combinations of Critical Event and First harmful Event that are shown in both Figure II-2 and in the Universal Description are useful for not only identifying the primary areas of safety improvement from a technology, but also for assessing the unintended consequences of technologies on secondary types of crashes. The methodology described in this report is primarily focused on intended consequences of new technologies, but the same approaches can be used to address unintended consequences. The methodology is based on the definitions and formulations discussed in Chapter III. In those formulations, the expectation is that there will be fewer crashes when a DAS is deployed compared to the number of crashes without the system. However, in some scenarios there may be more crashes with the system than without. This would indicate an unintended consequence of introducing the system. The formulations in Chapter III are equally applicable to either an improvement or a degradation of safety. Thus, the calculations would reflect the level of improvement, or degradation.

The definitions of the boundary between non-conflict and conflict conditions and between conflict and imminent crash conditions in Figure II-1 are an important part of the methodology. As seen in Chapters III and V, the boundary between conflict and imminent crash is used to separate the impact on exposure to imminent crashes and the impact of changes in driver performance when confronted with imminent crash conditions. One possible description of this boundary is when the time-to-collision reaches a value of 2.5 seconds or less. A similar description for the boundary between the non-conflict phase and the conflict phase is when the TTC equals 6 seconds. These values for the boundaries are based on anecdotal examples such as the following realistic situation:

> When following another vehicle with an initial range between the two vehicles of 175 ft, the lead vehicle suddenly begins to brake with a deceleration of 0.3 g. The TTC under these conditions is 6 seconds at the beginning of lead vehicle braking. For this situation, the following driver can avoid a crash by braking with a deceleration as low as 0.2 g and can wait as much as 5 seconds before braking. These conditions are an example of what the authors would call a conflict, but not an imminent crash. However, if the following driver hesitates for 3.5 seconds before making a decision to brake, the TTC will be just 2.5 seconds; and to avoid a crash, the deceleration will have to be at least 0.5 g and braking must begin within no more than 1.5 seconds. This limited range of options after the driver has waited until the TTC is only 2.5 seconds suggests that this is an imminent crash, rather than just a conflict.

Other descriptions of the criteria for an imminent crash and a conflict are possible and could be based on variables such as speeds, decelerations and relative locations.

Critical Event	First Harmful Event / Avoidance Maneuver	Non-Collision	Collision With non-fixed object	Collision With fixed object	Total
Subject vehicle loss of control	No maneuver	99,000	54,000	262,000	415,000
	Braking	22,000	46,000	71,000	139,000
	Steering	38,000	16,000	47,000	101,000
	Braking and steering	5,000	2,000	7,000	14,000
	Accelerating/others	0	0	2,000	2,000
	Total	**164,000**	**118,000**	**389,000**	**671,000**
Action by subject vehicle	No maneuver	25,000	2,284,000	195,000	2,504,000
	Braking	6,000	215,000	44,000	265,000
	Steering	64,000	109,000	89,000	262,000
	Braking and steering	3,000	12,000	7,000	22,000
	Accelerating/others	1,000	26,000	2,000	29,000
	Total	**99,000**	**2,646,000**	**337,000**	**3,082,000**
Action by another vehicle in subject vehicle's lane	No maneuver	2,000	3,064,000	1,000	3,067,000
	Braking	3,000	721,000	6,000	730,000
	Steering	7,000	199,000	18,000	224,000
	Braking and steering	2,000	64,000	6,000	72,000
	Accelerating/others	0	21,000	0	21,000
	Total	**14,000**	**4,069,000**	**31,000**	**4,114,000**
Encroachment by another in subject vehicle's lane	No maneuver	3,000	1,413,000	1,000	1,417,000
	Braking	7,000	482,000	6,000	495,000
	Steering	21,000	395,000	79,000	495,000
	Braking and steering	4,000	80,000	6,000	90,000
	Accelerating/others	1,000	11,000	1,000	13,000
	Total	**36,000**	**2,381,000**	**93,000**	**2,510,000**
Pedestrian and other nonmotorist	No maneuver	0	60,000	0	60,000
	Braking	0	30,000	0	30,000
	Steering	0	12,000	1,000	13,000
	Braking and steering	0	7,000	2,000	9,000
	Accelerating/others	0	1,000	0	1,000
	Total	**0**	**110,000**	**3,000**	**113,000**
Object or animal	No maneuver	2,000	217,000	2,000	221,000
	Braking	1,000	91,000	2,000	94,000
	Steering	13,000	70,000	42,000	125,000
	Braking and steering	0	11,000	3,000	14,000
	Accelerating/others	0	1,000	0	1,000
	Total	**17,000**	**390,000**	**48,000**	**455,000**
Grand Total		**330,000**	**9,716,000**	**899,000**	**10,945,000**

Table II-1: Universal description: Showing the pre-crash Critical Event, crash avoidance maneuver, and type of crash for each crash-related vehicle. (Imputed values from GES 2004)

CHAPTER III
Development of Basic Expressions for Estimating Benefits

The central step in this process is the actual calculation of estimated benefits. This step combines results from the objective tests with crash data (e.g., GES) and other data to produce the estimates. Three different formulations of the algorithms that can be used to estimate benefits are developed in this chapter. Variations on these three formulations have been used in the evaluations that are reviewed in Appendix A. Each of these formulations requires different types of data. For this reason, it is important to establish which formulation will be used so that appropriate data can be generated during the objective tests and other analysis.

Although there are three formulations, they all are based on the fundamental definition of benefits[2]:

$$B = N_{WO} - N_W \tag{1}$$

Where the benefits, B, can be number of crashes, number of fatalities, "harm," or other such measures. N_{wo} is the value of this measure, e.g., number of crashes, that occurs without the system and N_w is the value that would occur if the system is fully deployed.

The simplest extension of Equation (1) is the equivalent expression in terms of system effectiveness. This form is:

$$B = N_{WO} \times SE \tag{2}$$

where SE is the system effectiveness and N_{wo} is size of the problem.

It is important, when using the form in equation 2, to clearly specify the relevant population. For example, if N_{wo} is the number of intersection crashes without the system and a system can prevent 138,000 of these crashes per year, then the value of system effectiveness is 10 percent (there are 1,375,000 intersection crashes each year). However, if N_{wo} is the total number of crashes (approximately 6.5 million), then the system would only prevent 2 percent of this number, and the value of system effectiveness would be 2 percent.

An extension of this idea is that the overall system effectiveness consists of the effectiveness in addressing a number of specific scenarios; and that these individual values of effectiveness will not be equal. The weighted-sum of these values of effectiveness in individual scenarios is equal to the system effectiveness, as can be seen in the following expression:

$$SE = \sum \left(E_i \times \frac{N_{WOi}}{N_{WO}} \right) \tag{3}$$

This leads to the following basic general expression for estimating benefits.

$$B = \sum E_i \times N_{WOi} \tag{4}$$

Where the subscript "i" is used to denote individual scenarios. Thus, E_i is the effectiveness of the system in reducing the number of crashes in a specific crash-related scenario "i". The value for E_i range from zero to one, a value closer to one denotes high effectiveness of the system while a value close to zero denotes low effectiveness. N_{woi} is the baseline number of crashes in that scenario.[3]

Development of Type 1 expression for direct estimating benefits

The first type of formulation applies when available data supports direct estimation of either system effectiveness or the effectiveness of a system in an individual scenario. The values of the individual E_i are estimated using the following expressions

$$\widetilde{E}_i = \frac{\widetilde{N}_{WOi} - \widetilde{N}_{Wi}}{\widetilde{N}_{WOi}} \tag{5}$$

where the "~" over a letter denotes an estimate of the true value of that number. Thus, $\tilde{N}$ is an estimate of the number of crashes, fatalities, etc., either with or without the system.

Equation (5) is also often written as:

$$\widetilde{E}_i = 1 - \frac{\widetilde{N}_{Wi}}{\widetilde{N}_{WOi}} \tag{6}$$

Including this expression for estimates of effectiveness leads to the following expression for the estimate of benefits.

$$B = \sum \left(1 - \frac{\widetilde{N}_{Wi}}{\widetilde{N}_{WOi}} \right) \times N_{WOi} \quad = \sum \widetilde{E}_i \times N_{WOi} \tag{7}$$

Equation (7) is the Type 1 expression for estimating benefits. It uses estimates of the number of crashes (etc.) with and without the system, estimates of the ratio of the two numbers, or estimates of effectiveness.

Examples of recent evaluations that utilize Type 1 formulations are included in Appendix A.

Development of Type 2 expression for estimating benefits

The Type 2 formulation is used in analyses where the source of the number of crashes for vehicles without the system is different than the source of data for vehicles with the system. These two populations will have different levels of exposure. Thus, the expression for the Type 1 formulation needs to be modified to account for the difference in exposure. This is done by adjusting the number of crashes for vehicles with the technology to be consistent with the level of exposure of vehicles without the technology. Several measures of exposure are commonly used. They include mileage traveled, number of registered vehicles, and indirect measures based on a control group of vehicles that is not affected by the technology. The modified expression for effectiveness is then:

$$\widetilde{E}_i = \frac{\widetilde{N}_{WOi} - \widetilde{N}_{Wi}(\widetilde{X}_{WOi} / \widetilde{X}_{Wi})}{\widetilde{N}_{WOi}} \tag{8}$$

where $\widetilde{X}$ is an estimate of the measure of exposure.

The expression above that incorporates exposure can be rewritten as follows:

$$\widetilde{E}_i = \frac{\widetilde{N}_{WOi} / \widetilde{X}_{WOi} - \widetilde{N}_{Wi} / \widetilde{X}_{Wi}}{\widetilde{N}_{WOi} / \widetilde{X}_{WOi}} \tag{9}$$

or

$$\widetilde{E}_i = 1 - \frac{\widetilde{N}_{Wi} / \widetilde{X}_{Wi}}{\widetilde{N}_{WOi} / \widetilde{X}_{WOi}} \tag{10}$$

The estimate of effectiveness of the system from equation 10 can also be written in the form of Odds-Ratio[4] (OR).

$$\widetilde{E}_i = 1 - OR \tag{11}$$

Where

$$OR = \frac{\widetilde{N}_{Wi} / \widetilde{X}_{Wi}}{\widetilde{N}_{WOi} / \widetilde{X}_{WOi}} \tag{12}$$

The individual ratios in this form of the expression (equation 10) are sometimes referred to as rates or probabilities. Thus, if P is used to represent each of the two rates, the expression for the estimate of effectiveness is:

$$\widetilde{E}_i = \frac{\widetilde{P}_{WOi} - \widetilde{P}_{Wi}}{\widetilde{P}_{WOi}} \tag{13}$$

or

$$\widetilde{E}_i = 1 - \frac{\widetilde{P}_{Wi}}{\widetilde{P}_{WOi}} \tag{14}$$

where $\widetilde{P}$ is an estimate of a rate, such as crashes per hundred million vehicle miles traveled (100MVMT).

Equations (13) or (14) are called the Type 2 expression for estimating benefits. These expressions use values of the individual terms, numbers of events and level of exposure, or estimates of the ratios of numbers of events to level of exposure.

Examples of recent evaluations that utilize Type 2 formulations are included in Appendix A.

<u>Development of Type 3 expression for estimating benefits</u>

An underlying assumption of the Type 2 expressions is that the rate of relevant scenarios per vehicle mile traveled is invariant between driving without the system and driving with the system. However, many advanced technology systems change the rate of exposure to scenarios. To accommodate this feature of crash avoidance systems, Equation (8) can be rewritten where the measure of exposure, X, is written to include the rate of occurrence of the specific scenario. For example if the measure of exposure is VMT, then

$$X = VMT = \left(\frac{VMT}{S}\right) S \tag{15}$$

where S is the number of scenarios that occur.

Using this terminology, and continuing with VMT as the basic measure of exposure, Equation (10) can be rewritten as:

$$\widetilde{E}_i = 1 - \frac{\widetilde{N}_{Wi} \Big/ \left[\widetilde{S}_{Wi} \left(\dfrac{VMT_{Wi}}{\widetilde{S}_{Wi}} \right) \right]}{\widetilde{N}_{WOi} \Big/ \left[\widetilde{S}_{WOi} \left(\dfrac{VMT_{WOi}}{\widetilde{S}_{WOi}} \right) \right]} \tag{16}$$

This expression can be rearranged as follows:

$$\widetilde{E}_i = 1 - \left[\frac{\left(\dfrac{\widetilde{S}_{Wi}}{VMT_{Wi}} \right)}{\left(\dfrac{\widetilde{S}_{WOi}}{VMT_{WOi}} \right)} \right] \times \left[\frac{\left(\dfrac{\widetilde{N}_{Wi}}{\widetilde{S}_{Wi}} \right)}{\left(\dfrac{\widetilde{N}_{WOi}}{\widetilde{S}_{WOi}} \right)} \right] \tag{17}$$

It can be seen that this expression for the estimate of effectiveness is composed of rates of crashes per scenario and rates of scenarios per unit of exposure (in this example, VMT). The term in the first brackets is the number of occurrences of each scenario per unit of exposure (with and without the system), and the term in the second brackets is the ratio of the rate of crashes per scenario (with and without the system). Thus, a simplified form of Equation (17) is:

$$\widetilde{E}_i = \left(1 - ER_i \times PR_i\right) \tag{18}$$

Where ER is the ratio of number of occurrences of each scenario per unit of exposure. This is also known as the Exposure Ratio. The second ratio describes the effect on preventing crashes when a scenario occurs. It is ratio of the rate of crashes per scenario (with and without the system); and is also known as the Prevention Ratio.[5]

Equation (18) is the Type 3 form of the benefits expression. It is used for systems that affect both the frequency of relevant scenarios and the driver's crash prevention performance when confronted with a relevant scenario.

Examples of recent evaluations that utilize Type 3 formulations are included in Appendix A.

In general, a system will provide improved crash prevention performance for a variety of scenarios. However, the effectiveness of the system will not be the same for each of these scenarios. Thus, estimation of effectiveness must be done for each of the individual scenarios that are affected by the system. The estimated benefits, i.e., number of crashes prevented, are obtained by combining the estimates of effectiveness with the size of the subsets of the problem for each relevant scenario.

CHAPTER IV
An Example of Development of Test Conditions for Lane-Keeping/Road Departure Systems

Once the performance description of the driver assistance system is established in activity 1 of Figure I-1, relevant test conditions that can be used to evaluate the potential safety performance will need to be developed. This example addresses systems that help maintain a vehicle within the lane and/or help prevent road departure crashes. For this example, no specific system is considered and a more generic description of performance is used. This general description includes systems that provide warnings or take automatic actions; systems that encourage drivers to stay within the lane and systems that address departure from the edge of the paved shoulder; as well as systems that address excessive speed and loss of control.

The work in this program area builds on data from crash data files to determine the basic elements of objective tests that will be used to establish the safety-related performance of the each system.
The process consists of the following three steps:

1. Select the subsets of the Universal Description (Table II-1) that are relevant to the safety performance of the system being evaluated.
2. Consolidate the analysis of these subsets into basic test conditions. Test conditions are related to the scenarios defined in Chapter II. Test conditions are descriptions of the dynamic conditions that must be produced during a test of a DAS. These descriptions are generally at the same level of detail as the descriptions of driving condition scenarios. This correspondence between scenarios and test conditions is a key linkage to being able to use the results of the tests as part of the estimation of potential safety benefits.
3. Refine the test conditions, including consideration of distributions of crashes, injuries and fatalities.

Step 1. Select the subsets of the Universal Description that are relevant to the safety performance of the system being evaluated.
The process begins with a detailed analysis of critical events that precede these crashes. From the Universal Description, the following groups of the Critical Event data elements have the potential of producing a lane-keeping/road-departure-related crash. Thus, they form the basis for identifying potential test-conditions for a lane-keeping/road-departure system.
Critical Event (GES Variable V26) data elements, with SAS Code value[1]

- This vehicle loss of control due to:
  - 6; Traveling too fast for conditions
- This vehicle traveling:
  - 10; Over the lane line on left side of travel lane
  - 11; Over the lane line on right side of travel lane
  - 12; off the edge of the road on the left side

13; off the edge of the road on the right side
15; Turning left at intersection
16; Turning right at intersection

- Other motor vehicle in lane:
  50; Other vehicle stopped
  51; Traveling in same direction with lower steady speed
  52; Traveling in same direction while decelerating
  53; Traveling in same direction with higher speed
  54; Traveling in opposite direction
- Other motor vehicle encroaching into lane:
  60; From adjacent lane (same direction) over left lane line
  61; From adjacent lane (same direction) over right lane line
  62; From opposite direction over left lane line
  63; From opposite direction over right lane line
  64; From parking lane
  74; From entrance to limited access highway
- Pedestrian/animal etc:
  80-92; All pedestrian and animal data elements

Similarly, the major First Harmful Events (GES Variable A06)[1] that are likely outcomes of lane or road-departure events are:

- Non-collision:
  1; Rollover/overturn
- Collision with object not fixed:
  25; Motor vehicle in transport
  21, 22, or 24; Pedestrian, cyclist, or animal
  26; Parked motor vehicle
- Collision with fixed object:
  31-59; All fixed objects

Table IV-1 provides the modified Universal Description that corresponds to these features of the first harmful event and critical event.

First Harmful Event / Critical Event	Rollover (1)	Motor Vehicle in Transport (25)	Pedestrian/ Pedalcyclist /Animal/ Object (21, 22, 24)	Parked Vehicle (26)	Collision With Fixed Object (31-59)	Others (2-10, 27, 28, 29 , 99)	Total
Excessive speed (6)	44,000	50,000	0	11,000	272,000	5,000	382,000
Over the lane line on the left side (10)	2,000	349,000	0	23,000	9,000	0	383,000
Over the lane line on the right side (11)	1,000	201,000	1,000	88,000	9,000	1,000	301,000
Off the edge of the road on the left side (12)	11,000	5,000	1,000	9,000	109,000	1,000	136,000
Off the edge of the road on the right side (13)	21,000	5,000	2,000	30,000	203,000	2,000	263,000
Turning left at Intersection (15)	1,000	725,000	2,000	1,000	2,000	0	730,000
Turning right at intersection (16)	0	134,000	2,000	1,000	1,000	0	137,000
Other vehicle stopped (50)	2,000	1,128,000	0	3,000	7,000	1,000	1,141,000
Other vehicle traveling in the same direction with lower steady speed (51)	0	161,000	0	0	3,000	1,000	165,000
Other vehicle traveling in the same direction while decelerating (52)	3,000	587,000	0	1,000	12,000	1,000	604,000
Other vehicle traveling with higher speed (53)	1,000	1,772,000	0	0	2,000	1,000	1,776,000
Traveling in the opposite direction (54)	1,000	35,000	0	0	5,000	0	42,000
From adjacent lane (same direction) over the left lane (60)	1,000	284,000	0	1,000	22,000	1,000	311,000
From adjacent lane (same direction) over the right lane (61)	3,000	294,000	0	1,000	19,000	1,000	318,000
From opposite direction over the left lane line (62)	3,000	552,000	0	2,000	25,000	1,000	583,000
From opposite direction over the right lane line (63)	0	20,000	0	0	0	0	21,000
From parking lane (64)	0	35,000	0	0	2,000	0	38,000
From entrance to limited access highway (74)	0	8,000	0	0	0	1,000	9,000
Pedestrian, pedalcyclist , animal, or object (80-92)	8,000	15,000	396,000	3,000	50,000	63,000	535,000
Others	46,000	2,573,000	7,000	146,000	241,000	60,000	3,072,000
Total	148,000	8,933,000	411,000	320,000	993,000	139,000	**10,945,000**

Table IV-1: Modified Universal Description catering to lane-keeping/road-departure-related events.

This completes Step 1 of the test conditions development process.

Step 2. Consolidate the analysis of these subsets into basic test conditions.

In this step, the characteristics of the events shown in Table IV-1 are assessed to determine common characteristics. One obvious feature of these events is that the critical events lead to both multivehicle crashes and single-vehicle crashes. The predominant features of these two types of crashes are not the same so they are analyzed separately in the next two sections.

Multi Vehicle crashes:

This section addresses critical events that lead to lane-keeping/road-departure-related multivehicle crashes. These are described in Table IV-2. The starting points for the analysis of multivehicle lane-keeping/road-departure-related crashes are the two groups of vehicles that experienced a critical event where there was excursion into another lane or encroachment by another vehicle from an adjacent lane and the first harmful event was collision with another moving vehicle.

The first step in the analysis is to determine the critical events for the pairs of vehicles involved in a multivehicle crash. A multivehicle crash is any crash that involves two or more vehicles. Each vehicle involved in a multivehicle crash interacts with one or more other vehicles during the crash. However the data is not coded in a way that makes it possible to determine these intervehicle combinations. This complicates more detailed analysis. To circumvent this problem, the following analysis uses only two-vehicle crashes. Also, since the objective of the analysis is to provide data for determining possible test conditions, the use of only two-vehicle crashes is justified. This judgment is supported by the fact that in this subset of crashes, more than two vehicles account for only 6 percent of the crashes, as is seen in Table IV-2.

Critical Event	Two-vehicle crashes	Greater than two-vehicle crashes	Total
Excessive Speed	17,000	2,000	19,000
Over the lane line on the left side (10)	143,000	5,000	148,000
Over the lane line on the right side (11)	93,000	3,000	96,000
Off the edge of the road on the left side(12)	2,000	0	2,000
Off the edge of the road on the right side(13)	2,000	0	2,000
Turning left at intersection	207,000	10,000	217,000
Turning right at intersection	23,000	1,000	24,000
From adjacent lane (same direction) over the left lane (60)	117,000	11,000	128,000
From adjacent lane (same direction) over the right lane (61)	119,000	9,000	128,000
From opposite direction over the left lane line (62)	228,000	23,000	251,000
From opposite direction over the right lane line (63)	3,000	1,000	4,000
Total	**956,000**	**64,000**	**1,019,000**

Table IV-2: Distribution of critical events leading to lane-keeping/road-departure-related multivehicle crashes (unimputed).

Note: The number of vehicles in Table IV-2 is based on unimputed values for the respective critical events, rather than the imputed values used in the Universal Description and Table IV-1.

Table IV-3 summarizes all two-vehicle lane departure-related crashes. One idiosyncrasy of the coding of critical events in GES is that the values 60-63 for either vehicle actually describe the situation of the other vehicle. Also, the GES code does not have provision to identify Subject Vehicle (SV), and Principle Other Vehicle (POV) for lane-keeping scenarios. Thus, for cases where one vehicle has a code of either 10 or 11 and the other vehicle has a code of 60-63, the pair of values for the two vehicles describes the situation for only one of them. Thus, Table IV-3 can be broadly classified into three combinations of critical events that describe the lane departure scenarios**:**

- One vehicle is exceeding a safe speed while the other is encroaching across a lane line (one vehicle is coded as 6 and the other is coded as 60-63).
- Both vehicles are encroaching across a lane line (both vehicles are coded as 10-16 OR both vehicles are coded as 60-63).
- One vehicle is encroaching over a lane line and that encroachment is reflected in the critical event for both vehicles (one vehicle is coded as 10-16 and the other is coded as 60-63).

Vehicle 1 \ Vehicle 2		This vehicle					Other vehicle				
		6	**10**	**11**	**15**	**16**	**60**	**61**	**62**	**63**	**Grand Total**
This vehicle	**6**	0	0	0	0	0	6,000	4,000	17,000	0	27,000
	10	0	6,000	5,000	1,000	0	8,000	125,000	57,000	1,000	203,000
	11	0	4,000	1,000	0	0	120,000	4,000	3,000	0	132,000
	12	0	0	0	0	0	2,000	0	2,000	0	4,000
	13	0	0	0	0	0	1,000	1,000	2,000	0	4,000
	15	0	2,000	1,000	4,000	1,000	6,000	26,000	258,000	1,000	299,000
	16	0	0	0	2,000	1,000	23,000	2,000	1,000	2,000	31,000
Other vehicle	**60**	2,000	3,000	44,000	2,000	11,000	2,000	3,000	1,000	0	68,000
	61	1,000	48,000	1,000	17,000	1,000	2,000	2,000	0	0	73,000
	62	3,000	19,000	1,000	88,000	1,000	0	0	1,000	0	113,000
	63	0	1,000	1,000	1,000	0	0	0	0	0	3,000
	Grand Total	6,000	83,000	54,000	115,000	15,000	170,000	167,000	341,000	4,000	**956,000**

Table IV-3: Distribution of critical events for all two-vehicle lane-keeping/road-departure-related crashes (not imputed).

From Table IV-3 it is seen that several combinations should not be included for further analysis. For example, Code 63 describes a vehicle encroaching from the right side but traveling in the opposite direction. This traffic configuration is rare. Another example is the combination of 60 and 10. Code 60 describes vehicle 1 as encroaching into vehicle 2's lane from the left side while traveling in the same direction (i.e., vehicle 1 is moving over its own right lane edge but Code 10 describes vehicle 1 as moving over its own left lane edge). Other combinations that are removed from further analysis that do not include a

relevant lane-crossing are intersection crashes where either vehicles are turning or the vehicles are traveling in opposite directions. These inconsistent combinations are shown with a " * " in Table IV-4.

Table IV-4 summarizes the critical events for each of the two vehicles in these crashes where at least one of the vehicles has a critical event of crossing a lane line or road edge. Each cell in this table represents the basic outline of a test condition. The number of vehicles from the GES in each cell is a measure of the importance of that scenario.

Vehicle 1 \ Vehicle 2		This vehicle					Other vehicle				
		6	**10**	**11**	**15**	**16**	**60**	**61**	**62**	**63**	**Grand Total**
This vehicle	**6**	0	0	0	0	0	6,000	4,000	17,000	0	27,000
	10	0	6,000	5,000	1,000	0	*	125,000	57,000	*	194,000
	11	0	4,000	*	0	0	120,000	*	*	*	124,000
	15	0	2,000	1,000	*	*	6,000	25,000	*	*	34,000
	16	0	0	0	*	*	22,000	2,000	*	*	24,000
Other vehicle	**60**	2,000	*	44,000	2,000	11,000	*	3,000	*	*	62,000
	61	1,000	48,000	*	17,000	1,000	2,000	*	0	*	69,000
	62	3,000	19,000	*	*	*	0	0	1,000	*	23,000
	63	0	0	0	*	0	0	*	*	*	0
	Grand Total	6,000	79,000	50,000	20,000	12,000	156,000	159,000	75,000	0	**557,000**

Table IV-4: Distribution of critical events for all two-vehicle lane-keeping/road-departure-related crashes. Excludes irrelevant and inconsistent data (not imputed).

Legend for Tables IV-4 and IV-5

Critical Event SAS Number	Critical Event data element	
6	Excessive speed	This vehicle…
10	Over the lane line on the left side	This vehicle…
11	Over the lane line on the right side	This vehicle…
12	Off the edge of the road on the left side	This vehicle…
13	Off the edge of the road on the right side	This vehicle…
15	Turning left at intersection	This vehicle…
16	Turning right at intersection	This vehicle…
60	From adjacent lane (same direction) over the left lane	Other Vehicle…
61	From adjacent lane (same direction) over the right lane	Other Vehicle…
62	From opposite direction over the left lane line	Other Vehicle…
63	From opposite direction over the right lane line	Other Vehicle…

From Table IV-4 it is seen that there are eight vehicle configurations that produce multivehicle lane-keeping/road-departure-related crashes. These lane-keeping/road

departure-related critical events that lead to two-vehicle crashes are summarized (in rank order) in Table IV-5.

Critical events that lead to two-vehicle crashes	Number of crash vehicles	Percentage
This vehicle over the lane line on the left side (10)	273,000	25%
Other vehicle encroaching from adjacent lane (same direction) over the right lane (61)	228,000	20%
Other vehicle encroaching from adjacent lane (same direction) over the left lane (60)	218,000	20%
This vehicle over the lane line on the right side (11)	174,000	16%
Other vehicle encroaching from opposite direction over the left lane line (62)	98,000	9%
This vehicle turning left at intersection (15)	54,000	5%
This vehicle turning right at intersection (16)	36,000	3%
This vehicle, excessive speed (6)	33,000	3%
Total	**1,114,000**	100%

Table IV-5: Distribution of all vehicles involved in two-vehicle lane-keeping/road-departure-related crashes placed in their descending rank order (Not imputed)

Table IV-6 organizes these events by actions that were taken by the offending vehicles.

Critical event scenarios	Encroaching vehicle	Vehicle going straight	Total
Over the lane line on the left side (same direction)			
Excessive speed	5,000	5,000	10,000
No excessive speed	221,000	221,000	442,000
Other vehicle over the lane line	13,000	-	13,000
Over the lane line on the right side (same direction)			
Excessive speed	7,000	7,000	14,000
No excessive speed	207,000	207,000	414,000
Other vehicle over the lane line	13,000	-	13,000
Over the lane line on the left side (opposite direction)			
Excessive speed	20,000	20,000	40,000
No excessive speed	77,000	77,000	154,000
Other vehicle over the lane line	14,000	-	14,000
Total	**577,000**	**537,000**	**1,114,000**

Table IV-6: Summary table of combination of critical events involving encroaching vehicles for lane-keeping/road-departure-related crashes (not imputed).

In summary, the lane-keeping/road-departure-related scenarios that lead to two-vehicle crashes are:

1. Crossing to the left into adjacent lane in conflict with other vehicles traveling in the same direction
    a. Without excessive speed;
    b. With excessive speed;
    c. Coincident with encroachment by the other vehicle.
2. Crossing to the right into adjacent lane in conflict with other vehicles traveling in the same direction
    a. Without excessive speed;
    b. With excessive speed;
    c. Coincident with encroachment by the other vehicle.
3. Crossing to the left into adjacent lane in conflict with other vehicles traveling in the opposite direction
    a. Without excessive speed;
    b. With excessive speed;
    c. Coincident with encroachment by the other vehicle.

Single-vehicle crashes:
This section addresses critical events that lead to single-vehicle crashes. The detailed list of relevant Critical Events and First Harmful Events are presented in Table IV-1. All events that don't lead to multivehicle crashes are candidates for consideration in determining test conditions for single-vehicle crashes.

For the purposes of this section for determining meaningful test conditions, not all of these combinations of events will be considered. Most of the events that lead to *Collisions With Non-Fixed Objects* are not a relevant group. For example: Non-fixed objects such as *Motor Vehicle in Transport*, *Pedestrians* (often in the lane of travel), *Railway Trains* and *Animals* (also often in the travel lane) are not relevant. However, *Collision With a Parked Motor Vehicle* is a relevant combination. For this reason, this subgroup has been included for further analysis.

A summary of the relevant single-vehicle combinations of Critical Event and First Harmful Event is presented in Table IV-7.

First Harmful Event (A06) / **Critical Event (V26)**	**Rollover**	**Parked vehicle**	**Collision with fixed object**	**Grand total**
This vehicle, excessive speed (6)	44,000	11,000	267,000	322,000
This vehicle over the lane line on the left side (10)	2,000	23,000	8,000	33,000
This vehicle over the lane line on the right side (11)	1,000	87,000	8,000	96,000
This vehicle off the edge of the road on the left side (12)	11,000	9,000	106,000	126,000
This vehicle off the edge of the road on the right side)13)	20,000	30,000	201,000	251,000
Other vehicle stopped in lane (50)	1,000	3,000	6,000	10,000
Other vehicle traveling in lane in the same direction with lower steady speed (51)	*	*	2,000	2,000
Other vehicle traveling in lane in the same direction while decelerating (52)	2,000	*	10,000	12,000
Other vehicle traveling in lane in the opposite direction (54)	1,000	*	4,000	5,000
Other vehicle encroaching from adjacent lane (same direction) over the left lane (60)	1,000	1,000	15,000	17,000
Other vehicle encroaching from adjacent lane (same direction) over the right lane (61)	3,000	*	16,000	19,000
Other vehicle encroaching from opposite direction over the left lane (63)	2,000	2,000	22,000	26,000
Pedestrian/pedalcyclist/animal/object (80-92)	8,000	3,000	47,000	58,000
Grand total	96,000	169,000	712,000	**977,000**

Table IV-7: Distribution of Critical Events that lead to single-vehicle lane-keeping/road-departure-related crashes subdivided by their First Harmful Events (not imputed).

* Cells containing no data

Some observations from this table are:

- The Critical Events are of two general types: those where the lane departures are a consequence of driver action (code values 6 and 10-13); and those where the occurrence of the Critical Event is outside of the driver's control like pedestrians, animals, or objects (code values 60-63 and 80-92).
- Driver assistance systems will need to address the underlying action by the driver in the first type; and will need to assist the driver in crash avoidance action in the second type.
- The scenarios that have excessive speed as the Critical Event and result in a crash with an object outside of the lane of travel, or rollover, must also include a lane or road departure, and therefore need to be included in the development of tests.
- Off the edge of the road (defined in the "GES coding manual" as being beyond the shoulder area) is a significant Critical Event for single-vehicle crashes. However, this is not a significant event for scenarios that produce multivehicle crashes.

This leads to the following six primary test conditions that represent events that lead to single-vehicle lane-keeping/road departure-related crashes.

Inappropriate action by the driver:

- Excessive speed
- Traveling over the lane line
- Traveling off the edge of the road

Outside influence on driving conditions

- Another vehicle in the same lane
- Encroachment by another driver
- Encroachment by pedestrian, animal, etc.

These crash types (with percentage of total single-vehicle crashes) are shown in Table IV-8.

Single-vehicle crash basic test conditions	Total	Percentage
Traveling off the edge of the road (12,13)	377,000	39%
Excessive speed (6)	322,000	33%
Traveling over the lane line (10,11)	129,000	13%
Encroachment by another driver (60,61,63)	62,000	6%
Encroachment by pedestrian, animal, etc. (80-92)	58,000	6%
Another vehicle in the same lane (50,51,53,54)	29,000	3%
Grand total	**977,000**	**100%**

Table IV-8: Distribution of Critical Events that lead to a single-vehicle lane-keeping/road-departure-related crash shown in the descending order of significance (unimputed).

This concludes Step 2. The analysis during this step for the lane-keeping/road-departure system has identified 15 test conditions that are candidates for inclusion in the test program. These 15 conditions are also the scenarios that form the foundation for

estimation of benefits (see Chapter III). These are also the conditions that will be analyzed using naturalistic driving data as a means of establishing the baseline exposure rates for estimating benefits.

Step 3. Refine test conditions using GES.

In this step several measures are used as the basis for developing more detailed description of test conditions. These measures include the type of roadway, the driver's crash avoidance maneuver, curvature of the road, and the distribution of traveling speed. The basic set of categories that was developed in Step 2 is the starting point for this step. As in Step 2, multivehicle crashes are treated separately from single-vehicle crashes. The details of the analysis of GES data are presented in Appendix B and C.

Multivehicle crashes:

In Step 2, it was determined that there are nine basic pre-crash conditions that need to be considered. The list of these, with the number of encroaching vehicles and the number of non-encroaching vehicles (using unimputed numbers from GES) is shown in the following Table IV-9.

Critical event scenarios	Encroaching vehicle	Vehicle going straight	Total
Over the lane line on the left side (same direction)			
Excessive speed	5,000	5,000	10,000
No excessive speed	221,000	221,000	442,000
Other vehicle over the lane line	13,000	-	13,000
Over the lane line on the right side (same direction)			
Excessive speed	7,000	7,000	14,000
No excessive speed	207,000	207,000	414,000
Other vehicle over the lane line	13,000	-	13,000
Over the lane line on the left side (opposite direction)			
Excessive speed	20,000	20,000	40,000
No excessive speed	77,000	77,000	154,000
Other vehicle over the lane line	14,000	-	14,000
Total	**577,000**	**537,000**	**1,114,000**

Table IV-9: Summary table of combination of critical events involving encroaching vehicles for lane-keeping/road-departure-related crashes.

From this table it is seen that the majority of crashes are the result of a vehicle encroaching into the travel lane of the other vehicle. About 5 percent of the crashes involve both vehicles encroaching into a common travel lane. Based on this small percentage, scenarios with encroachment by both vehicles will not be included in the test conditions.

- Travel Speed

The details of traveling speed are provided in Tables B1-B8 in Appendix B. These details are summarized in Figure IV-1 (two-vehicle, speed distribution). There is insufficient data to obtain a meaningful distribution of speed for the conditions where one vehicle is encroaching and is traveling at excessive speed. The distributions of travel speed for the

other four conditions are shown in this figure. It can also be seen in Tables B1-B8, the distribution of travel speed is essentially the same for both vehicles. However, other research[6 7] has shown that overtaking vehicles in the adjacent lane are a common element of lane change crashes. Based on this data and the need to address situations that produce significant injury, the 80-percentile speed is used as the basis for the two-vehicle test conditions. This is approximately 40 mph for all four scenarios. Note that in the opposite direction, this means that both vehicles are traveling at 40 mph and the speed of the confederate in the same direction tests should be higher than the subject vehicle. Thus, the speed of the confederate in the same direction tests should be higher than the subject vehicle.

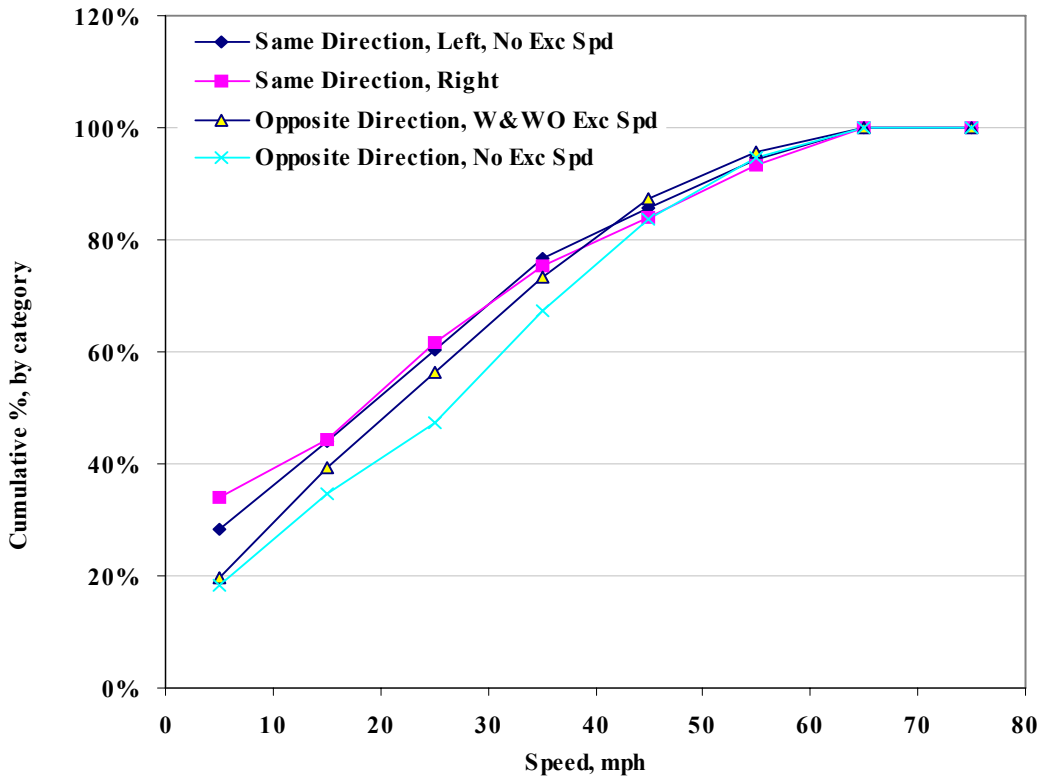


Figure IV-1: Speed distribution for two-vehicle lane-keeping/road departure-related crashes

- Trafficway

The distributions of trafficway for the two-vehicle crashes are shown in Tables B9-B16 of Appendix B. From this data it is seen that scenarios where both vehicles are traveling in the same direction are evenly divided between undivided trafficways and multilane divided trafficways. However, the scenarios where the vehicles are traveling in opposite directions occur predominantly (greater than 80%) on two-lane undivided trafficways. Thus, the conclusion is that the test conditions should reflect two-lane undivided trafficways for the test in opposite directions and should reflect both undivided and divided trafficways in the tests traveling in the same direction. However the lane configurations for multilane undivided and divided are similar so there can be a single test for vehicles traveling in the same direction.

- Corrective Action

There is limited data in GES on the corrective action taken by each of the drivers. However, based on this data, it appears that more drivers take corrective action when the vehicles are traveling in opposite directions than when they are traveling in the same direction. These results are summarized in Table IV-10. Based on these results, the test conditions need to accommodate systems that address the situations where neither driver takes corrective action.

Same Direction	*Non-Encroaching Vehicle*			
		No Maneuver	Brake	Steer
Encroaching Vehicle	No Maneuver	85%	3%	6%
	Brake	2%	0%	0%
	Steer	3%	0%	2%

Opposite Direction	*Non-Encroaching Vehicle*			
		No Maneuver	Brake	Steer
Encroaching Vehicle	No Maneuver	58%	0%	17%
	Brake	8%	0%	0%
	Steer	8%	0%	8%

Table IV-10: Known avoidance maneuvers in two-vehicle crashes for vehicles traveling the same direction and opposite direction

- Road Curvature

The distribution of road curvature is interesting for these crashes. For the crashes where both vehicles were traveling in the same direction, the likelihood of the crash being on a curve is only 7 percent. However, for crashes where the vehicles were traveling in opposite directions, the likelihood of the crash being on a curve is 44 percent. Details for this analysis are contained in Tables B1-B8 in Appendix B. Based on these results, the test conditions for vehicles traveling in the same direction need only address straight roads; however, the test conditions for vehicles traveling in opposite directions need to address straight and curvy roads.

Summary of multivehicle crash test conditions based on GES data

Based on the detailed analysis above, it is concluded that two basic conditions will be tested:

(1) The host vehicle and a confederate vehicle traveling in the same direction, and

(2) The host vehicle and a confederate vehicle traveling in opposite directions.

Same direction:

Both vehicles traveling at 40 mph on a straight road that emulate either

- A divided multilane roadway, or
- A multilane undivided roadway.

In addition to this basic configuration of the two vehicles, it is necessary to establish the relative position and speed of the two vehicles. Other research[6] has shown that the vehicle that is not changing lanes, the confederate vehicle, is often overtaking the subject vehicle at a higher speed. For this reason it is recommended that the confederate vehicle should be traveling at a speed of 45 mph. A distance that corresponds to a time-to-collision of 3 seconds has been selected as the point at which the lane change begins. This provides an opportunity for warning, or automatic control, systems to effectively intervene. The analysis provided in Appendix D of this paper supports the additional criteria that the encroaching vehicle should cross the lane line at an angle of 3 degrees.

Opposite direction:

Both vehicles traveling at 40 mph on a two-lane undivided roadway. Two test conditions should be used:

- On a straight road segment, and
- On a curve of appropriate radius.

In addition to this basic configuration of the two vehicles, it is necessary to establish the relative position and speed of the two vehicles. The relative distance between the two vehicles is based on time-to-collision. A distance that corresponds to a 3-second time-to-collision is recommended. This provides an opportunity for warning, or automatic control, systems to effectively intervene. If both vehicles are traveling at 40 mph, this distance is 350 feet. The analysis provided in the appendix to this paper supports the additional criteria that the encroaching vehicle should cross the lane line at an angle of 3 degrees. The radius-of-curvature for the second condition has not been established. The crash data files, such as GES and the Crashworthiness Data System do not include details on radius-of-curvature. Thus, it will be necessary to do additional analysis of naturalistic driving data, similar to the analysis in Appendix D, or other sources to determine this value.

The tests in both conditions should accommodate systems that assist drivers who would otherwise take no evasive action.

Single-vehicle crashes:

In Step 2, it was determined that there are six basic test conditions that need to be considered. The list of these values from Table IV-8 is repeated below in Table IV-11.

No	Single-vehicle crash basic test conditions	Total	Percentage
1	Excessive speed	322,000	33%
2	Traveling over the lane line	129,000	13%
3	Traveling off the edge of the road	377,000	39%
4	Another vehicle in the same lane	29,000	3%
5	Encroachment by another driver	62,000	6%
6	Encroachment by pedestrian, animal, etc.	58,000	6%
7	Grand total	**977,000**	**100%**

Table IV-11: Distribution of critical events that lead to a single-vehicle lane-keeping/ road-departure-related crash shown in the descending order of significance (not imputed).

- Travel speed

The details of traveling speed are provided in Tables C2 to C7 in Appendix C. These details are summarized in Figure IV-1.

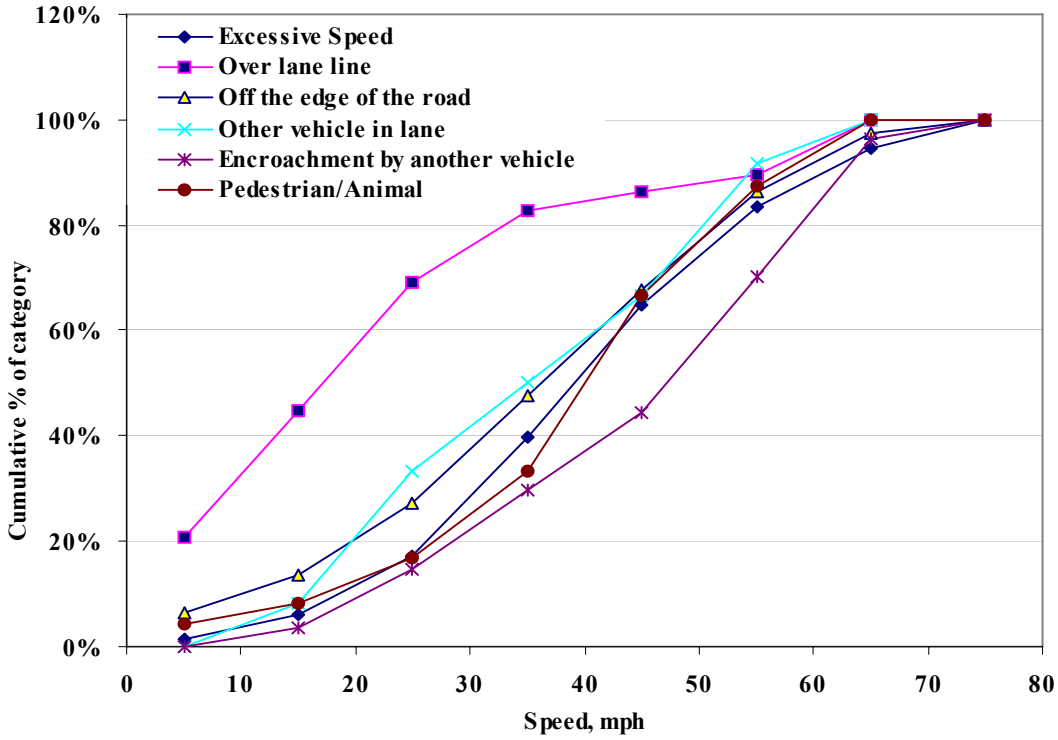


Figure IV-2: Summary of travel speeds for single-vehicle crashes for various critical events

From this figure, it is seen that the speed distribution for "Over the lane line" events that lead to crashes occur at lower speeds than do the other types of single-vehicle scenarios; and in contrast, the events that begin with "Encroachment by another vehicle" occur at higher speeds. Based on this data, and the need to address scenarios that produce significant injury, the 80-percent speed is used as the basis for the single-vehicle test

conditions. This is approximately 30 mph for "Over the lane line" scenarios, 60 mph for "Encroachment by another vehicle," and 50 mph for the other four types of event.

- Trafficway

The distributions of trafficway for the single-vehicle crashes are also shown in Tables C2-C7 of Appendix C. From this data, it is seen that the single most common type of trafficway (ranging from 40% for encroachment type events to 73% for pedestrian/animal events) for these events are two-lane undivided highways (one lane in each direction). The second most common type of trafficway are two-lane divided highways (two lanes in each direction). For those events that are initiated by encroachment, about 25 percent occur on divided highways with more than two lanes in each direction. Based on this data, the conclusion is that the test conditions should reflect two-lane undivided trafficways for all six categories of event as well as multilane divided trafficways for encroachment events.

- Corrective Action

From Table IV-12 below, it's seen that, for events where this variable is known, 48 percent of the drivers steered and 11 percent braked, but 36 percent did not attempt an avoidance maneuver.

Avoidance Maneuver Critical Event	No Maneuver	Brake	Steer	Brake and Steer	Total
Traveling off the edge of the road (12,13)	63,000	11,000	41,000	3,000	118,000
Excessive speed (6)	48,000	16,000	14,000	2,000	80,000
Encroach by another driver(60-64)	0	3,000	51,000	4,000	58,000
Encroach by pedestrian, Animal (80-92)	2,000	2,000	42,000	2,000	48,000
Traveling over the lane line 10,11)	16,000	2,000	9,000	0	27,000
Another vehicle in the same lane(50-54)	1,000	5,000	16,000	5,000	27,000
Grand total	130,000	39,000	173,000	16,000	**358,000**
Percentage	36%	11%	48%	5%	**100%**

Table IV-12: Distribution of avoidance maneuvers in single-vehicle lane-keeping/ road-departure-related events

Based on this data, the test conditions need to accommodate situations where the driver attempts no maneuver as well as those where the driver either steers or brakes.

- Road Curvature

The percentage of events that occur on curves for each category is shown in Table IV-13 below.

No	Category	% on curve
1	Excessive speed	50%
2	Over the lane line	14%
3	Off the edge of the road	35%
4	Other vehicle traveling in the same lane either stopped/slower /steady speed	17%
5	Over the lane line from adjacent lane traveling the same/opposite direction	27%
6	Pedestrian /pedalcyclist/animal/object	27%

Table IV-13: Percentage distribution of crashes for each critical event on curves

From this table, it is seen that events that involve lane line crossings and encroachment by other vehicles occurs on straight roads. The other four categories of events frequently (between 27% and 50%) occur on curves. Based on these results, the test conditions for single-vehicle events should include both straight and curves; except for lane line crossings and encroachment by other vehicles that would be tested only on straight road segments.

Two additional considerations are the types of crash that result from these single-vehicle events and the level of injury that results from these crashes.

- Types of crash

The distributions of First Harmful Events for each of the six broad categories of single-vehicle lane-keeping/road-departure–related events are shown in Figure IV-3 below.

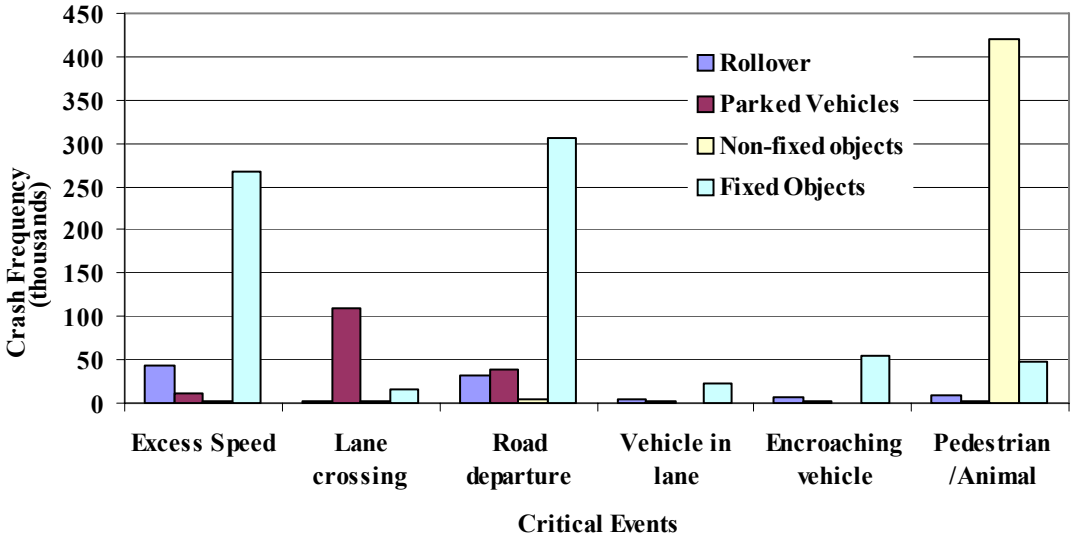


Figure IV-3: Distribution of First Harmful Event for single-vehicle lane-keeping/road-departure-related events

Several helpful observations can be made from this table:

First: Consider the events that result from a pedestrian or animal (Category 6). This category was included in this analysis because of the potential for the avoidance maneuvers in these events leading to off-road crashes. This figure shows that although there are a few of this type crash, the vast majority of the First Harmful Events are a collision with the pedestrian or animal. These collisions may occur either on or off the road. Thus, this type of event is not a good choice for evaluating the performance of lane-keeping/road-departure systems. For this reason, it will be dropped from further consideration.

Second: Categories 4 and 5 (actions by other vehicles) contribute only a small fraction to the total problem. For this reason, they will also be dropped from further consideration.

Third: The remaining three categories produce three main types of harmful event; impacts with fixed objects (trees, poles, bridges, etc.), rollovers, and parked vehicles.

The conclusions from this part of the analysis are that the test conditions should reflect the first three categories of critical event (excessive speed, lane line crossing and road departure) and should be based on environments that may lead to rollovers, crashes with fixed objects, and crashes with parked vehicles.

Summary of single-vehicle test conditions:
Based on this analysis, two tests are needed:

- A test that combines the attributes of excessive speed and road departure. This test will be on a roadway that reflects a two-lane undivided roadway (this probably means a narrow shoulder). The vehicle should be traveling at 50 mph and the event should occur on a curve of appropriate radius.
- A test on a roadway with sufficient shoulder width to accommodate a parked vehicle. The vehicle should be traveling at 30 mph on a straight section of road with a vehicle parked on the shoulder.

The radius-of-curvature for the first condition has not been established. The crash data files, such as GES and the Crashworthiness Data System, do not include details on radius-of-curvature. Thus, it will be necessary to do additional analysis of naturalistic driving data, similar to the analysis in the Appendix D to this paper, or other sources to determine this value. As noted in the discussion of two-vehicle test conditions, it is necessary to establish the relative position of the two vehicles for the second condition. A distance that corresponds to a 3-second time-to-collision is recommended. This provides an opportunity for warning, or automatic control, systems to effectively intervene. If the subject vehicle is traveling at 30 mph, this distance is 132 feet. The analysis provided in Appendix D supports the additional criteria that the subject vehicle should cross the lane line at an angle of 3 degrees for both test conditions.

The tests should accommodate systems that assist drivers who would otherwise take no evasive action, as well as drivers that steer or brake.

Step 4. Refine test conditions using FARS.[8]
In the preceding two sections, data from the GES has been used to establish the basic test conditions for lane-keeping/road-departure systems and to refine the test conditions for those systems. The analysis in Step 2 leads to *nine basic two-vehicle test conditions* and *six single-vehicle test conditions*. The more detailed analysis in Step 3 leads to the following five tests that should be run to assess the safety performance of these systems.

Multivehicle crash test conditions
Same direction:

- Both vehicles traveling at 40 mph on a straight road that emulate either
- A divided multilane roadway, or
- A multilane undivided roadway.

Opposite direction:

- Both vehicles traveling at 40 mph on a two-lane undivided roadway. Two test conditions should be used:
  - On a straight road segment, and
  - On a curve of appropriate radius.

Single-vehicle crash test conditions:

- A test that combines the attributes of excessive speed and road departure. This test will be on a roadway that reflects a two-lane undivided roadway (this probably means a narrow shoulder). The vehicle should be traveling at 50 mph and the event should occur on a curve of appropriate radius. However, the crash data files, such as GES, FARS, and the Crashworthiness Data System, do not include details on radius-of-curvature. Thus, it will be necessary to do additional analysis of naturalistic driving data, similar to the analysis in the Appendix D, or other sources to determine this value.

- A test on a roadway with sufficient shoulder width to accommodate a parked vehicle. The vehicle should be traveling at 30 mph on a straight section of road with a vehicle parked on the shoulder

In this section, data from FARS is used to refine these test conditions to reflect crashes that produce serious injury and death. The process used in this section is somewhat different than the process used in the preceding section. This difference is necessitated by the absence of a Critical Event variable (similar to V26 in GES) in FARS. The process used in this section begins with the detailed events that are identified from GES and then uses available FARS[8] variables to determine speed, type of highway, and driver's crash avoidance maneuvers for the same conditions that were identified in the preceding section.

The data is divided into scenarios that produce multivehicle crashes and scenarios that produce single-vehicle-crashes. The multivehicle scenarios are divided between situations where both vehicles are traveling in the same direction and scenarios where they are traveling in opposite directions. The single-vehicle scenarios are separated into those that produce rollovers, those that produce collisions with fixed objects and scenarios that produce collisions with parked vehicles. Three aspects of each of these types of scenario are analyzed in this section using FARS data: the speed distribution, the type of roadway, and the occurrence of a crash avoidance maneuver by the driver. The results of the analysis are then compared with the results from the analysis of GES data as described in Step 3.

The FARS variables used to analyze single and multivehicle crashes are:

- Number of Vehicles (A4),
- Manner of Collision (A18),
- First Harmful Event (A17),
- Relation to Roadway (A20),
- Roadway Alignment (A24),
- Travel Speed (V15), and
- Crash Avoidance Maneuver (V17).

For two-vehicle crashes, codes A4=2 and A18=3, 6, 7 are used to define two vehicles with crashes in the same direction and codes A4=2 and A18=2, 4, 8 used to define two vehicles with crashes in the opposite direction. For single-vehicle crashes, codes A4=1 and A17=1;14;17, 50, 52, 46, 48, 53, 19 - 43 are used to define single-vehicle off-road crashes with harmful events of a rollover, collision with a parked vehicle, and a collision with a fixed object, respectively. Also, single-vehicle crashes involving parked vehicles are sometimes coded as a two-vehicle crash due to inclusion of the stationary vehicle. Hence, these specific scenarios are defined by codes A4=2 and A17=14 and are included in the single-vehicle crash analysis.

Two-vehicle crashes

The analysis of multivehicle scenarios begins with the separation of vehicles traveling in the same direction and vehicles traveling in the opposite direction. This separation forms the basis for all further analysis of two-vehicle crashes. Table IV-14 shows the various collision types for two-vehicle crashes based on the direction of travel. It can be seen that 89 percent of the vehicles were traveling in the opposite direction while only 11 percent of these vehicles were traveling in the same direction.

Manner of Collision	Total	
Front to-front(head-on)	7,222	Opposite Direction
Angle-opposite direction	4,968	
Sideswipe-opposite direction	486	
Angle-same direction	790	Same Direction
Angle-unknown direction	110	
Sideswipe-same direction	622	
Grand total	14,198	

Table IV-14: Distribution of two-vehicle crashes for their accident type based on the direction of travel

The vehicles are analyzed for their speed distributions, type of roadway, and their crash avoidance maneuvers and compared with the GES data as seen below:

- **Travel Speed**

The distributions of speeds for lane-keeping/road departure crashes in FARS are shown below in Table IV-15 and Figure IV-4 for vehicles traveling in the same direction (1,522 vehicles) and vehicles traveling in opposite directions (12,676 vehicles).

Speed	Opposite direction	Same direction	Total
0-10	513	90	603
10-20	359	52	411
20-30	335	32	367
30-40	809	61	870
40-50	1,354	83	1,437
50-60	1,611	167	1,778
60-70	643	151	794
70-80	142	45	187
80-90	40	17	57
90 and higher	43	11	54
Others/unknown	6,827	813	7,640
Total	**12,676**	**1,522**	**14,198**

Table IV-15: Speed Distribution for two-vehicle-lane-keeping/road departure-related crashes where the vehicles were traveling in the same and opposite direction.

A comparison of Figure IV-4 with Figure IV-1 shows that the traveling speeds for the crashes in FARS are greater than the travel speeds for crashes in GES. The conclusion from this is that the test speeds for two-vehicle crashes should be approximately 55 mph for opposite direction scenarios and 65 mph for same direction. These conditions would ensure adequate performance for 80 percent of the victims of fatal crashes.

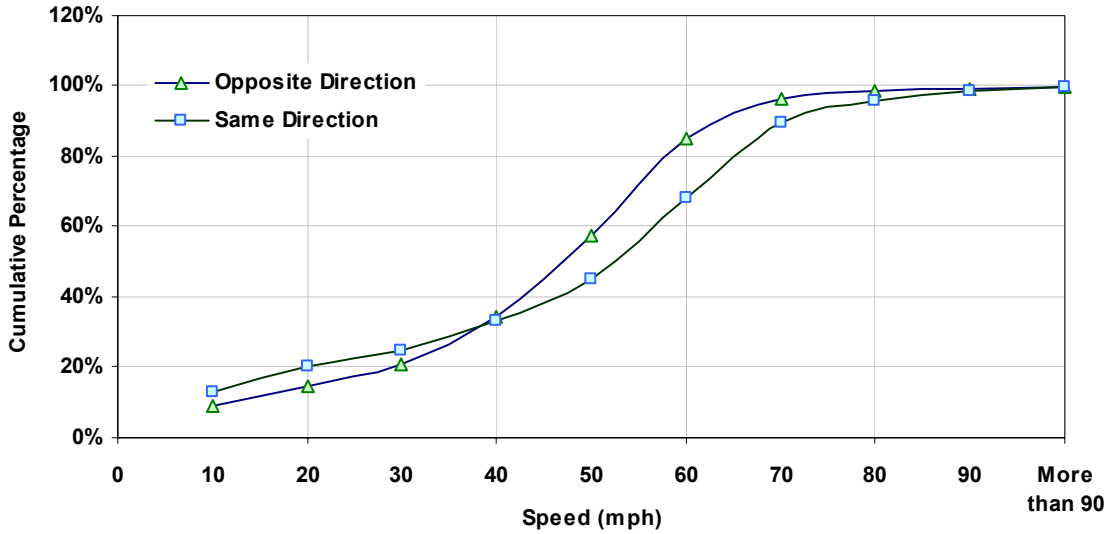


Figure IV-4; Cumulative distribution of speeds for crashes involving two vehicles traveling in the same and opposite directions.

- **Trafficway and curvature**

The distribution of trafficway and alignment along with the trafficway flow are shown in Table IV-16 below. For all lane-keeping road/departure crashes involving two vehicles, 72 percent of the crashes were on two-way highways that were not physically divided, 2

percent were on a undivided highway with a two-way continuous left turn lane, 20 percent were on a divided highway without a traffic barrier and 5 percent were on a divided highway with a traffic barrier. Also, 51 percent of those crashes were head on crashes and 38 percent were sideswipe/angled crashes.

Two-vehicle crashes involving vehicles traveling in the opposite directions (head-on, side-swipe) accounted for 89 percent of the crashes whereas vehicles traveling in the same direction account for 11 percent of the crashes. Among the vehicles traveling in the *opposite direction* (12,676), 75 percent (9,530) of the vehicles were going straight and 25 percent were on a curve. For vehicles going straight, 72 percent (6,842) of them were on undivided highways and 22 percent of them were on divided highways. For vehicles on curves, 89 percent were on undivided highways and 1 percent of them occur on divided highways.

For vehicles traveling in the *same direction* (1,522), 86 percent (1,314) were going straight and 14 percent (208) on curves. For vehicles going straight, 40 percent (528) of them were on undivided highways and 57 percent (744) of them were on divided highways. For vehicles on curves, 45 percent (94) were on undivided highways and 50 percent of them were on divided highways.

	Opposite direction				**Same Direction**			
Alignment / **Traffic Flow**	**Straight**	**Curve**	**Unknown**	**Total**	**Straight**	**Curve**	**Total**	**Grand Total**
Not Physically Divided	6,842	2,698	68	**9,608**	528	94	**622**	**10,230**
Divided Highway (without traffic barrier)	2,066	254	20	**2,340**	458	60	**518**	**2,858**
Divided Highway (with traffic barrier)	310	54	0	**364**	286	44	**330**	**694**
One way traffic	38	6	0	**44**	6		**6**	**50**
Not physically divided (with two-way continuous left turn lane)	222	28	4	**254**	22	2	**24**	**278**
Entrance/Exit Ramp	30	6	0	**36**	12	8	**20**	**56**
Unknown	22		8	**30**	2		**2**	**32**
Grand Total	9,530	3,046	100	**12,676**	1,314	208	**1,522**	**14,198**

Table IV-16: Distribution of trafficway flow, roadway alignment for vehicles involved in two-vehicle-lane-keeping/road departure-related crashes traveling in the same and opposite directions.

Comparison of Table IV-16 and the tables in Appendix B highlights the difference and similarities between results from GES and results from FARS. One difference is the distribution between same-direction and opposite-direction crashes. The majority of the fatal crashes occur when vehicles travel opposite to each other. However, the GES data shows that the majority of the lane-keeping/road-departure-related crashes involved vehicles traveling in the same direction. This is suggestive of the fact that the direction of the travel determines the severity of injury in these lane-keeping/road-departure-related crashes. This difference supports the need for tests that address both scenarios. The

distribution of type of roadway and presence of curves is similar between the GES results and the FARS results for both same-direction and opposite-direction crashes. Thus the conclusions in this regard from GES also apply to tests based on FARS.

- **Avoidance maneuver**

Table IV-17 shows the distribution of crash avoidance maneuvers for vehicles involved in two-vehicle fatal crashes traveling in same and opposite directions. For all two-vehicle lane-keeping/road departure-related crashes, 32 percent of the drivers with known responses had some sort of an avoidance maneuver and 68 percent of the drivers did not attempt any maneuver at all. Among the known maneuvers, 22 percent of them steered and 10 percent braked. These percentages are similar to the percentages found in GES.

Direction of Travel / Avoidance Maneuver	Opposite Direction	Same Direction	Total
No maneuver	5,393	727	6,120
Braking	840	83	923
Steering	1,805	187	1,992
Others/unknown	4,638	525	5,163
Total	**12,676**	**1,522**	**14,198**

Table IV-17: Distribution of crash avoidance maneuvers and direction of travel for vehicles involved in two-vehicle-lane-keeping/road-departure-related crashes.

From the above data, the tests need to account for vehicles that not only steered and maneuvered but also vehicles that do not take any action. These results are similar to the conclusions arrived at with the GES data.

Single-vehicle crashes:

The analysis of single-vehicle fatal crashes begins with the conclusions that are summarized in Figure IV-3. Based on this summary, and the lack of a Critical Event variable in FARS necessitates the use of First Harmful Events, specifically, *Rollover*, *Collision With Parked Vehicle* and *Collision With a Fixed Object*, as the basis for the analysis of single-vehicle crashes. It can be seen from Table IV-18 below that 3 percent of the vehicles are involved in crashes with parked vehicles, 24 percent involve rollovers, and 73 percent of them are involved in collisions with fixed objects.

First Harmful Event	Number of crashes	Percent
Parked vehicle	467	3
Rollover	3,841	24
Collision with a fixed object	11,599	73
Total	**15,907**	**100**

Table IV-18: Distribution of vehicles in crashes involving a parked vehicle, rollover, or collision with a fixed object.

This separation forms the basis for all further analysis of single-vehicle crashes. Speed distributions, types of roadways, and crash avoidance maneuvers are analyzed. The results of the analysis are compared with the GES data and conclusions are drawn based on the comparison as shown below.

- **Travel speed**

As seen earlier, the analysis is divided into three basic sets;

- Crashes with rollovers (3841; A4=1 and A17 =1);
- Collision with a parked vehicle (467; A4=1, 2 and A17=14); and
- Collision with a fixed object (11,599; A4= 1 and A17=17, 50, 52, 46, 48, 53, 19 - 43).

The distribution of speeds for the three categories is shown in Table IV-19 below.

Speed	Parked Vehicle	Rollover	Fixed Object	Total
0-10	10	9	15	34
10-20	0	14	24	38
20-30	13	30	122	165
30-40	17	58	343	418
40-50	15	161	735	911
50-60	33	328	1,303	1,664
60-70	42	515	1,110	1,667
70-80	19	337	631	987
80-90	7	110	294	411
90 and higher	7	66	270	343
Others/unknown	304	2,213	6,752	9,269
Grand total	**467**	**3,841**	**11,599**	**15,907**

Table IV-19; Distribution of speeds for vehicles involved in Parked Vehicle, Rollover, or Fixed Object crashes.

Figure IV-5 below shows the cumulative distribution of speeds for single-vehicle lane-keeping/road departure-related crashes. It can be seen that the majority of the crashes occur greater than 55-75 mph. The 80th percentile speed for all these types of crashes falls between 70 and 75 mph.

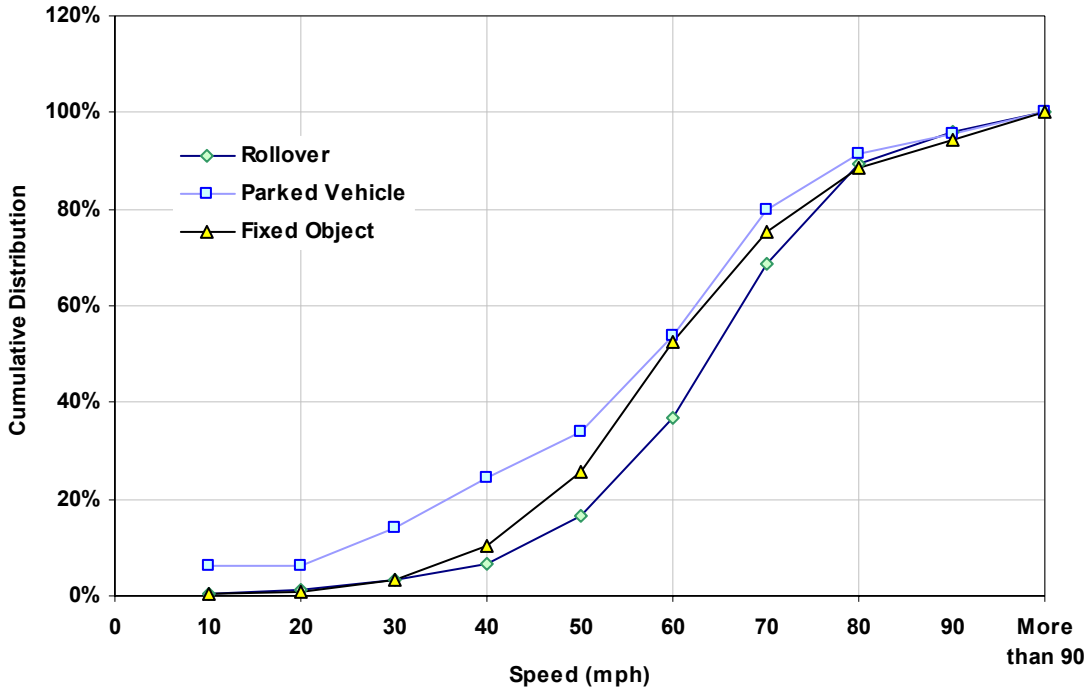


Figure IV-5: Cumulative distribution of speeds for crashes involving single vehicles involved in Rollover, Parked Vehicle, and Fixed Object crashes.

A comparison of Figure IV-5 above and Figure IV-2 for GES shows that the speeds for crashes in FARS are substantially higher than speeds for crashes in GES. This comparison shows that off-road tests should be run at 75 mph and parked vehicle tests should be run at 70 mph. This condition would ensure adequate performance for 80 percent of the victims for fatal crashes.

- **Traffic flow and curvature**

The distribution of traffic flow and road alignment for crashes involving single vehicles is shown in Table IV-20. For all single-vehicle fatal crashes, 68 percent of the crashes involve vehicles on trafficways that are not physically divided, 19 percent on divided trafficways with a traffic barrier, 9 percent on divided trafficways without a traffic barrier and 4 percent on other types of trafficways (one-way, Entrance/exit ramp, etc.).

For vehicles in R*ollovers* (3,841), 61 percent (2,299) were on straight roads and 39 percent (1,497) were on curved roads. For vehicles on a curve (1,497), 75 percent (1,117) of the crashes were on undivided roadways. For vehicles on straight roads (2,299), 50 percent (1,161) of them were on undivided highways and 48 percent (1,096) of them on divided highways.

For vehicles in *Parked Vehicle crashes* (467), 84 percent (391) of them were on straight roads and 16 percent (74) of them were on curved roads. For vehicles on curved roads (74), 57 percent (42) of the crashes were on undivided highways and 38 percent (28) on divided highways. For vehicles on straight roads (391), 47 percent (185) of them were on undivided highways and 47 percent (183) of them are on divided highways.

For vehicles involved in *Fixed Object crashes* (11,599), 57 percent (6,594) of them were on straight roads, and 42 percent (4,912) of them were on curved roads. Of the vehicles on straight roads (6,594), 67 percent (4,328) were on undivided highways and 31 percent (2,045) were on divided highways. For vehicles on curves (4,912), 80 percent (3,900) of the crashes were on undivided highways and 16 percent (772) on divided highways.

Alignment / Trafficway flow	First Harmful Event			
	Rollover			
	Straight	Curve	Unknown	Total
Not physically divided	1,161	1,117	26	**2,304**
Divided highway (without traffic barrier)	869	222	7	**1,098**
Divided highway (with traffic barrier)	227	79	1	**307**
One-way traffic	9	3	0	**12**
Not physically divided (with two-way continuous left turn lane)	15	3	0	**18**
Entrance/exit ramp	14	71	2	**87**
Unknown	4	2	9	**15**
Total	**2,299**	**1,497**	**45**	**3,841**
	Parked Vehicle			
	Straight	Curve	Unknown	Total
Not physically divided	185	42	0	**227**
Divided highway (without traffic barrier)	104	20	1	**125**
Divided highway (with traffic barrier)	79	8	1	**88**
One-way traffic	12	0	0	**12**
Not physically divided (with two-way continuous left turn lane)	5	0	0	**5**
Entrance/exit ramp	4	4	0	**8**
Unknown	2		0	**2**
Total	**391**	**74**	**2**	**467**
	Collision With a Fixed Object			
	Straight	Curve	Unknown	Total
Not physically divided	4,328	3,900	58	**8,286**
Divided highway (without traffic barrier)	1,368	498	9	**1,875**
Divided highway (with traffic barrier)	677	274	5	**956**
One-way traffic	60	25	0	**85**
Not physically divided (with two-way continuous left turn lane)	85	35	0	**120**
Entrance/exit ramp	58	164	2	**224**
Unknown	18	16	19	**53**
Total	**6,594**	**4,912**	**93**	**11,599**
Grand total	**9,284**	**6,483**	**140**	**15,907**

Table IV-20: Distribution of trafficway flow, roadway alignment for vehicles involved in single-vehicle lane-keeping/road departure-related crashes subdivided by their First Harmful Events.

Comparison of the FARS conclusions with the GES data shows that the results seem consistent in that the test procedure must predominantly include *undivided highways* and *multilane divided highways without a traffic barrier*. The tests must also include vehicles on both *straight* and *curved roads*. For vehicles on curves the test should be performed on an *undivided highway.*

- **Avoidance maneuver**

The distribution of crash avoidance maneuvers is shown below in Table IV-21. For all known single-vehicle crash maneuvers, 926 (9%) of them braked, 3,301 (31%) of them steered and 6,282 (60%) of them did not perform any maneuver.

First Harmful Event / Avoidance Maneuver	Rollover	Parked Vehicle	Collision With a Fixed Object	Total
No maneuver	1,109	204	4,969	6,282
Braking	220	25	681	926
Steering	1,421	30	1,850	3,301
Others/unknown	1,091	208	4,099	5,398
Total	**3,841**	**467**	**11,599**	**15,907**

Table IV-21: Distribution of crash avoidance maneuvers for vehicles involved in single-vehicle lane-keeping/road-departure-related crashes.

Comparison of Table IV-21 and Table IV-13 shows that the distribution of responses is similar between GES and FARS data.

Summary of FARS section

Comparisons between FARS and GES show that conclusions from avoidance maneuvers, traffic flow, and road curvature data are similar. However, the difference arises in the speed of the vehicles, which is significantly higher in FARS than that of GES. Thus the tests must accommodate for these differences in speeds while keeping the same road and traffic conditions.

Summary

In this chapter we have developed test conditions for systems that assist drivers in preventing crashes associated with lane changes or road departures. They are based on data from both GES and FARS. The following table provides a summary of the test conditions. The speeds shown in this table correspond to the 80th percentile of crashes in either GES or FARS.

Type	Roadway	Specifics	Speed (80% of all crashes)	Speed (80% of fatal crashes)
Two-vehicle; opposite direction	- Two-lane - Undivided - Curve	- 350 ft separation (485 ft at 55 mph) - 3-degree approach angle	40 mph, both vehicles	55 mph, both vehicles
Two-vehicle; opposite direction	- Two-lane - Undivided - Straight	- 350 ft separation (485 ft at 55 mph) - 3-degree approach angle	40 mph, both vehicles	55 mph, both vehicles
Two-vehicle; same direction	- Multilane - Straight	- 3-degree approach angle	40 mph, lead vehicle 45 mph, following vehicle	65 mph, lead vehicle, 70 mph-following vehicle
Single-vehicle	- Two-lane - Undivided - Curve	- Narrow shoulder - 3-degree approach angle	50 mph	75 mph
Single-vehicle	- Multilane - Straight	- Shoulder with parked vehicle - 3-degree approach angle	30 mph	70 mph

Table IV-22: Summary table for test conditions for lane-keeping/road-departure-related systems based on data from GES and FARS.

The tests should accommodate systems that assist drivers who would otherwise take no evasive action as well as systems that assist drivers who brake or steer, but inadequately to prevent a crash. Additional insights on data for developing crash scenarios might be obtained by conducting analyses on Crashworthiness Data System and National Motor Vehicle Crash Causation Study data.

CHAPTER V
Analysis of Naturalistic Driving Data

Naturalistic driving studies analyze the driver behavior in a natural setting. These studies collect data from a suite of vehicle sensors and unobtrusively placed video cameras while drivers go about their normal day-to-day activities. The drivers are given no special instructions, no experimenter is present, and the data collection instrumentation is unobtrusive. Naturalistic driving data fills a gap in other data collection methods such as epidemiological, simulator, and test-track studies. A primary goal of naturalistic driving studies is to provide vital exposure and pre-crash data that are necessary for understanding causes of crashes, supporting the development and refinement of crash avoidance countermeasures, and estimating the potential of these countermeasures to reduce crashes and their consequences. Some naturalistic driving studies (such as the 100-Car Study[12]) include driving without the help of a driver assistance systems while other studies (such as ACAS,[9] Volvo HV,[11] and Road Departure[10]) include driving both with and without (baseline driving) the DAS being active.

In this chapter we discuss three applications of naturalistic driving data; and describe how each application fits into the process shown in Figure I-1 and/or the Benefits Equation described in Chapter III. The three applications are: estimation of technical parameters for the purpose of defining test conditions, estimation of Exposure Ratio, and anecdotal illustration of system performance.

Estimation of technical parameters for the purpose of defining test conditions

In this example, naturalistic driving data is used to determine lane change angle. The 100-car naturalistic study[12] is the source of data for the study. The data elements used in the study are the lane offset, lane width, delta time frame (time increment), vehicle speed, and longitudinal acceleration. Two hundred twenty-three lane change maneuvers were identified from 781 near-crash-time histories in the 100-car study (details of the study are presented in Appendix D). A summary of the analysis of lane change angle is:

> The magnitude of lane change angle decreases with increase in vehicle travel speeds. At higher travel speeds (greater than 50 mph) there are no lane change maneuvers with lane change angle greater than 3 degree, while at lower travel speeds (between 20 and 30 mph) 50 percent of lane change maneuver are at angles greater than 3 degrees. Therefore the conclusion is that 3 degrees can be used as an appropriate approach angle for testing lane-keeping and road departure systems.

Estimation of Exposure Ratio

Another use of naturalistic driving data is in the estimation of the Exposure Ratio. As seen in Chapter III, Equation 17, the Exposure Ratio reflects the change in exposure to imminent crashes that result from introduction of a driver assistance system. The ER complements the Prevention Ratio in the estimation of system effectiveness.

The relevant expression for the ER from Chapter III is repeated here for clarity.

$$\widetilde{E}_i = 1 - \left[\frac{\left(\dfrac{\widetilde{S}_{Wi}}{VMT_{Wi}} \right)}{\left(\dfrac{\widetilde{S}_{WOi}}{VMT_{WOi}} \right)} \right] \times \left[\frac{\left(\dfrac{\widetilde{N}_{Wi}}{\widetilde{S}_{Wi}} \right)}{\left(\dfrac{\widetilde{N}_{WOi}}{\widetilde{S}_{WOi}} \right)} \right] \tag{19}$$

Where N is the number of crashes (with and without the DAS) for each of the scenarios. S_{woi} and S_{wi} are the number of times that the ith scenario occurs, without and with the DAS active respectively. VMT is the relevant exposure and E_i is the effectiveness of the DAS in preventing crashes that otherwise would occur when drivers experience each scenario. The first term in brackets is the Exposure Ratio.

The ER quantifies the extent to which drivers with DAS drive in a manner that reduces the number of times a conflict becomes an imminent crash. A value of ER less than one reflects an improvement in driver safety due to a reduction in the number of imminent crash events.

This section describes an approach for computation of the ER that uses naturalistic driving data.* The approach considers the fact that in the period leading up to an imminent crash, drivers with a DAS might avoid an imminent crash that they would otherwise experience. The approach utilizes driver reaction time data in conjunction with data from naturalistic driving without a DAS.

Steps in this process for estimating the Exposure Ratio are as follows:

1. Define the scenarios to which the DAS applies. This analysis is normally included as part of Activity 2 in Figure I-1.
2. Identify a dataset of driving events that contains all occurrences of relevant scenarios. Subdivide the data set into each relevant scenario, e.g., lead vehicle stopped, and identify the events that include an imminent crash. The number of these events is S_{WOi} in the Exposure Ratio equation.

   Note: some naturalistic driving data may include driving with the DAS engaged (e.g., field operational tests). However, only data while driving without the DAS are used for the purpose of estimating the Exposure Ratio of a pre-production system.
3. For each event in the S_{WOi} subset, superimpose intervention algorithms on the time history of the event. Overlaying the algorithm on the appropriate time histories for each event in the data subset provides a means of determining when the DAS would have intervened if it had been active during the naturalistic driving.
4. Compute the difference between the time of intervention and the beginning of the imminent crash phase from Step 2.
5. From the cumulative distribution of reaction times that corresponds to the value of the difference, determine the fraction of drivers who react within that difference. The fraction of drivers with a reaction time less than the difference in Step 4 are the

* Unpublished analysis of naturalistic data by Robert Miller, 2007

drivers that could be expected to have avoided the imminent crash phase if the DAS had intervened in this situation.

6. Estimate the number of these events that would enter the imminent crash phase by summing the values of the fractions in Step 5 for all events in the set. This is the value of S_{Wi} in the Exposure Ratio equation.
7. Estimate the Exposure Ratio for each scenario.

This estimation of the Exposure Ratio would be part of Activities 3 and 7 in Figure I-1.

Example

These steps are illustrated with the following example. The data for this example is from the heavy truck FOT of a DAS that consisted of a combination collision warning, adaptive cruise control, and an advanced electronic braking system.[11] The data for this example is from the baseline phase of the test. During this phase the DAS was not activated.

For the purpose of this example, the Aggressive Kinetic Motion Equation (A-KME) is considered to be the threshold for an imminent crash. The A-KME is a term that was used in the FOT. It is defined to be the point in time that is 0.5 seconds prior to the latest point in time at which a driver could avoid a crash by braking at a level of 12 or less ft/s^2 (0.37 g). Similarly, the Conservative Kinetic Motion Equation (C-KME) is used as the threshold for the conflict phase. The C-KME is also a term that was used in the FOT. It describes the point in time that is 1.5 seconds prior to the latest point in time at which a driver could avoid a crash by braking at a level of 8 or less ft/s^2 (0.25 g). Both these thresholds are depicted graphically in Figures V-1 and V-2, respectively.

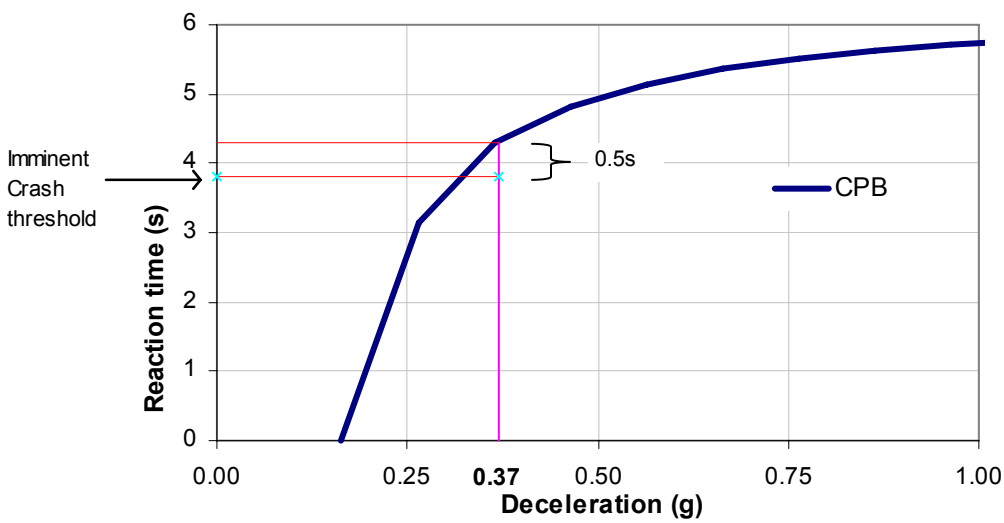


Figure V-1: Imminent crash threshold in Crash Prevention Boundary format, for an example where lead and subject vehicles are traveling at 60 mph with a separation of 1.5s (132 ft). The lead vehicle begins to decelerate at 0.2g.

These figures show the limiting driver performance (0.5 sec before the latest time that a crash can be avoided by braking at 0.37 g and 1.5 sec before the latest time that a crash can be avoided by braking at 0.25 g) in the Crash Prevention Boundary format[13] for an event where the lead vehicle decelerates at 0.2 g from an initial speed of 60 mph.

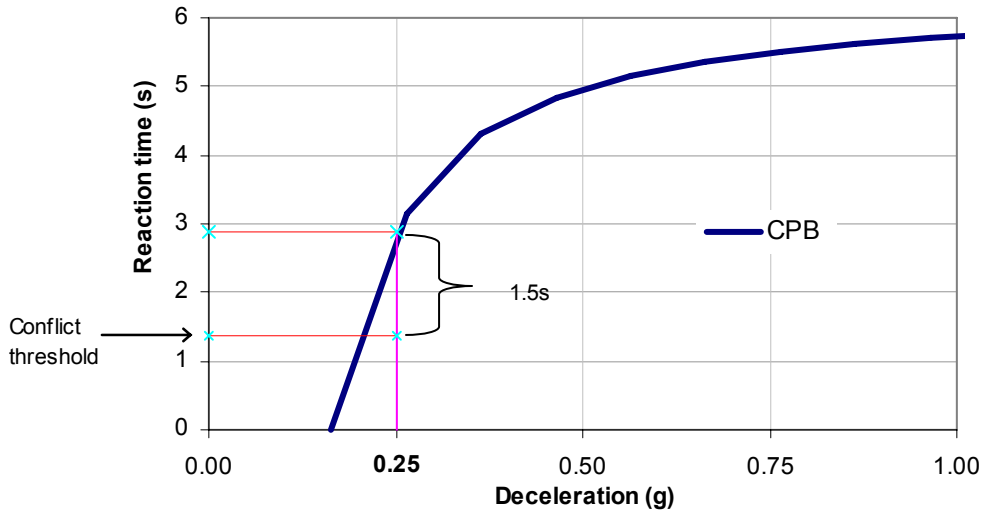


Figure V-2: Conflict threshold in Crash Prevention Boundary format, for an example where lead and subject vehicles are traveling at 60mph with a separation of 1.5s (132 ft). The lead vehicle begins to decelerate at 0.2g.

Step 1. Define the Scenarios

The identification of relevant scenarios are normally obtained through analysis of crash data files. A general sequence of events is typically as follows without and with a DAS.

<u>Event Sequence Without Warning</u>	<u>Event Sequence With Warning</u>
1. Conflict starts	1. Conflict starts
2. Conflict ends/imminent crash begins	2. Warning
3. Driver brakes	3. Driver brakes earlier
4. May or may not have a crash	4. Conflict ends/imminent crash begins for a percentage of drivers less than 100 percent; no imminent crash period begins for the remaining percentage of drivers.

It is also possible for the warning to precede the conflict start. Knowing the time period between the warning and the start of the imminent crash period creates a "margin" of time within which the driver could react. The question is what percentage of drivers would react in time so that an imminent crash condition is eliminated in some (but not all) events where a warning is given to the driver.

The analysis in Chapter IV is an example of this process. For this example, however, the relevant scenarios were rear-end crash scenarios defined by the FOT team. The scenarios are described in Table V-1.

Types of scenario	Subject Vehicle Speed	Lead Vehicle Speed
1. Closing with constant velocity	Constant	Constant
2. Closing with both vehicles decelerating	Decelerating	Decelerating
3. Closing with constant velocity preceded by lane change	Constant	Constant
4. Closing on stopped lead vehicle	Constant or Decelerating	Stopped
5. Closing with decelerating lead vehicle	Constant	Decelerating

Table V-1: Relevant rear-end crash scenarios from heavy-truck FOT.[11]

Step 2. Identify the relevant set of data

The scenario selected for this example is an event where the lead vehicle was decelerating. This example uses events from a large data set where a warning system was not operative (i.e., baseline data). All of the events had a decelerating lead vehicle in the subject vehicle's lane and hence are examples of either conflict Type 2 or 5. In addition, all of the events chosen had a conflict followed by an imminent crash. A time plot sample will help illustrate the various segments of the conflict/imminent crash period for clarity.

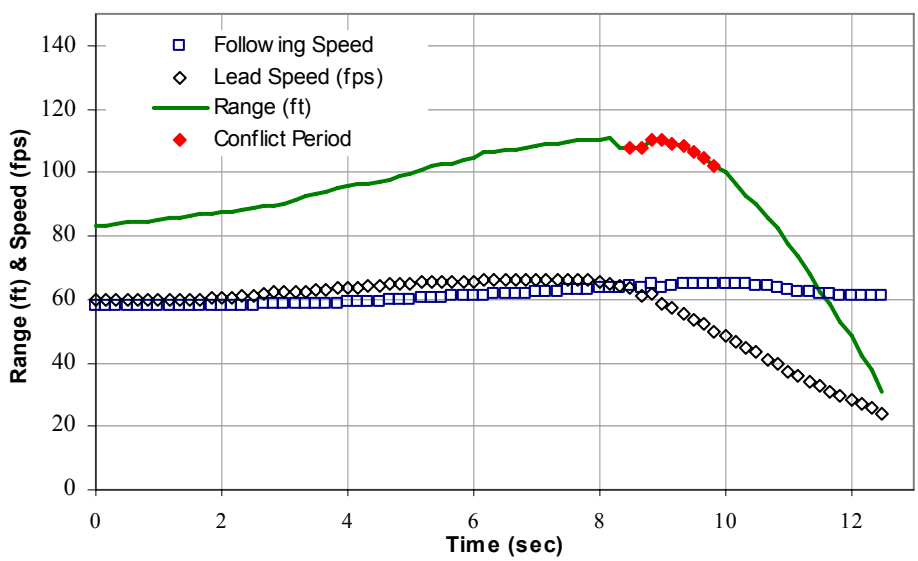


Figure V-3 Sample time plot showing conflict

In Figure V-3 the red segment of the range trace depicts the conflict phase. At the time that the lead vehicle begins to decelerate (t ~ 8 sec.) there is less than 1.5 seconds to avoid a crash by braking at 0.25 g. Therefore, the conflict phase starts immediately when the lead vehicle decelerates. The imminent crash phase consists of the time after the conflict phase

(t > 10 sec.). Data collection for this event was terminated at about 13 seconds. A crash (range = 0) is predicted if nothing changes.

Step 3. Superimpose driver assistance system intervention (warning algorithm) on the event

Of the candidate events selected in Step 2, it was additionally necessary that the kinematics were such that a warning was produced. The warning algorithm used here is the same as was used in the FOT. The algorithm produces an audible warning to the driver if the headway (headway is the ratio of range to subject vehicle speed) is less than 2 seconds. At this point all the events which would have caused a warning and had a conflict followed by an imminent crash were identified. A total of 12 events resulted from this step; samples 8 and 2 are depicted in Figures V-4 and V-5 respectively.

The warning algorithm was applied to each event from Step 2. Figure V-4 shows the time plot of Figure V-3 with the warning superimposed (the yellow triangle) on the range trace. The warning would have been given immediately after the lead vehicle began to brake because the headway was less than 2 seconds at that time.

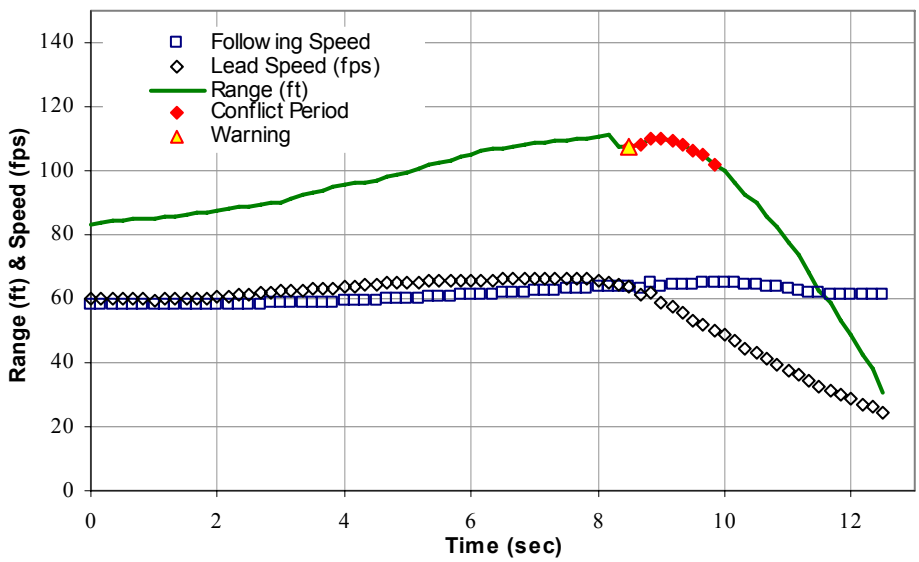


Figure V-4 Sample time plot showing conflict and warning before conflict start

Figure V-5 is an additional sample where the superimposed warning occurs after the conflict phase. The conflict phase begins after the lead vehicle begins to brake followed by the warning.

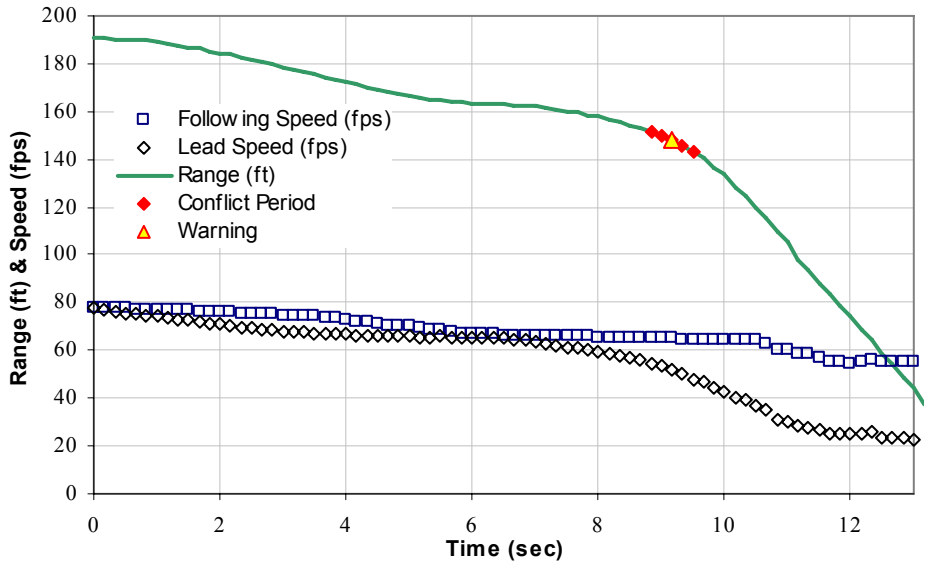


Figure V-5 Sample time plot showing conflict and warning after conflict start

Step 4. Compute the difference between the warning and the start of imminent crash phase

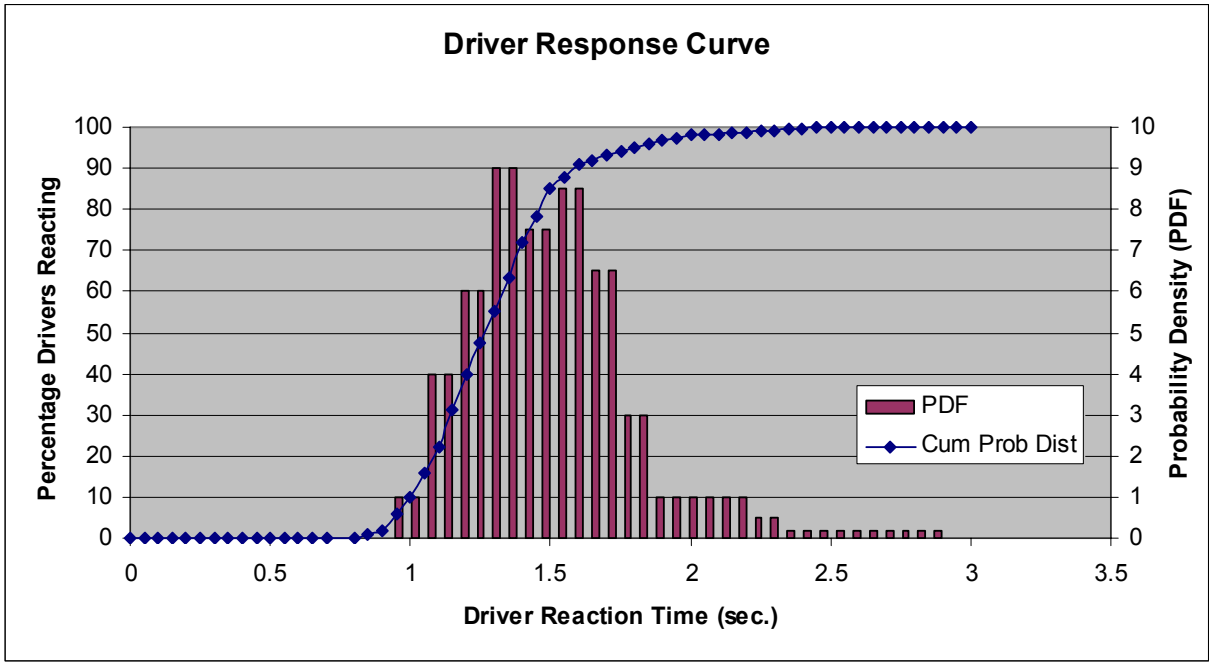
For each of the 12 events from Step 3, the difference between the warning and imminent crash start was computed. This is termed the margin for each of the 12 events. Table V-2 is a summary of this computation.

Sample	Warning Time	Conflict Start Time	Imminent Crash Start Time	Margin Duration
1	**11.5**	11.00	11.67	**0.17**
2	**9.0**	9.17	9.5	**0.50**
3	**9.33**	9.17	10.0	**0.67**
4	**9.17**	8.67	10.0	**0.83**
5	**9.0**	8.83	9.83	**0.83**
6	**9.67**	10.5	10.83	**1.16**
7	**8.33**	8.83	9.5	**1.17**
8	**8.33**	8.67	10.0	**1.67**
9	**8.0**	9.67	10.0	**2.00**
10	**9.33**	9.67	11.67	**2.34**
11	**7.17**	9.33	10.0	**2.83**
12	**12.0**	11.00	14.83	**2.83**

Table V-2: 12 Sample events from Volvo FOT

The percentage of drivers who would react within a certain time due to a perceived threat may be derived from human factors data. Such a typical reaction response curve is shown in Figure V-6. This figure shows the percentage of drivers that would react as a function of reaction time. Based on the curve, very few drivers would react within a 0 to 0.75-second

period; but all drivers (100%) could be expected to react within 3 seconds with an average reaction time of about 1.25 seconds.



FigureV-6: Distribution of driver's reaction time. [12]

Step 5. Determine the relative fraction of drivers who would respond for each margin
Table V-3 shows the percentage of drivers that would react within the margin given for each sample in Table V-2. For the 12 data samples selected, those approximate relative percentages are presented in Table V-3.

Sample	Margin Duration	Approximate Relative Fraction of Drivers Reacting
1	**0.17**	0.00
2	**0.5**	0.00
3	**0.67**	0.00
4	**0.83**	0.01
5	**0.83**	0.01
6	**1.16**	0.31
7	**1.17**	0.31
8	**1.67**	0.93
9	**2**	0.98
10	**2.34**	0.99
11	**2.83**	1.00
12	**2.83**	1.00

Table V-3: Approximate fraction of drivers reacting to the warning

Step 6. Estimate the number of imminent Crash Events with the warning
The set of 12 selected data events for computation of ER presented in Table V-2 all included a conflict phase, and an imminent crash phase; and not the conditions for activating a warning.

Considering the fraction of drivers that would respond from Table V-3 within the margin duration so as to avoid the imminent crash start (ICS), the value of ER will be less than one. In order to find the relative amount of the ER reduction, the number of ICSs eliminated as a function of reaction time is found.

F_j is the fraction of ICSs eliminated as a function of reaction time, j. The number of ICSs remaining as a function of reaction time will then be $1 - F_j$. If the total number of ICSs without the warning as a function of reaction time j is N_j, then the total number of ICSs remaining after the warning effect is applied is summed over all reaction times as equation [20]. Table V-4 shows the corresponding numbers represented by this sample of 12 events.

$$S_{wi} = \sum N_j \left(1 - F_j\right) \tag{20}$$

Reaction Time (Bins)	ICS Samples per Reaction Time Bin - N_j	Driver Response Fraction - F_j	Remaining Samples per Bin After Driver Reaction	Cumulative Remaining Samples - Swi
0.2	1	0.000	1.00	1.00
0.35	0	0.000	1.00	2.00
0.5	1	0.000	0.00	2.00
0.65	0	0.000	0.00	2.00
0.8	1	0.000	1.00	3.00
0.95	2	0.060	1.88	4.88
1.1	0	0.220	0.00	4.88
1.25	2	0.475	1.05	5.93
1.4	0	0.720	0.00	5.93
1.55	0	0.850	0.00	5.93
1.7	1	0.920	0.08	6.01
1.85	0	0.950	0.00	6.01
2	0	0.975	0.00	6.01
2.15	1	0.986	0.01	6.02
2.3	0	0.992	0.00	6.02
2.45	1	0.998	0.00	6.03
2.6	0	1.000	0.00	6.03
2.75	0	1.000	0.00	6.03
2.9	2	1.000	0.00	6.03
3.05	0	1.000	0.00	6.03
3.2	0	1.000	0.00	6.03
Total	**12**		**6.03**	

Table V-4: Number of imminent crash eliminations with the warning

Thus, for all 12 events considered, then the number of imminent crashes with the warning would be less than 12 and is represented by S_{Wi} in (20). Thus by rate of occurrence, 5.97 ICS events could be eliminated by the warning system and 6.03 would remain.

Step 7. Estimate Exposure Ratio

The total number of imminent crash events with the DAS active warning system, S_{Wi}, is the numerator of the equation for ER and the corresponding number of imminent crash events without the DAS, S_{WOi}, is the denominator.

$$ER_i = \frac{S_{wi}}{S_{woi}} \tag{21}$$

Note that although in Equation 19 the denominator and numerator include a rate term in the denominators of S_{WOi} and S_{Wi} . These denominators are the same when using this process and cancel out.

Based on this small sample of 12 events and the warning algorithm used, the estimate of Exposure Ratio for the decelerating lead-vehicle scenario due to the warning DAS:

$$ER_i = \frac{6.03}{12} = 0.50$$

Summary of the 7-step process for estimating Exposure Ratio

A warning system is expected to reduce the value of Exposure Ratio. A sample calculation using naturalistic, on-road driving data demonstrates how much a warning system could be expected to reduce ER from a value of 1 (no improvement) in equation (19). If a driving conflict event occurs, followed by a warning, followed by earlier braking than without the warning; it is possible that the imminent crash period will not occur depending on the time and level of driver braking due to the warning.

In the above examples, the 7-step process was used to estimate ER. Twelve events were chosen from a database where the lead vehicle was decelerating. Warning time, conflict Start time, imminent crash time, and margin values were determined from the kinematic data of the 12 samples. Margin times were determined for each of the individual event samples and compared with a cumulative distribution of driver reaction time. The percentage of drivers reacting within the given margin time was used to estimate the number of imminent crash events that could be eliminated with a warning. Knowing the number of imminent crash events with and without the warning provided the basis for the estimate of ER.

The process used here for the calculation of Exposure Ratio relied on data where no warning was actually available to the driver. It presumes that if a warning would have been given, a certain percentage of drivers would have avoided the imminent crash phase

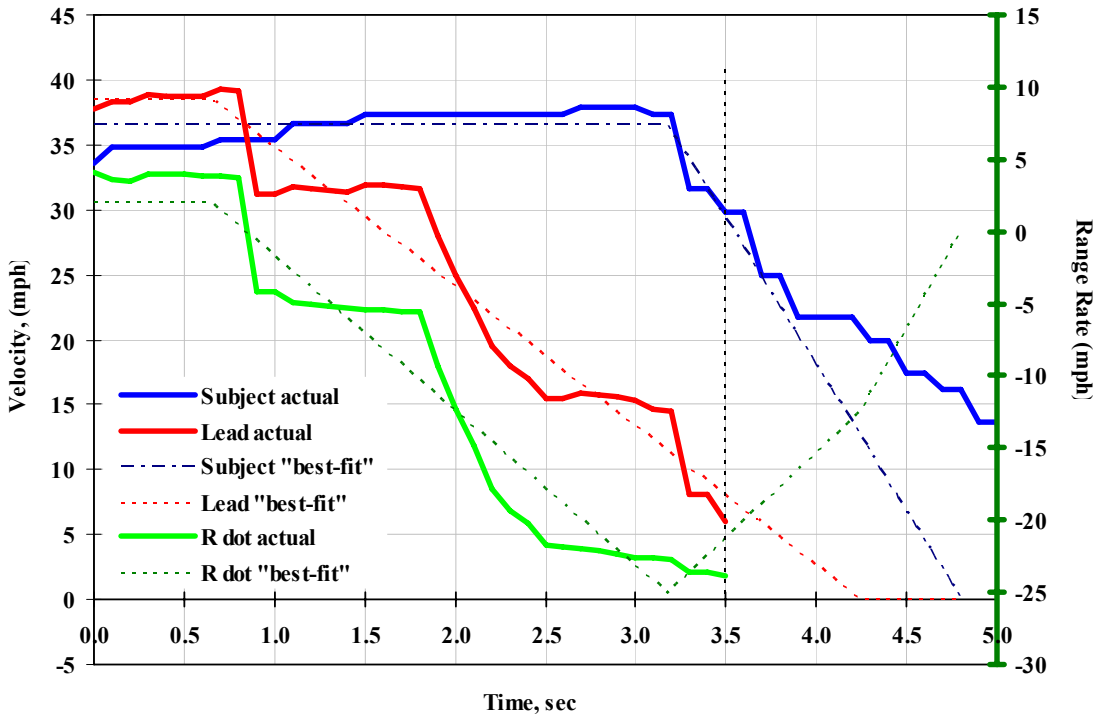
of the event. The time margin between when warning would have been given and the beginning of each imminent crash is the basis for estimating Exposure Ratio. For the group of events and the warning algorithm that were used in this exercise, the estimated value of Exposure Ratio is 0.5. This value would be combined with other terms in the Safety Benefits equation, such as Prevention Ratio, to estimate the overall effectiveness of the DAS in avoiding crashes for each event.

Anecdotal illustration of system performance

Brake assist system example

Another use of naturalistic driving data is to provide anecdotal examples of the effect of specific countermeasures. In the following example from the 100-car study,[12] it is shown how a brake assist system might intervene in a specific crash scenario. In this selected example the subject vehicle brakes and then steers right to avoid a collision with a decelerating lead vehicle. However, the steering input causes the subject vehicle to clip the corner of the lead vehicle, depart from the roadway, and eventually crash into a utility pole. The velocity profiles for both subject and lead vehicle are shown in Figure V-7. Initially the subject and the lead vehicle are traveling at 36 and 38 mph respectively. The subject vehicle initiates braking 2.5 seconds after the lead vehicle starts to brake. There is a significant increase in absolute values of range-rate (R dot) due to braking of the lead vehicle.

The intensity of braking by the subject vehicle at the start is about 1 g, but the driver does not maintain this intensity, noticed from the change in the slope of the subject vehicle velocity profile at about 3.9 seconds. Figure V-10 also includes "best-fit"[13 14 18] profiles for the lead and subject vehicle velocities, fitted for the time span 0 to 3.5 seconds.



FigureV-7: Subject and lead vehicle velocities and their difference (R dot) along with "best-fit" approximations

Figure V-8 shows the deceleration profiles associated with "best fit" lead and subject vehicle velocities. Figure V-9 shows the actual range between the two vehicles and the approximation based on the decelerations shown in Figure V-11. It can be seen that the minimum range, or estimated closest approach, is 3.4 ft, i.e., the subject vehicle would have stopped at 3.4 ft behind the lead vehicle if it had continued to brake at 1.0g. A brake assist system could have helped the driver maintain this level of braking.

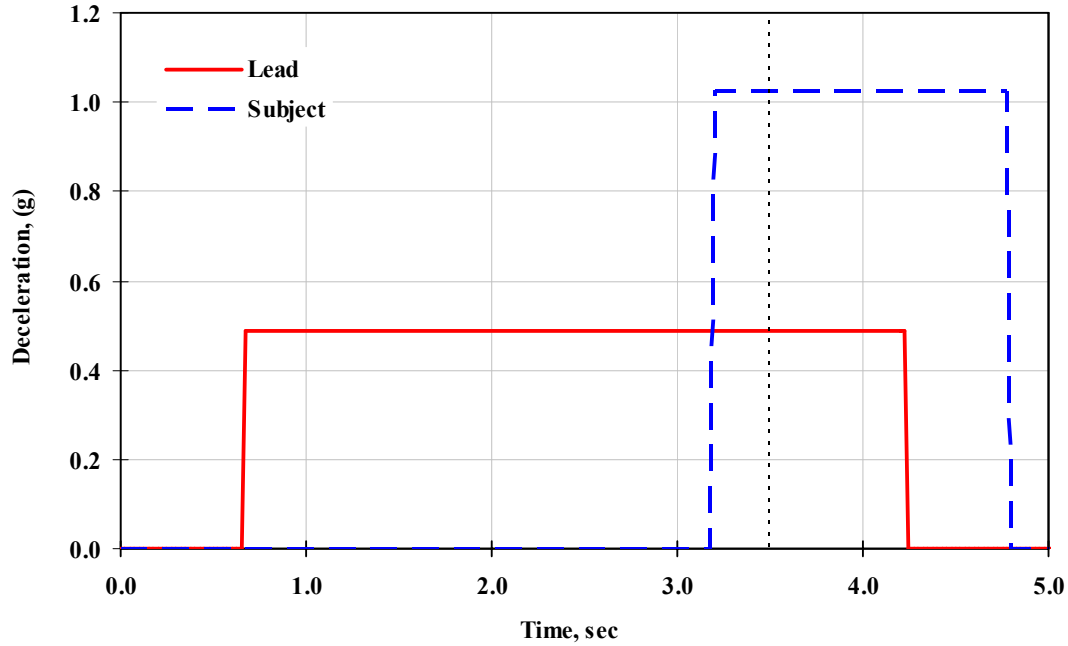


Figure V-8: "Best fit" deceleration levels for the subject and lead vehicles.

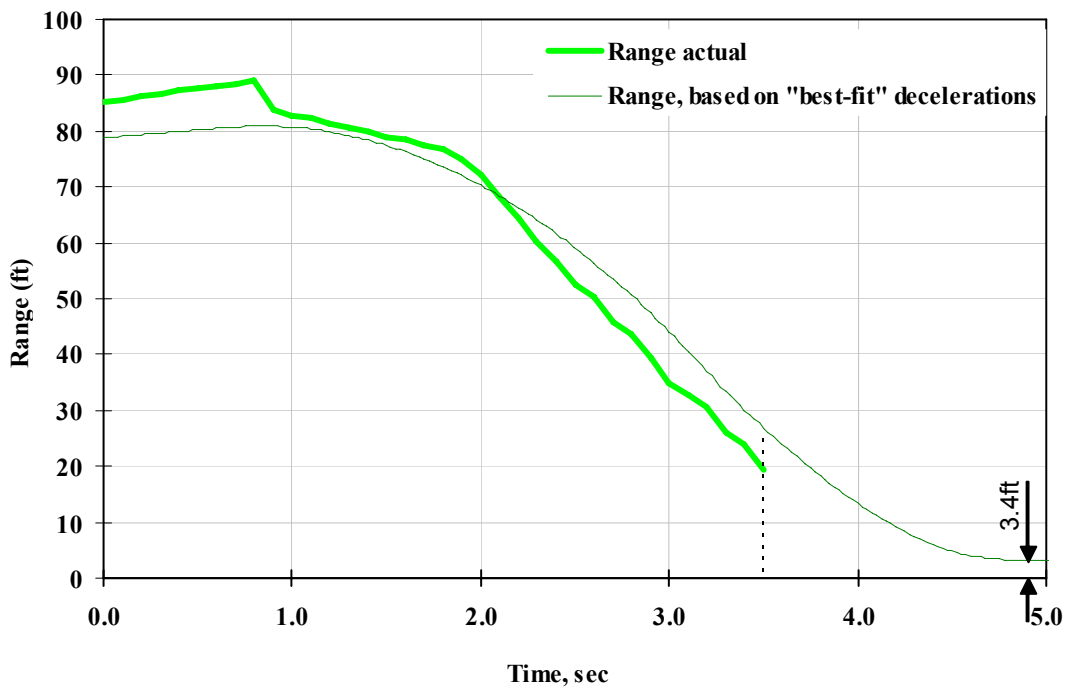


Figure V-9: Range between the subject and the lead vehicle and its "best fit" approximation.

This anecdotal example provides insight into how a brake-assist system could have helped a driver maintain a deceleration level equal to the initial braking level. If this had happened, the subject vehicle would have stopped 3.4 ft behind the lead vehicle; and if the driver had not steered off the road, there would not have been a crash.

CHAPTER VI
Objective Tests

Activity 5 in the methodology outlined in Figure I-1 is the development of objective tests that can be used to establish differences in driver performance when a DAS is available. This chapter describes an experimental design for these objective tests. The tests described here would be used in conjunction with test conditions such as those that are described in Chapter IV.

A central element of this methodology is that the tests be objective. The definition of objective tests was clarified in 1972 when the United States Court of Appeals for the Sixth Circuit provided the following explanation[16]:

> "Objective means that tests to determine compliance must be capable of producing identical results when test conditions are exactly duplicated, that they be decisively demonstrable by performing a rational test procedure, and that compliance is based upon the readings obtained from measuring instruments as opposed to the subjective opinions of human beings."

As discussed in Chapter III, an inherent aspect of assessing safety benefits is the variability of driver performance. Thus, the tests must not only be objective, as defined above, but they must also reflect the variability of performance of drivers. The following outline of six steps describes how both of these objectives can be met.

- The basic dynamic conditions of the objective tests (such as speeds, headway, lead vehicle deceleration, etc.) will be developed in the preceding tasks.
- Each test will consist of a series of test runs on an appropriate test track (or driving simulator).
- The first subset of test runs will be performed with the DAS inactive and will use a sample of volunteer drivers. A total of 16 drivers will be recruited for each test. This set of 16, one male and one female representative for each of the age groups used in Traffic Safety Facts,[15] is shown in Figure VI-1. The use of these age and gender groups are key factors in relating test results to previous crash conditions.
- The second subset of test runs will be identical to the first, except that the system will be active and the vehicle will be controlled by an automatic controller
- During each test run in the first subset, the vehicle will be controlled by the volunteer driver and details of vehicle movements and driver responses will be recorded in detail.
- During each test run in the second subset, the vehicle motion control inputs will be provided by an automatic controller that is programmed to repeat the performance of each of the volunteer drivers in the first subset. The controller will faithfully replicate the input from each of the drivers in the first subset of test runs up to the point that the DAS intervenes. After this point the control input will be modified to correspond to expected change in driver reaction time and/or automatic control inputs.

AGE	Gender	Percent of drivers in GES
16-20	M	10.1
	F	7.3
21-24	M	6.4
	F	4.5
25-34	M	12.0
	F	8.6
35-44	M	11.2
	F	8.0
45-54	M	9.0
	F	6.0
55-64	M	5.2
	F	3.3
65-74	M	3.4
	F	2.0
>74	M	1.7
	F	1.3

Table VI-1. Age/gender categories from Traffic Safety Facts.[15]

In summary, the procedures outlined above not only provide objective data on system performance, but also address the inherent variability of drivers. Objectivity is assured through the use of recorded driver performance when testing with the DAS and driver variability is addressed by using one subject from each of 16 age/gender groups. In Chapter VII there is further discussion of additional steps that can be taken to improve the consistency of results when using a single subject per age/gender group.

One concern about using a single driver for each of the 16 groups is that a single driver will not statistically represent the entire group. Approaches to overcome this limitation, but without expanding the number of subjects can be developed. One such example is to have a mini-competition among a larger number, e.g., 20, of potential subjects. Each of these potential subjects would be given a simple test to determine a relevant performance feature, such as reaction time. One such test is to drop a meter-stick and have the candidate grab it as soon as possible.[17] Results from these tests of candidates would provide a basis for establishing the distribution within the age/gender group of that performance feature. The candidate with the score closest to a given measure of the distribution, e.g., 85th percentile, would be selected as the representative of the group. This approach would provide a set of subjects for the actual driving tests that have less variability of a basic performance feature than the population as a whole.

However, in some circumstances there may be a need to emphasize the variability of drivers rather than objectivity. In these circumstances, the tests may need to involve more than one driver in each of the 16 groups. By involving more than one subject driver for each age/gender group, the variability in performance of drivers due to factors including

response time, risk-taking capability, braking intensity, cognitive capability, and response to false alarms can be addressed.

A combination of more subjects per group and traditional experimental design provides a basis for estimating bounds on variability. The use of more subjects per group also provides a basis for partitioning variability into within-and between-subject variances. The number of subjects per group will depend on factors such as available resources and restrictions on the maximum size of confidence intervals. Details of selecting the appropriate number of subjects per group are beyond the scope of this report.

In spite of the availability of various designs, the choice of the design depends on a number of factors including, the resources available, and the degree of control the experimenter desires to have on error. For the purpose of this report, the details of these experimental design procedures are not discussed in detail.

It should be noted that the objective tests described here are not the same as validation tests in field operational tests. These objective tests are for the purpose of providing data that can be used to estimate potential safety benefits for the DAS while validation tests are conducted for the purpose of verifying system performance.

CHAPTER VII
Conversion From Measures of Performance to Measures of Effectiveness

Conversion from measures of performance, obtained from the objective tests, to measures of effectiveness is a key element in assessing the safety impact of a crash avoidance system. This element provides the bridge between the quantitative description of safety performance that is obtained from objective tests described in Chapter VI and calculation of benefits as described in Chapter III.

The purpose of each objective test is to provide data that can be used to estimate potential safety benefits for the system. The underlying formulations for estimating benefits are developed in Chapter III. For purposes of this discussion, the final formulation in Chapter III will be used. That formulation is:

$$B = \sum E_i \times N_{WOi}$$

Where,

$$E_i = 1 - ER_i \times PR_i$$

ER is the exposure ratio and PR is the prevention ratio.

Subscript "i" denotes individual scenarios.

In Chapter VI a set of steps was outlined for development of objective tests. Each test will consist of a series of test runs on an appropriate test track or driving simulator. The first subset of test runs will be performed with the system inactive and will utilize a sample of volunteer drivers. A total of 16 drivers will be recruited for each test. There will be representative from each of the age/gender groups shown in Table VI-1. The second subset of test runs will be identical to the first, except that the system will be active and the vehicle will be controlled by an automatic controller. During each test run in the second subset, the vehicle motion control inputs will be provided by an automatic controller that is programmed to repeat the performance of each of the volunteer drivers in the first subset.

In this Chapter we describe the following steps for mapping the results of objective tests into estimates of potential safety benefits:

1. Determine the distribution of baseline driver performance without the system (e.g., time of initiation of response and level of effort of response) from the first subset of test runs.
2. Convert these descriptions of driver performance to intermediate measures that are relevant to estimation of effectiveness, such as the estimated closest approach (ECA). The ECA,[18] [19] as the name suggests, is an approximation of how close to each other two vehicles come during the event. A positive value of the ECA means that there was room to spare, and that there was not a crash during the event. By contrast, a negative value of the ECA means that there was a crash during the event.
3. Determine the distribution of "equivalent" driver performance with the system from the second subset of tests.

4. Convert these descriptions of driver performance to intermediate measures that are relevant to estimation of effectiveness, such as the ECA.
5. Use these intermediate measures to estimate measure of effectiveness such as the probability of a crash. One approach is to use the fraction of drivers that are likely to have a crash, based on GES distribution shown in Table VI-1.
6. Combine the probabilities of a crash to compute the Prevention Ratio and estimate benefits.

The following example, a hypothetical brake-assist system, is used as a means of amplifying the description of these steps.

For this example, consider a generic brake-assist system. For purposes of this example, the system is described by the following four characteristics:

Activation criteria---The brake-assist system will be activated if the driver applies the brake pedal at a rate greater than an appropriate threshold.

Time of activation---The brake-assist will begin to adjust the braking at the instant brake pedal rate is greater than the threshold.

Level of braking---The brake-assist system will produce maximum possible deceleration for the given conditions of brake, tire, road, and weather.

Duration of activation---The brake-assist system will continue to apply maximum possible deceleration until the driver releases the brake pedal.

For the purposes of this example, application of the procedures described in Chapter IV lead to the following test that represents one of many relevant scenarios.

The example consists of the host vehicle following a lead vehicle at a speed of 50 mph (80th percentile from GES) with a space between them of 100 ft (this corresponds to a time headway of 1.4 sec). Once this relationship between the two vehicles has been established the driver of the lead vehicle begins to decelerate at a constant level of 0.35g. The time-to-collision at the beginning of this event is 4.2 seconds. This is a situation that is manageable by most alert drivers, but is also representative of situations that produce rear-end crashes

Although this is a hypothetical example, these conditions are consistent with crash data from GES.

As described above, the tests will be run twice: once with volunteer drivers and a second time with the same driver inputs, but this time provided by a programmed controller. The second time also includes intervention by the brake-assist system.

The two measures of performance for these tests are the time at which effective host-vehicle braking begins (measured from when the lead vehicle begins to decelerate) and the effective level of host vehicle deceleration. The combination of these two parameters determines whether a crash will be prevented in this situation or not. Values for these two descriptors can be shown graphically as in Figure VII-1.

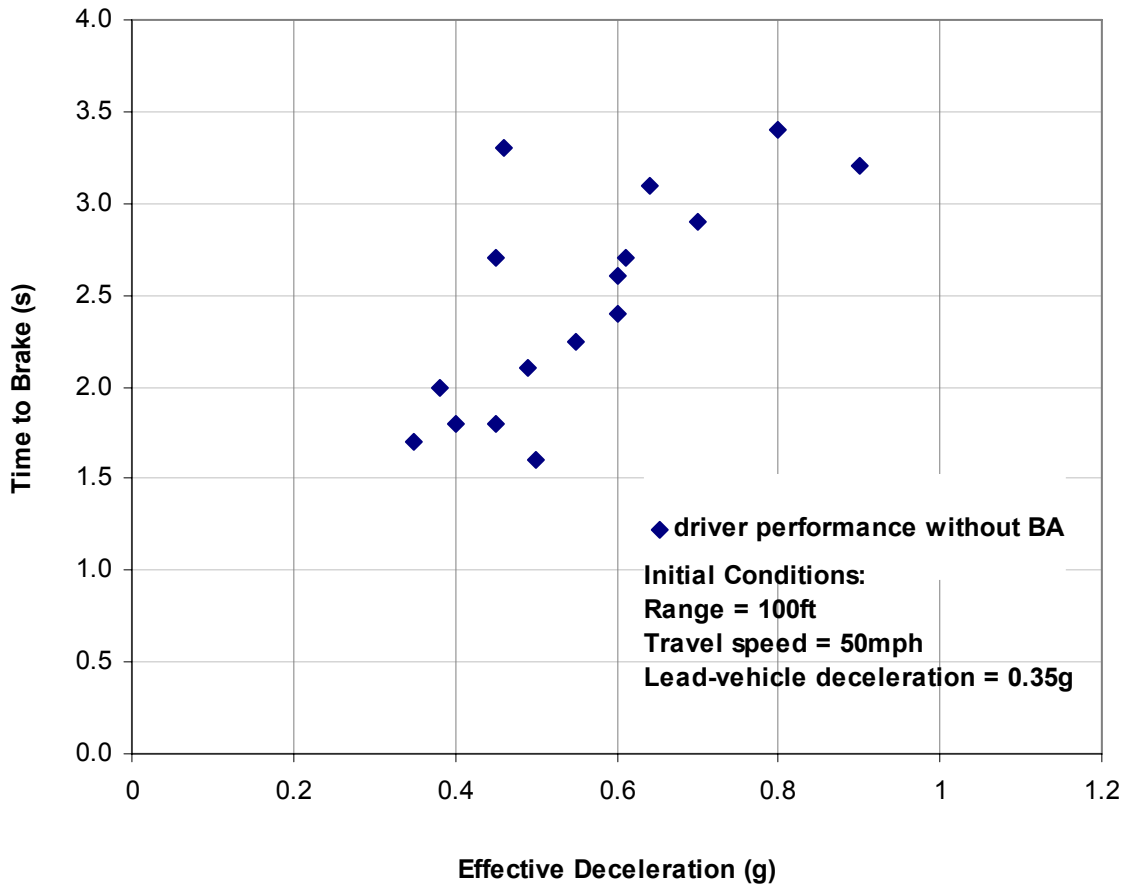


Figure VII-1. Hypothetical performance of 16 drivers, in terms of effective deceleration level and time to brake; no brake-assist available for the host vehicle.

The location of these descriptors for each driver can also be compared to the crash/no-crash performance boundary for the test. This boundary is called the crash prevention boundary or CPB.[13] The CPB delineates the region of driver performance that is adequate to prevent a crash from the region of performance that will not prevent a crash. The goal of safe driving is to always perform in a manner that places the location of the descriptors to the right of the CPB. The comparison of the description of individual performance for each subject to the CPB for this decelerating lead vehicle situation is shown in Figure VII-2. In this figure the 11 drivers to the right of the boundary did not have a crash; and the 6 drivers to the left of the boundary did have a crash. (Note, however, the test will be run in a way that prevents any crashes from actually occurring.)

The distance between the location of the performance descriptors and the CPB in Figure VII-2 is indicative of the value of the ECA. The values of performance by each baseline driver and the corresponding value of ECA are summarized in Table VII-1.

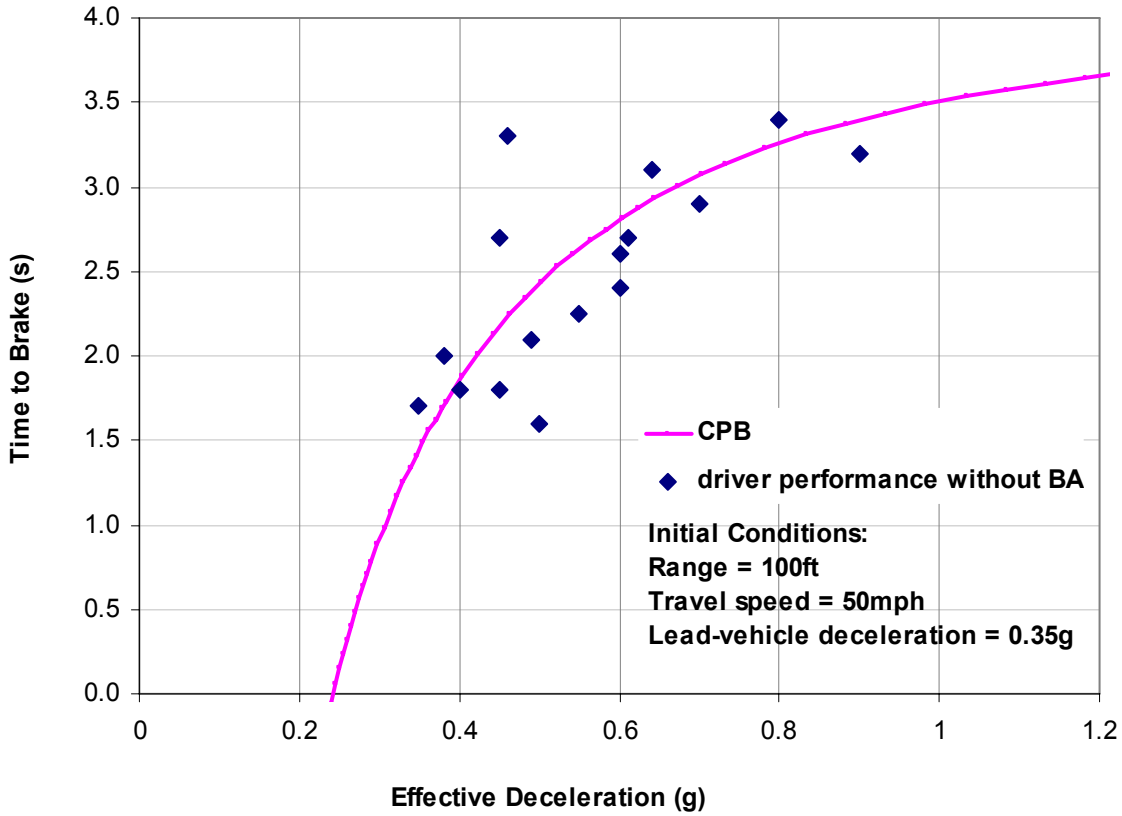


Figure VII-2. Comparison of driver performance to the crash prevention boundary for baseline driving scenarios.

AGE	Sex	Time to Brake (s)	Effective deceleration level (g)	ECA (ft)
16-20	M	1.7	0.35	-18
	F	1.6	0.5	60
21-24	M	1.8	0.4	4
	F	1.8	0.45	28
25-34	M	2	0.38	-21
	F	2.1	0.49	21
35-44	M	2.25	0.55	29
	F	2.4	0.6	30
45-54	M	3.3	0.46	-78
	F	2.6	0.6	16
55-64	M	2.7	0.61	11
	F	2.7	0.45	-38
65-74	M	2.9	0.7	13
	F	3.1	0.64	-12
>74	M	3.2	0.9	15
	F	3.4	0.8	-8

Table VII-1. Summary of driver performance in baseline conditions for decelerating lead vehicle example.

A similar process is followed for assessing the performance of "equivalent" drivers in the tests with the brake-assist system active. During these tests, the vehicle is controlled by a programmed controller that faithfully reproduces the driver actions during the baseline tests. The effect of the brake-assist system is to increase the level of braking but to not affect the time at which braking begins. For this hypothetical example, it is assumed that the brake-assist system raises the effective level of braking to a maximum level for the given conditions. The brake-assist system is activated when the brake pedal rate is greater than the threshold rate.

For this example the brake-assist system did not activate on two occasions as the driver applied the brake at brake pedal rate less than the threshold. This effect is seen in Figure VII-3, where the performance of equivalent drivers with brake-assist is shown graphically for this situation. The time of braking for each driver is the same, but the level of braking is raised to the maximum level. A summary of equivalent driver performance with brake-assist is shown in Table VII-2.

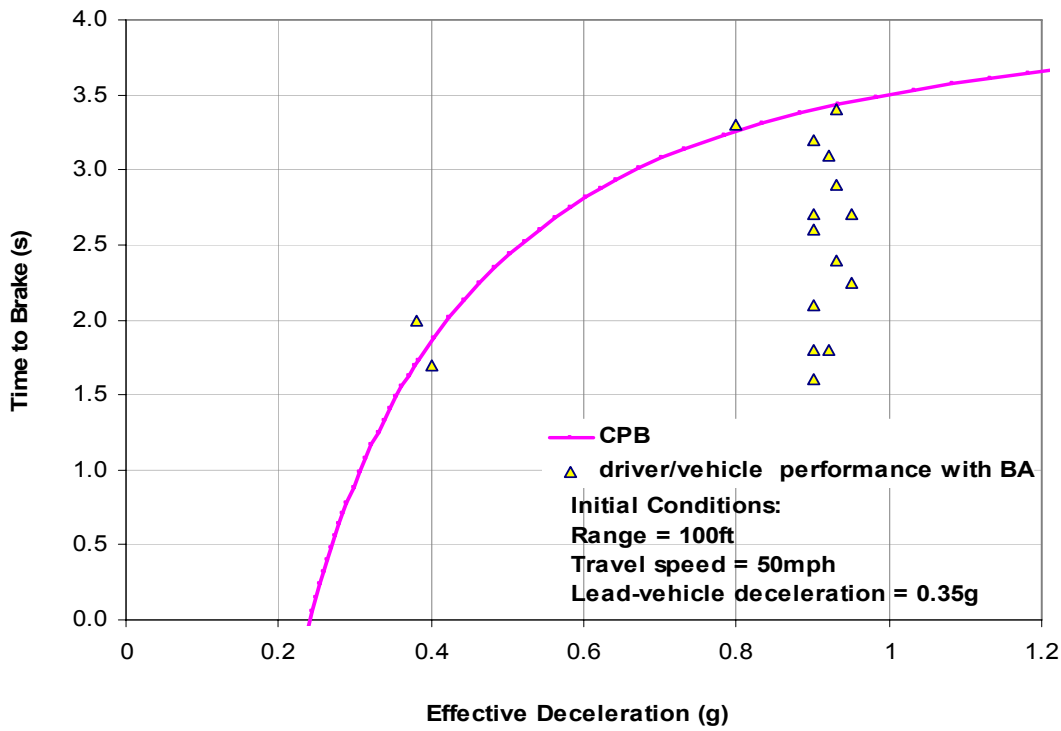


Figure VII-3. Comparison of driver performance to the crash prevention boundary for brake-assist system activated driving scenario.

AGE	Sex	Time to Brake (s)	Effective Deceleration Level (g)	ECA (ft)
16-20	M	1.7	0.4	19
	F	1.6	0.9	104
21-24	M	1.8	0.9	94
	F	1.8	0.92	95
25-34	M	2	0.38	-21
	F	2.1	0.9	79
35-44	M	2.25	0.95	73
	F	2.4	0.93	65
45-54	M	3.3	0.8	-0.2
	F	2.6	0.9	52
55-64	M	2.7	0.95	49
	F	2.7	0.9	46
65-74	M	2.9	0.93	36
	F	3.1	0.92	23
>74	M	3.2	0.9	15
	F	3.4	0.93	3

Table VII-2. Summary of "equivalent" driver performance with the brake-assist system activated for decelerating lead vehicle example.

The next step is to convert the values of ECA to a measure of effectiveness, in this case the probability of a crash, for baseline conditions and for equivalent driving with the brake-assist system active. Keeping in mind (as discussed in Chapter VI) that each subject is representative of their age and gender, each value of ECA is weighted by the respective fraction of crash-involved drivers. These weighted values are used to produce the cumulative distributions of ECA for the tests without the brake-assist system and for the tests with the brake-assist system. The values of ECA are shown in Tables VII-1 and VII-2. The cumulative distributions of ECAs for with and without the brake-assist system are shown in FigureVII-4. Also seen in the figure are the respective best-fit normal distributions of the ECA.

Noting that positive values of ECA correspond to situations where there was no crash and negative values correspond to situations where there was a crash, the fraction of each distribution that is negative is the probability of a crash in that situation.

For this example, the estimated probability of a crash without the brake-assist system (baseline) = 0.42 and the probability of crash with brake-assist system activated = 0.21. The value of prevention ratio (PR) for this example situation is then:

$$PR = \frac{P_W}{P_{WO}} = \frac{0.21}{0.42} = 0.5$$

Where,

Pw = probability of crash with brake-assist

Pwo = probability of crash without brake-assist system

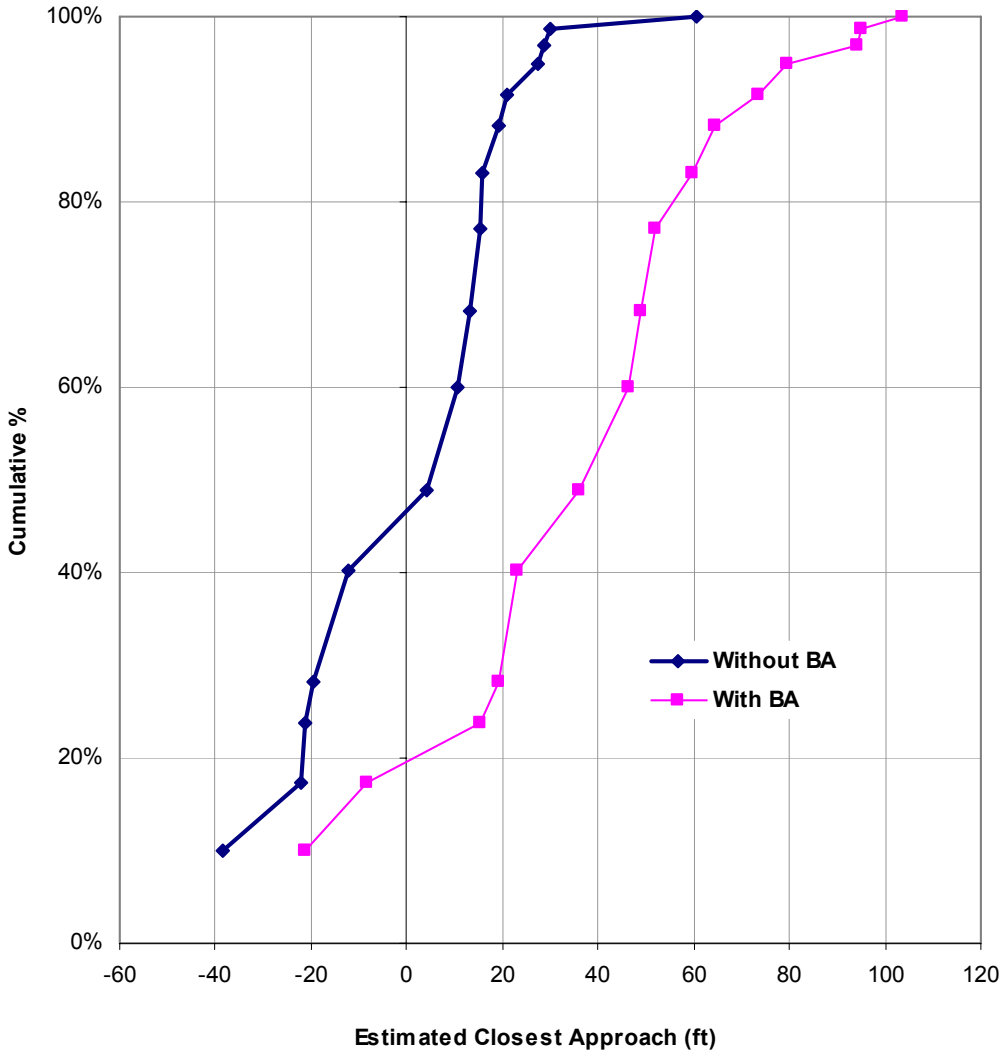


Figure VII-4. Cumulative distribution of ECA, with and without the brake-assist system active.

Similar test conditions to estimate benefits can be developed for other subsets of crashes relevant to brake-assist system. Summation of all these individual benefits would give the overall safety benefit of the brake-assist system.

This chapter describes a process for making the critical linkage between measures of performance and measures of effectiveness. The process includes a controlled experiment with volunteer drivers; however, each subject represents a specific age/gender group and they all have a similar level within their group of a relevant performance feature. The results of the tests are used, along with age and gender distributions in GES, to estimate probabilities of a crash with and without a DAS. These probabilities of a crash are then used to estimate the Prevention Ratio and the system effectiveness.

Chapter VIII
Summary and Suggestions

This report presents a methodology for estimating potential crash-avoidance benefits for pre-production systems. The process is described in Chapter I followed by a discussion of crash timeline, the role of crash data, and an overview of basic benefits equations that are used for computing the estimates. Discussion of how data from a variety of sources can be brought together to "fill in the blanks" of the benefits equations, and details of individual steps in the process. For example, Chapter II describes a novel method for organizing crash data into mutually exclusive sets. This organization, called the Universal Description, provides a uniform foundation for starting the analysis of the performance of any system. The development in Chapter III shows the commonality between computations that are done for the purpose of regulatory evaluation, computations that are done for the purpose of evaluating the safety impact of systems based on field operational test data, and the computations that need to be done to assess the potential impact of pre-production systems. Chapter IV provides a detailed roadmap for analyzing GES and FARS data to develop a set of test conditions for systems that help drivers avoid crashes that result from straying out of their travel lane. Chapter V focuses on how data from naturalistic driving experiments (i.e. experiments where participants drive instrumented vehicles on public roads in unstructured "daily routine" driving) can be used as a source of data for some of the terms in the benefits equations. Chapters VI and VII focus on objective tests that can be performed in a test track environment or on a driving simulator and use of the data for estimating potential safety benefits. Table VIII-1 summarizes the connections between the steps in the methodology, the elements of the benefits equations and the sources of data that are described in the report.

Activity Figure I-1	Data source	Benefits Equation term	Chapter numbers
Describe the system performance (not in scope of this report)	Engineering data from suppliers	The starting point for identifying relevant scenarios	N/A
Analyze crash data files	GES, FARS, CDS	The baseline number of crashes in each scenario and test conditions	IV
Analyze real-world data	Naturalistic driving, and field operational tests	Exposure Ratio for each scenario and details of test conditions	IV & V
Develop relationship between MOP and MOE: objective tests	GES, and human factor data	Basis for calculating the Prevention Ratio for each scenario.	VI
Perform tests, based on developed objective tests	Test programs	Data for calculating Prevention Ratio.	VII
Estimate Benefits	All Sources	Benefits	VII

Table VIII-1. Overview of the report.

Key finding in the report is a set of test conditions that can form the basis for assessing the impact of lane-keeping/road departure driver assistance systems. These test conditions are the product of a detailed analysis of data from the GES and FARS crash data files as well as data from a naturalistic driving experiment. They are shown in the following table.

Type	Roadway	Specifics	Speed (80% of all crashes)	Speed (80% of fatal crashes)
Two-vehicle; opposite direction	- Two-lane undivided curve	- 350 ft separation (485 ft at 55 mph) - 3-degree approach angle	40 mph, both vehicles	55 mph, both vehicles
Two-vehicle; opposite direction	- Two-lane undivided straight	- 350 ft separation (485 ft at 55 mph) - 3-degree approach angle	40 mph, both vehicles	55 mph, both vehicles
Two-vehicle; same direction	- Multilane straight	- 3-degree approach angle	40 mph, lead vehicle 45 mph, following vehicle	65 mph, Lead Vehicle, 70 mph following vehicle
Single - vehicle	- Two-lane undivided curve	- Narrow shoulder - 3-degree approach angle	50 mph	75 mph
Single - vehicle	- Multilane-straight	- Shoulder with parked vehicle - 3-degree approach angle	30 mph	70 mph

Table VIII-2. Summary of conditions for lane-keeping/road departure-related systems based on data from GES and FARS

This report provides a framework for, and several examples of, the detailed analysis, and testing that would be needed for assessment of any specific system. The report also provides a foundation for exploratory analysis of future research areas and technologies.

Suggestions for future work

There are also other topics that deserve to be studied and developed as adjuncts and complements to the material in this report. Some of these areas are:

1. More detailed consideration of driver characteristics such as distraction and state of alertness:
   The test program described in Chapter VI is based on a single representative of each of 16 age/gender groups. As pointed out in that chapter, it may be important to include a larger sample for each group. It may also be necessary to have special groups of subjects if a countermeasure is designed to assist certain people or to apply only to certain conditions, such as drowsiness. The analysis of crash data described in Chapter IV would need to be tailored to each specific population in these cases. Similarly, the benefits would be based on these limited populations.

These considerations can be accommodated in the benefits equations described in Chapter III.

2. Extension of the crash avoidance focus of this report to include crash severity mitigation:
   Many systems that can help drivers avoid crashes can also help reduce speeds at the point of impact when a crash does occur. Reductions in speed should result in lower levels of injury severity. Estimation of these reductions in harm can be accomplished through relatively straight forward extensions of the equations in Chapter III. Some of the considerations that would need to be included are type of crash, restraint use, victim's age and vehicle occupancy. One example of this extended process can be found in the paper "Pre-Crash Sensing Countermeasures and Benefits." [23]

3. Extensions of the methodology to support future provisions of the New Car Assessment Program (NCAP):
   Starting as early as 1996 when the National Academy of Science issued a report on the NCAP program,[20] and as recently as at a recent public meeting,[22] NHTSA has been considering ways to provide a summary safety rating for new vehicles that combines the relative importance of crashworthiness and crash avoidance features of a vehicle.[21] The methodology presented in this report, and extensions noted above, have the potential to provide a means for assessing relevant safety benefits that could support these advancements in the NCAP.

4. Validation and calibration of the methodology:
   One aspect of the methodology that is not covered in this report is the validation of its usefulness as a benefits estimation tool. One approach to checking the validity of the methodology would be to apply it to a commercially available technology. However, to be able to compare real-world crash rates to those predicted by this methodology, it is important to keep in mind that this methodology requires a series of tests that are based on crash data files. The development of these tests, including use of a vehicle controller, requires time and resources. So, while a validation experiment is desirable, it would require a conscious effort to develop and implement the relevant tests.

5. Include measure of accuracy:
   The methodology used in this report focuses on point estimates of safety benefits. Confidence intervals (CI) will help indicate the reliability of the benefit estimates. For analysis having a large sample size, CI can be estimated using descriptive statistics (CHMSL[24]). But at instances when values or estimates for mean and variance are not available, as in case of safety benefits estimate, methods such as the one using "asymptotic" or "approximate" standard errors (ASE) can be used to calculate the CI for the benefit estimates (ESC [25]). So, CI provides a viable means of statistical inference for quantities being estimated whose probability distributions are known. Ideally, a short interval with high degree of confidence is preferred.

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APPENDIX A

This appendix provides a short summary of the methodologies used to estimate potential safety benefits from a selected sample of relevant reports. The summaries are organized into the three types of calculation that are discussed in Chapter III.
The basic expression is:

$$B = \sum \widetilde{E}_i \times N_{WOi}$$

Where the benefits, B, can be number of crashes, number of fatalities, "harm," or other such measures and the subscript "i" is used to denote individual situations. Thus, E_i is the effectiveness of the system in reducing the number of crashes in a specific crash-related situation and N_{woi} is the baseline number of crashes in that situation

<u>The first set of reports are based on the Type 1 formulation of the benefits equations</u>:

$$\widetilde{E}_i = 1 - \frac{\widetilde{N}_{Wi}}{\widetilde{N}_{WOi}}$$

In this form of the benefits equation, the pre-crash situations that will be affected by the countermeasure are determined by engineering analysis of the countermeasure, the number of crashes or casualties for each situation are drawn from nationally representative crash files and estimates of effectiveness of the countermeasure for each situation are based on experimental data or other analysis.

Paper 1

*Preliminary Regulatory Impact Analysis for NPRM on tire pressure monitoring system FMVSS No. 138**

Countermeasure for which the benefit is estimated:
Tire pressure-monitoring system (TPMS).

Type of benefits
1. Reduced Fatalities.
2. Reduced Injuries.

Summary:
The measure of benefits in this paper is the number of fatalities and injuries reduced each year. The authors present three crash situations that are relevant to the introduction of TPMS. They are (1) skidding and loss of control, (2) change in stopping distance, and (3) flat tires and blowouts. Based on NASS CDS the numbers of fatalities associated with these three crash situations are 247, 6,903, and 414 respectively; and number of injuries is 23,130, 1,126,134 and 10,275 respectively. Estimates of effectiveness of TPMS in reducing fatalities and injuries for each of these three situations are based on NHTSA tire tests.

* Detailed references are at the end of this Appendix

Paper 2

Development of a forward collision warning algorithm evaluation methodology with evaluation of three alert algorithms; 100-car follow-on Subtask 5

Countermeasure for which the benefit is estimated:
Hypothetical warning systems; each based on different algorithm for determining when an imminent crash warning should be given to the driver. The three collision avoidance system algorithms are:

1. Knipling et al. (1993) – Equations developed by Knipling et al. for LV stationary and LV moving scenarios.
2. CAMP Linear – The linear regression approach described in early CAMP work (Kiefer et al., 1999) that predicts a required deceleration after response based on test-track braking by drivers in different scenarios.
3. NHTSA – An algorithm developed by Brunson et al. (2002) that incorporates multiple warning levels and sensitivity settings.

The measure of benefits in this report is the number of rear end crashes. The authors use a three-step process to obtain their estimates of effectiveness. [Editor: From GES, the number of passenger-vehicle rear-end crashes is 1.281 million.]

The estimates of effectiveness in reducing number of crashes are based on 13 crashes and 60 near-crashes from the 100-Car Study's braking at three different levels: 0.5g, 0.675g, and 0.85g. The first step is to use kinematic analysis to establish, for each of the 73 events, the latest point that a driver could brake and still avoid the crash. The authors use three different potential levels of braking; 0.5g, 0.675g, and 0.85g for this analysis. For the near-crashes, authors assume that the driver did not brake to avoid the crash. The second step was to determine at what point in the event would each of the algorithms have given a warning. In the third step, the difference between the time of the warning and the latest possible time for braking is compared to a distribution of driver reaction times. This distribution is based on previous research. Thus, a percentage of drivers who could have avoided the crash by braking at each of the three specified levels in response to a warning based on one of the algorithms is determined for each event. The average over the 73 events is the estimate of effectiveness for that algorithm. The process yields three estimates of effectiveness, one for each of the specified levels of braking, for each algorithm.

Paper 3

Effectiveness Estimation Method for Advanced Driver Assistance Systems and Its Applications to Collision Mitigation Brake System

Countermeasure for which the benefit is estimated:
Collision mitigation braking system (CMBS).

The measure of benefits in this paper is the number of rear-end crashes. The authors present six crash situations that are relevant to rear-end crashes. They are, lead vehicle:

stopped for at least 4 seconds, stopped for less than 4 seconds, decelerating, constant speed, and changing lanes. [Editor: From GES, the number of passenger-vehicle-rear-end crashes is 1.281 million.]
Estimate of effectiveness is obtained from a subset of 50 NASS–CDS rear-end crashes.
These 50 crash scenarios are reconstructed into 6 simulation models representing the 6 relevant rear-end crash scenarios. For the baseline simulation, which constitutes without CBMS, there is no warning and no driver reaction to the collision event other than the regulation of the speed and lane position time history imported from the accident reconstruction. Twenty-two simulation-runs which determine crash or no-crash are executed for each crash scenario by controlling parameters; reaction type (brake, steer, steer & brake), human reaction time, and emergency braking amplitude. The ratio of with and without (baseline) simulation results is the estimate of the effectiveness for each crash type. Summation of these estimates for all six crash types gives the total effectiveness of the CBMS in preventing a rear-end crash.

<u>The second set of reports are based on the Type 2 formulation of the benefits equations</u>:

$$\widetilde{E}_i = 1 - \frac{\widetilde{N}_{Wi} / \widetilde{X}_{Wi}}{\widetilde{N}_{WOi} / \widetilde{X}_{WOi}}$$

This form of benefits equation differs from the preceding form in the manner of estimating effectiveness. In this form, estimates of crash rates or number of crashes and measures of exposure from representative crash data are used to estimate effectiveness for each relevant situation.

Paper 4
Preliminary results analyzing the effectiveness of electronic stability control (ESC) systems

Countermeasure for which the benefit is estimated:
Electronic Stability Control (ESC).

Summary:
The measure of benefits in this paper is reduction in number of single-vehicle crashes and fatal single-vehicle crashes. The author identifies single-vehicle crashes as the type of crash situation that is relevant to introduction of ESC. The estimation of effectiveness uses crash data from 5 States that have Vehicle Identification Number (VIN) recorded in crash data files
[Editor: from GES, the number of single-vehicle crashes in 2003 was; cars: 1,0347,93; SUV: 227,770. and from FARS was cars 9,915; SUVs 3,158.}
The VIN allows the data to be separated by vehicles with and without an ESC. The author uses multivehicle crashes as the basis of normalizing exposure, based on the assumption that ESC has no effect on multivehicle crashes. Thus, use of the number of single- and multivehicle crashes for this five-State set of data can be used with this form of benefit equation to estimate the impact of ESC. The values from these subsets are used for estimating the effectiveness in reducing single-vehicle crashes:

$\widetilde{N}_w$ = Number of single-vehicle crashes with ESC: 699 passenger cars.

$\widetilde{N}_{wo}$ = Number of single-vehicle crashes without ESC: 1,483 passenger cars.

$\widetilde{X}_w$ = Number of multivehicle crashes with ESC: 14,090 passenger cars.

$\widetilde{X}_{wo}$ = Number of multivehicle crashes without ESC: 19,444 passenger cars.

Paper 5

Preliminary Evaluation of the Effectiveness of Rear-Wheel Antilock Brake System for Light Trucks

Countermeasure for which the benefit is estimated:
Rear-Axle Anti-Lock Brakes.

Type of benefits
Single-vehicle rollover crashes of pickup trucks

The measure of benefits in this paper is single-vehicle rollover crashes of pick-up trucks. [Editor: From GES, the number of single-vehicle rollover crashes of pickup trucks in 2003 was 23,278] This paper is very similar to the preceding paper. Thy both use multivehicle crashes to normalize exposure and use data from state files that include VIN.] The values from this set of data that are used to estimate effectiveness are:

$\widetilde{N}_w$ = Number of single-vehicle rollover crashes with ABS: 737.

$\widetilde{N}_{wo}$ = Number of single-vehicle rollover crashes without ABS: 1,095.

$\widetilde{X}_w$ = Number of multivehicle crashes with ABS: 4,215

$\widetilde{X}_{wo}$ = Number of multivehicle crashes without ABS: 3,634

Paper 6

The Effectiveness of Primary Safety Features in Passenger Cars in Germany

Countermeasure for which the benefit is estimated:
Electronic Stability Program

The authors identify passenger car crashes classified as "Driving Accidents" as the crashes addressed by ESP. Driving Accidents are defined as "accidents caused by driver's losing control of their vehicle, due to not adapted speed or misjudgment of course or the condition of the road." [Editor: From GES, there were 252,854 passenger cars involved in crashes similar to "Driving Accidents" in 2003.]
The estimate of effectiveness is obtained by using data from the German Federal Statistics office. Accidents for the years between1998 and 2002 for passengers with registration 1998 or later and have been assigned sensitive to ESP are used in the analysis. The authors identify crashes caused by pedestrians crossing roads, and accidents involving stationary vehicles as not sensitive to ESP. The non-sensitive crashes are used as the basis of normalizing exposure.

The values from this data set that are used for estimating effectiveness are:

$\widetilde{N}_w$ = Vehicle equipped with ESP and involved in ESP Sensitive Accident: 3535.

$\widetilde{N}_{wo}$ = Vehicle not equipped with ESP but involved in ESP Sensitive Accident. 10,387 crashes.

$\widetilde{X}_w$ = Vehicle not equipped with ESP but involved in ESP Sensitive Accident: 9075.

$\widetilde{X}_{wo}$ = Vehicle not equipped with ESP and not involved in ESP Sensitive Accident: 18035.

Paper 7

The Effectiveness of Electronic Stability Control (ESC) in Reducing Real-Life Crashes and Injuries

Countermeasure for which the benefit is estimated:
Electronic stability control

The measure of benefits in this paper is the number of police-reported crashes with at least one injury. The authors identify several situations that are relevant to the performance of ESC systems. The primary situation is all crashes except rear-end crashes on dry roads. This broad class of situations is further subdivided by level of injury, slipperiness of the road, and a combination of "single car, oncoming and overtaking." [Editor: From GES, the number of passenger vehicle crashes that are not rear-end crashes on a dry road in 2003 was 610,000]

The estimates of effectiveness in reducing the number of crashes are based on data from police-reported crashes with at least one injured person in Sweden during the years 1998-2004 for vehicles from model years 1998-2005. The authors have identified rear-end crashes on dry roads as a type of crash that is not affected by ESC, and use the number of this type of crash to normalize exposure. The total number of crashes in this database that involve vehicles with ESC is 1942 and the total number of crashes in this database that involve vehicles without ESC is 8242. No separation of these numbers is provided.

Paper 8

Benefits Estimation for Selected Collision Avoidance Systems; Fourth World Congress on Intelligent Transport Systems

Countermeasure for which the benefit is estimated:
Rear-end Crash Avoidance system

The measure of benefits in this paper is the number of police-reported crashes. This paper describes three types of CAS: (1) rear-end; (2) single-vehicle road departure; and (3) lane change. Only rear-end CAS is studied in this review. The authors identify two pre-crash conditions relevant to rear-end CAS. They are lead vehicle decelerating and lead vehicle not moving. [GES 1994, 1.547 million rear-end crashes are categorized by above two pre-crash conditions.]

The estimate of effectiveness is based on Monte Carlo modeling analysis. These models incorporate time delay and brake actions for driver, system and vehicle brake systems. The output from Monte Carlo simulation is the number of events tested with and without the

system as well as the number of crashes for vehicles with CAS and vehicles without. For applications, such as Monte Carlo analysis, the number of events acts as measure of exposure. These results were then used directly to compute the estimated crash rates or probability of crash for both situations at two road conditions. Market penetration and use of the CAS are assumed to be 100 percent.

Paper 9
Evaluation of the Intelligent Cruise Control System

Countermeasure for which the benefit is estimated:
Intelligent Cruise Control.

The measure of benefits in this report is the number of police-reported crashes. The authors identify two situations that are relevant to the performance of an ICC system. The two situations are (1) lead vehicle braking, (2) lead vehicle traveling at a constant speed lower than the following vehicle, and the following vehicle is traveling at least 40 mph on a freeway. The situations are described by three parameters: type of roadway, speed of the subject or the following vehicle, and action of the lead vehicle. From 1996 GES, the authors determined that the number of passenger vehicle police-reported crashes that occurred on freeways at speeds of 40 km/h or greater was 75,000.
The estimate of effectiveness is determined from the combination of FOT data and Monte Carlo modeling output. ICC utilization rate, distribution of velocities, distribution of range, distribution of range-rate, and distribution of lead vehicle braking levels are estimated from FOT data. This, along with estimates of the distribution of subject emergency braking levels from earlier research, makes up the input to the Monte Carlo simulation model. The output from Monte Carlo simulation is the number of events tested with and without the system as well as the number of crashes for vehicles with ICC active and vehicles without ICC active. For applications, such as Monte Carlo analysis, the number of events acts as measure of exposure. These results were then used to directly compute the estimated crash rates or probability of a crash for both situations at each of the eight ranges of speed. These estimates of the probability of a crash provide the basis for estimating effectiveness.

Paper 10
Preliminary assessment of crash avoidance systems benefits

Countermeasure for which the benefit is estimated:
Rear-end crash warning systems.

This report measures benefits in number of police-reported rear-end crashes. The author identifies pre-crash scenarios on lead vehicle moving (LVD) and lead vehicle not moving (LVNM) as relevant to this countermeasure rear-end crash warning system. Each pre-crash scenario is further broken down on the basis of road condition, i.e., dry and slippery road condition. Based on 1994 GES 1.20 million crashes are relevant to this countermeasure.

The effectiveness of the countermeasure rear-end crash warning system in preventing a crash for each distinct pre-crash situation is computed by estimating crash probabilities using the Monte-Carlo simulation method.

<u>The third set of reports are based on the Type 3 formulation of the benefits equations</u>:

$$\widetilde{E}_i = 1 - (ER_i \times PR_i)$$

where ER is the ratio of number of occurrences of each situation per unit of exposure; also known as the Exposure Ratio. The second ratio describes the effect on preventing crashes when a situation occurs. It is the ratio of the rate of crashes per situation (with and without the system); and is also known as the Prevention Ratio.

This form is used for systems that affect both the frequency of relevant situations and the driver's crash prevention performance when confronted with a relevant situation.

Paper 11

Estimating safety benefits for the IVI Generation 0 field operation tests

Countermeasure for which the benefit is estimated:
Rear-end crash warning system.

This paper measures benefits as reduction in number of tractor-trailer trucks rear-ending a lead vehicle with the assistance of the countermeasure intelligent vehicle safety system (IVSS). The author identifies driving conflicts that have lead vehicle constant LVC (stopped/constant speed) and lead vehicle decelerating (LVD) as relevant to the countermeasure. Between 1992 and 1998, there were 149,283 relevant tractor-trailer rear-end crashes.

The probability of occurrence of driving conflicts and resultant Exposure Ratio are estimated from GES and FOT data. The Prevention Ratio is estimated using Monte-Carlo simulation.

Paper 12

Evaluation of the Freightliner Intelligent Vehicle Initiative Field Operational Test

Countermeasure for which the benefit is estimated:
Rollover advisor and control system.

The measure of benefits in this paper is the number of untripped rollover crashes of tanker tractor-trailers. The authors identify seven types of situation that are the predominant subsets of this type of crash. Of these seven situations, the largest one (accounting for 55% of this type of crash) is "turning or negotiating a curve at excessive speed." This is the situation that is addressed by the rollover advisor system. Based on 1995-2000 GES, the authors estimate that there are 84 crashes annually of tanker tractor-trailers turning or negotiating curves at excessive speed and 1,884 crashes annually of tractor-trailers of all types turning or negotiating a curve at excessive speed.

In this report, estimates of exposure ratio and Prevention Ratio are based on data from the FOT and additional simulations of near-rollover events. The Exposure Ratio is obtained directly from the FOT data. The value of Exposure Ratio is the rate of conflicts per 1000 VKMT for baseline trucks divided by the corresponding rate for trucks with the rollover advisor.

The authors of this paper use a combination of FOT data and baseline crash rate for the fleet of trucks in this FOT to estimate the Prevention Ratio. There are several steps and assumptions in this process. The first assumption is that the severity of a conflict can be measured by the relative increase in speed, from the actual speed of the conflict that would be needed to produce a rollover. The speed that will produce a rollover is determined by a combination of experimental measurements of the propensity to rollover and computer modeling of rollover dynamics during conflict situations. The second assumption is that the distribution of severity for all conflicts is Gaussian. The third assumption is that the variance for the distribution for each conflict, whether for baseline or system-on conditions, is the product of the square of the actual speed and a constant, σ_o^2. The value of σ_o^2 is determined by matching the probabilities of a crash for the conflicts of the baseline fleet with the historical crash experience of the fleet in the FOT. After determining the value of σ_o^2, the second step is to determine, for each conflict, the probability that the speed for that conflict will exceed the rollover threshold for the conflict. The average of this probability for all conflicts with the system is the numerator of the Prevention Ratio and the average of this probability for all baseline conflicts is the denominator.

Paper 13

Evaluation of an Automotive Rear-End Collision Avoidance System

Countermeasure for which the benefit is estimated:
Forward Collision Warning System with Adaptive Cruse Control.

The measure of benefits in this paper is the reduction in number of rear-end crashes. The authors identify rear-end, pre-crash scenarios where the host vehicle is closing in on a lead vehicle, which is stopped, moving at a slower constant speed, decelerating, or accelerating as relevant to ACAS. The evaluation process breaks the relevant pre-crash scenarios into four levels: low-intensity conflicts, high-intensity conflicts, low-intensity near-crashes, and high-intensity near-crashes. These levels are based on intensity of time-to-collision, headway (t_h) and range-rate. Estimation of effectiveness used data from the Automotive Collision Avoidance System (ACAS) FOT, which included driving data of 163,000 km by 66 test subjects.

Exposure Ratio is estimated by determining the reduction in number of near-crashes and conflicts per 100 km, when the ACAS system is enabled to when it is not available. The calculation of Prevention Ratio is effectiveness in reducing the probability of rear-end crashes is based on Monte Carlo simulation for each of the statistically significant pre-crash scenarios by using representative data of TTC, deceleration level by host and lead vehicle, and travel speed of the lead vehicle for both with and without the assistance of ACAS.

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APPENDIX B

Tables describing external factors like *speed, alignment, trafficway, and number of lanes* for each possible offending vehicle combination in a two-vehicle lane-departure-related crash

NO EXCESS SPEED

Straight										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	6,000	3,000	2,000	1,000	0	1,000	0	0	4,000	17,000
11-20	2,000	4,000	1,000	1,000	1,000	0	0	0	0	9,000
21-30	2,000	1,000	4,000	3,000	1,000	0	0	0	1,000	12,000
31-40	1,000	1,000	1,000	4,000	1,000	0	1,000	0	0	9,000
41-50	1,000	0	0	0	1,000	1,000	0	0	1,000	4,000
51-60	1,000	0	0	0	0	2,000	1,000	0	1,000	5,000
61-70	0	0	0	0	0	1,000	2,000	0	0	3,000
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	4,000	1,000	1,000	0	1,000	1,000	0	0	98,000	106,000
Total	**17,000**	**10,000**	**9,000**	**9,000**	**5,000**	**6,000**	**4,000**	**0**	**105,000**	**165,000**
Curve										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	1,000	0	0	0	0	0	0	0	0	1,000
11-20	0	0	0	0	0	0	0	0	0	0
21-30	0	1,000	0	0	0	0	0	0	0	1,000
31-40	0	0	0	1,000	0	0	0	0	0	1,000
41-50	0	0	0	0	1,000	0	0	0	0	1,000
51-60	0	0	0	0	0	1,000	0	0	0	1,000
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	7,000	7,000
Total	**1,000**	**1,000**	**0**	**1,000**	**1,000**	**1,000**	**0**	**0**	**7,000**	**12,000**
Unknown										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	1,000	1,000	0	2,000	0	0	0	0	1,000	5,000
11-20	0	1,000	1,000	1,000	0	0	0	0	0	3,000
21-30	1,000	0	1,000	0	0	0	0	0	0	2,000
31-40	0	0	0	1,000	0	0	0	0	0	1,000
41-50	0	0	0	0	1,000	1,000		0	0	2,000
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	1,000	0	0	1,000
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	2,000	0	0	1,000	0	0	0	0	27,000	30,000
Total	**4,000**	**2,000**	**2,000**	**5,000**	**1,000**	**1,000**	**1,000**	**0**	**28,000**	**44,000**
Grand total	**22,000**	**13,000**	**11,000**	**15,000**	**7,000**	**8,000**	**5,000**	**0**	**140,000**	**221,000**

Table B-1: Distribution of speed and road alignment for all two-vehicle lane-keeping/road-departure-related crashes with vehicles *"traveling in the same direction"* involving *"excursion on the left side of the roadway"* with *"no excessive speed."*

Straight										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	9,000	2,000	1,000	1,000	0	0	0	0	4,000	16,000
11-20	2,000	1,000	2,000	0	0	0	0	0	0	6,000
21-30	1,000	0	5,000	2,000	1,000	0	0	0	1,000	10,000
31-40	1,000	0	1,000	3,000	1,000	0	0	0	1,000	6,000
41-50	0	0	0	1,000	2,000	1,000	0	0	0	4,000
51-60	0	0	0	0	1,000	4,000	0	0	0	5,000
61-70	0	0	0	0	0	1,000	3,000	0	0	5,000
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	7,000	0	1,000	0	1,000	0	0	0	91,000	100,000
Total	**20,000**	**3,000**	**10,000**	**7,000**	**6,000**	**6,000**	**3,000**	**0**	**97,000**	**152,000**
Curve										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	1,000	0	0	0	0	0	0	0	0	1,000
11-20	0	0	1,000	0	0	0	0	0	0	1,000
21-30	0	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	8,000	8,000
Total	**1,000**	**0**	**1,000**	**0**	**0**	**0**	**0**	**0**	**8,000**	**10,000**
Unknown										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	2,000	1,000	0	0	0	0	0	0	1,000	4,000
11-20	1,000	1,000	0	0	0	0	0	0	0	2,000
21-30	0	0	1,000	0	0	0	0	0	0	1,000
31-40	0	0	1,000	2,000	0	0	0	0	0	3,000
41-50	0	0	0	0	1,000	0	0	0	0	1,000
51-60	0	0	0	0	0	1,000	0	0	0	1,000
61-70	0	0	0	0	0	0	0	0	1,000	1,000
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	2,000	0	0	1,000	0	0	0	0	28,000	31,000
Total	**5,000**	**2,000**	**2,000**	**3,000**	**1,000**	**1,000**	**0**	**0**	**30,000**	**44,000**
Grand total	**26,000**	**5,000**	**13,000**	**10,000**	**7,000**	**7,000**	**3,000**	**0**	**135,000**	**206,000**

Table B-2: Distribution of speed and road alignment for all two-vehicle lane-keeping/road-departure-related crashes with vehicles *"traveling in the same direction"* involving *"excursion on the right side of the roadway"* with *"no excessive speed.*

Straight										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0	0
21-30	0	0	1,000	0	0	0	0	0	1,000	0
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	1,000	0	0	0	0	1,000	0
51-60	0	0	0	0	1,000	0	0	0	1,000	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	2,000	2,000	0
Total	**0**	**0**	**1,000**	**1,000**	**1,000**	**0**	**0**	**2,000**	**5,000**	**0**
Curve										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	1,000	1,000	0	0	0	0	0	0	0	2,000
21-30	0	1,000	1,000	0	0	0	0	0		2,000
31-40	0	1,000	0	1,000	0	0	0	0	1,000	3,000
41-50	0	0	0	1,000	1,000	0	0	0	0	2,000
51-60	0	0	0	0	0	1,000	0	0	0	1,000
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	18,000	18,000
Total	**1,000**	**3,000**	**1,000**	**2,000**	**1,000**	**1,000**	**0**	**0**	**19,000**	**28,000**
Unknown										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	1,000	0	0	0	0	0	0	0	0	1,000
11-20	0	0	1,000	0	0	0	0	0	0	1,000
21-30	0	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	6,000	6,000
Total	**1,000**	**0**	**1,000**	**0**	**0**	**0**	**0**	**0**	**6,000**	**8,000**
Grand total	**6,000**	**4,000**	**3,000**	**5,000**	**5,000**	**3,000**	**0**	**0**	**51,000**	**77,000**

Table B-3: Distribution of speed and road alignment for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the opposite direction*" involving "*excursion on the left side of the roadway*" with "*no excessive speed.*"

EXCESS SPEED

Straight									
Speed	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0
21-30	0	0	1,000	0	0	0	0	0	1,000
31-40	0	0	0	0	0	0	0	0	0
41-50	0	0	0	1,000	0	0	0	0	1,000
51-60	0	0	0	0	1,000	0	0	0	1,000
61-70	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	2,000	2,000
Total	**0**	**0**	**1,000**	**1,000**	**1,000**	**0**	**0**	**2,000**	**5,000**
Curve									
Speed	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0
21-30	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	1,000	1,000
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,000**	**1,000**
Unknown									
Speed	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10		0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0
21-30	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,000**	**1,000**
Grand total	**0**	**0**	**1,000**	**1,000**	**1,000**	**0**	**0**	**4,000**	**7,000**

Table B-4: Distribution of speed and road alignment for all two-vehicle lane-keeping/road-departure-related crashes with vehicles *"traveling in the same direction"* involving *"excursion on the right side of the roadway"* with *"excessive speed."*

Straight									
	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0
21-30	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0
41-50	0	0	0	1,000	0	0	0	0	1000
51-60	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0
Unknown	0	0	1,000	0	0	0	0	1,000	2,000
Total	**0**	**0**	**1,000**	**1,000**	**0**	**0**	**0**	**1,000**	**3,000**
Curve									
	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0
21-30	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	1,000	1,000
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,000**	**1,000**
Unknown									
	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	**0**
11-20	0	0	0	0	0	0	0	0	**0**
21-30	0	0	0	0	0	0	0	0	**0**
31-40	0	0	0	0	0	0	0	0	**0**
41-50	0	0	0	0	0	0	0	0	**0**
51-60	0	0	0	0	0	0	0	0	**0**
61-70	0	0	0	0	0	0	0	0	**0**
Greater Than 70	0	0	0	0	0	0	0	0	**0**
Unknown	0	0	0	0	0	0	0	0	**0**
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,000**	**1,000**
Grand total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3,000**	**5,000**

Table B-5: Distribution of speed and road alignment for all two-vehicle lane-keeping/road-departure-related crashes with vehicles *"traveling in the same direction"* involving *"excursion on the left side of the roadway"* with *"excessive speed."*

Straight										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	1,000	0	0	0	0	0	0	0	0	1,000
21-30	0	1,000	0	1,000	0	0	0	0	0	2,000
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	5,000	5,000
Total	**1,000**	**1,000**	**0**	**1,000**	**0**	**0**	**0**	**0**	**5,000**	**8,000**
Curve										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	1,000	0	0	0	0	0	0	0	0	1,000
11-20	0	0	1,000	0	0	0	0	0	0	1,000
21-30	0	1,000	1,000	0	0	0	0	0	0	2,000
31-40	0	0	0	0	0	0	0	0	0	
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	7,000	7,000
Total	**1,000**	**1,000**	**2,000**	**0**	**0**	**0**	**0**	**0**	**7,000**	**11,000**
Unknown										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0	0
21-30	0	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	1,000	1,000
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,000**	**1,000**
Grand total	**3,000**	**2,000**	**1,000**	**1,000**	**1,000**	**0**	**0**	**0**	**12,000**	**20,000**

Table B-6: Distribution of speed and road alignment for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the opposite direction*" involving "*excursion on the left side of the roadway*" with "*excessive speed.*"

BOTH VEHICLES IN OPPOSITE DIRECTION

Straight										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0	0
21-30		0	0	1,000	0	0	0	0	0	1,000
31-40	0	0	0	1,000	0	0	0	0	0	1,000
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	1,000	0	0	1,000
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	5,000	5,000
Total	**0**	**0**	**0**	**2,000**	**0**	**0**	**1,000**	**0**	**5,000**	**8,000**
Curve										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	0	0	1,000	0	0	0	0	0	0	1,000
21-30	0	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	1,000	1,000
Total	**0**	**0**	**1,000**	**0**	**0**	**0**	**0**	**0**	**1,000**	**2,000**
Unknown										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0	0
21-30	0	0	1,000	0	0	0	0	0	0	1,000
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	2,000	2,000
Total	**0**	**0**	**1,000**	**0**	**0**	**0**	**0**	**0**	**2,000**	**3,000**
Grand total	**0**	**0**	**2,000**	**2,000**	**0**	**0**	**1,000**	**0**	**8,000**	**13,000**

Table B-7: Distribution of speed and road alignment for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the same direction*" involving "*excursion on the left /right side of the roadway*" with "*other vehicle also encroaching the lane.*"

Straight										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	1,000	0	0	0	0	0	0	0	1,000
11-20	0	0	0	0	0	0	0	0	0	0
21-30	0	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	3,000	3,000
Total	**0**	**1,000**	**0**	**0**	**0**	**0**	**0**	**0**	**3,000**	**4,000**
Curve										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0	0
21-30	0	0	1,000	0	0	0	0	0	0	1,000
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	1,000	1,000
Total	**0**	**0**	**1,000**	**0**	**0**	**0**	**0**	**0**	**1,000**	**2,000**
Unknown										
Speed	0-10	11-20	21-30	31-40	41-50	51-60	61-70	Greater Than 70	Unknown	Total
0-10	0	0	0	0	0	0	0	0	0	0
11-20	0	0	0	0	0	0	0	0	0	0
21-30	0	0	0	0	0	0	0	0	0	0
31-40	0	0	0	0	0	0	0	0	0	0
41-50	0	0	0	0	0	0	0	0	0	0
51-60	0	0	0	0	0	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
Greater Than 70	0	0	0	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	1,000	1,000
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,000**	**1,000**
Grand total	**0**	**1,000**	**1,000**	**0**	**0**	**0**	**0**	**0**	**5,000**	**7,000**

Table B-8: Distribution of speed and road alignment for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the opposite direction*" involving "*excursion on the left side of the roadway*" with "*other vehicle also encroaching the lane.*"

Trafficway / No. of Lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided traffic-way	One-way traffic	Unknown	Grand Total
1	0	0	0	1,000	0	1,000
2	0	30,000	26,000	9,000	3,000	68,000
3	2,000	9,000	24,000	7,000	2,000	44,000
4	1,000	16,000	14,000	6,000	1,000	38,000
5	7,000	11,000	5,000	0	0	23,000
6	0	2,000	1,000	0	0	3,000
7 or more	1,000	1,000	0	0	0	2,000
9	1,000	8,000	6,000	2,000	25,000	42,000
Total	**12,000**	**77,000**	**76,000**	**25,000**	**31,000**	**221,000**

Table B-9: Distribution of trafficway and number of lanes for all two-vehicle lane-keeping/road-departure-related crashes with vehicles *"traveling in the same direction"* involving *"excursion on the left side of the roadway"* with *"no excessive speed."*

Trafficway / No. of Lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One-way traffic	Unknown	Grand Total
1	0	0	0	0	0	0
2	0	24,000	25,000	4,000	1,000	54,000
3	1,000	7,000	23,000	3,000	2,000	36,000
4	0	21,000	13,000	1,000	1,000	36,000
5	9,000	9,000	5,000	0	1,000	24,000
6	0	3,000	2,000	0	0	5,000
7 or more	1,000	1,000	0	0	0	2,000
9	1,000	11,000	5,000	1,000	31,000	49,000
Total	**12,000**	**76,000**	**73,000**	**9,000**	**36,000**	**206,000**

Table B-10: Distribution of trafficway and number of lanes for all two-vehicle lane-keeping/road-departure-related crashes with vehicles *"traveling in the same direction"* involving *"excursion on the right side of the roadway"* with *"no excessive speed."*

Trafficway / No. of Lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided traffic-way	Unknown	Grand Total
1	0	0	0	0	0
2	0	55,000	2,000	1,000	58,000
3	1,000	1,000	1,000	0	3,000
4	0	3,000	1,000	0	4,000
5	1,000	2,000	0	0	3,000
6	0	0	0	0	0
7 or more	0	1,000	0	0	1,000
9	0	5,000	0	3,000	8,000
Total	**2,000**	**67,000**	**4,000**	**4,000**	**77,000**

Table B-11: Distribution of trafficway and number of lanes for all two-vehicle lane-keeping/road-departure-related crashes with vehicles *"traveling in the opposite direction"* involving *"excursion on the left side of the roadway"* with *"no excessive speed."*

Trafficway / No. of Lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One-way traffic	Unknown	Grand Total
1	0	0	0	0	0	0
2	0	1,000	2,000	0	0	3,000
3	0	0	2,000	0	0	2,000
4	0	1,000	2,000	0	0	3,000
5	0	0	0	0	0	0
9	0	0	0	0	0	0
Grand Total	**0**	**2,000**	**6,000**	**0**	**0**	**8,000**

Table B-12: Distribution of trafficway and number of lanes for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the same direction*" involving "*excursion on the right side of the roadway*" with "*excessive speed.*"

Trafficway / No. of Lanes	Not physically divided (two-way traffic)	Divided trafficway	One way traffic	Unknown	Grand Total
1					
2	1,000	1,000	0	0	2,000
3	0	2,000	0	0	2,000
4	0	1,000	0	0	1,000
5	0	0	0	0	0
6	0	0	0	0	0
9	0	0	0	0	0
Grand Total	**1,000**	**4,000**	**0**	**0**	**5,000**

Table B-13: Distribution of trafficway and number of lanes for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the same direction*" involving "*excursion on the left side of the roadway*" with "*excessive speed.*"

Trafficway / No. of Lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One way traffic	Unknown	Grand Total
1	0	0	0	0	0	0
2	0	14,000	1,000	0	0	15,000
3	0	0	0	0	0	0
4	0	1,000	0	0	0	1,000
5	1,000	0	1,000	0	0	2,000
6	0	0	0	0	0	0
9	0	1,000	0	0	1,000	2,000
Grand Total	**1,000**	**16,000**	**2,000**	**0**	**1,000**	**20,000**

Table B-14: Distribution of trafficway and number of lanes for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the opposite direction*" involving "*excursion on the left side of the roadway*" with "*excessive speed.*"

Trafficway / No. of Lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One way traffic	Unknown	Grand Total
1	0	0	0	0	0	0
2	0	2,000	2,000	0	0	4,000
3	0	0	2,000	0	0	2,000
4	0	1,000	1,000	0	0	2,000
5	0	0	1,000	0	0	1,000
7 or more	0	0	0	0	0	0
9	0	1,000	0	0	3,000	4,000
Grand Total	**0**	**4,000**	**6,000**	**0**	**3,000**	**13,000**

Table B-15: Distribution of trafficway and number of lanes for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the same direction*" involving "*excursion on the left/right side of the roadway*" with "*other vehicle also encroaching the lane.*"

Trafficway / No. of Lanes	Not physically divided (two-way traffic)	Divided trafficway	Unknown	Grand Total
2	5,000	0	0	5,000
4	0	0	0	0
5	0	0	0	0
9	1,000	0	1,000	2,000
Grand Total	6,000	0	1,000	**7,000**

Table B-16: Distribution of trafficway and number of lanes for all two-vehicle lane-keeping/road-departure-related crashes with vehicles "*traveling in the opposite direction*" involving "*excursion on the left of the roadway*" with "*other vehicle also encroaching the lane.*"

Due to the presence of many unknowns for travel speed in GES data for multivehicle crashes, other approaches for determining travel speed could be derived. One such method is by correlating travel speed with speed limits to provide a suitable model that represents travel speeds.

APPENDIX C

Tables describing external factors like *speed, alignment, traffic-way and number of lanes* for each possible offending vehicle combination in a single-vehicle-lane-departure-related crash

Category A

Alignment / Speed	Straight	Curve	Unknown	Grand Total
0-10	1,000	1,000	0	2,000
11-20	3,000	3,000	0	6,000
21-30	6,000	8,000	1,000	15,000
31-40	13,000	14,000	3,000	30,000
41-50	14,000	16,000	3,000	33,000
51-60	11,000	12,000	2,000	25,000
61-70	8,000	5,000	2,000	15,000
Greater Than 70	3,000	3,000	1,000	7,000
Unknown	80,000	76,000	32,000	188,000
Total	139,000	138,000	44,000	**321,000**

Traffic Flow / No. of lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One way traffic	Unknown	Grand Total
1	0	0	2,000	11,000	0	13,000
2	0	155,000	52,000	5,000	3,000	215,000
3	1,000	3,000	20,000	1,000	1,000	26,000
4	0	6,000	7,000	0	0	13,000
5	1,000	3,000	1,000	0	0	5,000
6	0	1,000	0	0	0	1,000
7 or more	0	0	0	0	0	0
Unknown	0	17,000	5,000	2,000	24,000	48,000
Total	3,000	185,000	87,000	19,000	28,000	**321,000**

Table C-1: Summary of external factors for all single-vehicle lane-keeping/road-departure-related crashes when the critical event was "excessive speed."

Category B

Alignment / Speed	Straight	Curve	Unknown	Grand Total
0-10	5,000	0	0	5,000
11-20	4,000	1,000	2,000	7,000
21-30	4,000	2,000	2,000	8,000
31-40	2,000	1,000	1,000	4,000
41-50	1,000	0	0	1,000
51-60	0	1,000	0	1,000
61-70	2,000	0	1,000	3,000
Greater than 70	0	0	0	0
Unknown	71,000	9,000	20,000	100,000
Total	88,000	13,000	28,000	**129,000**

Traffic Flow / No. of lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided traffic way	One way traffic	Unknown	Grand Total
1	0	1,000	1,000	2,000	0	4,000
2	0	59,000	5,000	1,000	3,000	68,000
3	0	1,000	2,000	1,000	0	4,000
4	0	2,000	2,000	0	1,000	5,000
5	0	1,000	1,000	0	1,000	3,000
6	0	0	0	0	0	0
7 or more	0	0	0	0	0	0
Unknown	1,000	13,000	1,000	1,000	29,000	45,000
Total	1,000	76,000	12,000	5,000	35,000	**129,000**

Table C-2: Summary of external factors for all single-vehicle lane-keeping/road-departure-related crashes when the critical event was "this vehicle over the lane line."

Category C

Alignment / Speed	Straight	Curve	Unknown	Grand Total
0-10	6,000	1,000	3,000	10,000
11-20	7,000	2,000	2,000	11,000
21-30	12,000	6,000	2,000	20,000
31-40	17,000	11,000	3,000	31,000
41-50	17,000	10,000	4,000	31,000
51-60	17,000	9,000	2,000	28,000
61-70	9,000	5,000	3,000	17,000
Greater Than 70	2,000	2,000	1,000	5,000
Unknown	113,000	61,000	49,000	223,000
Total	200,000	108,000	69,000	**376,000**

Traffic Flow / No. of lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One-way traffic	Unknown	Grand Total
1	0	2,000	2,000	8,000	0	12,000
2	0	187,000	45,000	4,000	6,000	242,000
3	2,000	5,000	13,000	2,000	0	22,000
4	0	9,000	7,000	0	0	16,000
5	4,000	4,000	3,000	0	1,000	12,000
6	0	0	0	0	0	0
7 or More	0	0	0	0	0	0
Unknown	1,000	27,000	5,000	1,000	38,000	72,000
Total	7,000	235,000	75,000	15,000	44,000	**376,000**

Table C-3: Summary of external factors for all single-vehicle lane-keeping/road-departure-related crashes when the critical event was "this vehicle off the edge of the road."

Category D

Alignment / Speed	Straight	Curve	Unknown	Grand Total
0-10	0	0	0	0
11-20	1,000	0	0	1,000
21-30	2,000	1,000	0	3,000
31-40	1,000	0	1,000	2,000
41-50	1,000	0	1,000	2,000
51-60	3,000	0	0	3,000
61-70	1,000	0	0	1,000
Greater Than 70	0	0	0	0
Unknown	11,000	3,000	4,000	18,000
Total	20,000	4,000	6,000	**30,000**

Traffic Flow / No. of lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One way traffic	Unknown	Grand Total
1	0	0	0	1,000	0	1,000
2	0	13,000	5,000	0	1,000	19,000
3	0	0	3,000	0	0	3,000
4	0	1,000	1,000	0	0	2,000
5	0	0	1,000	0	0	1,000
6	0	0	0	0	0	0
7 or more	0	0	0	0	0	0
Unknown	0	1,000	1,000	0	2,000	4,000
Total	0	15,000	10,000	1,000	3,000	**30,000**

Table C-4: Summary of external factors for all single-vehicle lane-keeping/road-departure-related crashes when the critical event was "other vehicle in-lane movement."

Category E

Alignment / Speed	Straight	Curve	Unknown	Grand Total
0-10	0	0	0	0
11-20	1,000	0	0	1,000
21-30	2,000	1,000	0	3,000
31-40	2,000	1,000	1,000	4,000
41-50	2,000	1,000	1,000	4,000
51-60	4,000	1,000	2,000	7,000
61-70	5,000	1,000	1,000	7,000
Greater Than 70	1,000	0	0	1,000
Unknown	21,000	9,000	6,000	36,000
Total	38,000	14,000	11,000	**63,000**

Traffic Flow / No. of lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One-way traffic	Unknown	Grand Total
1	0	0	0	1,000	0	1,000
2	0	22,000	10,000	1,000	1,000	34,000
3	0	1,000	8,000	0	0	9,000
4	0	2,000	3,000	0	0	5,000
5	1,000	1,000	2,000	0	0	4,000
6	0	0	1,000	0	0	1,000
7 or more	0	0	0	0	0	0
Unknown	0	2,000	2,000	1,000	4,000	9,000
Total	1,000	28,000	26,000	3,000	5,000	**63,000**

Table C-5: Summary of external factors for all single-vehicle- lane-keeping/road-departure-related crashes when the critical event was "Other vehicle encroaching into lane."

Category F

Alignment / Speed	Straight	Curve	Unknown	Grand Total
0-10	1,000	0	0	1,000
11-20	1,000	0	0	1,000
21-30	1,000	1,000	0	2,000
31-40	3,000	1,000	0	4,000
41-50	4,000	2,000	2,000	8,000
51-60	3,000	1,000	1,000	5,000
61-70	2,000	0	1,000	3,000
Greater Than 70	0	0	0	0
Unknown	20,000	8,000	6,000	34,000
Total	35,000	13,000	10,000	**58,000**

Traffic Flow / No. of lanes	Not physically divided (center two-way left turn)	Not physically divided (two-way traffic)	Divided trafficway	One-way traffic	Unknown	Grand Total
1	0	0	0	0	0	0
2	0	33,000	6,000	0	1,000	40,000
3	0	1,000	1,000	0	0	2,000
4	0	0	1,000	0	0	1,000
5	0	1,000	1,000	0	0	2,000
6	0	0	0	0	0	0
7 or more	0	0	0	0	0	0
Unknown	0	4,000	1,000	0	8,000	13,000
Total	0	39,000	10,000	0	9,000	**58,000**

Table C-6: Summary of external factors for all single-vehicle lane-keeping/road-departure-related crashes when the critical event was "Pedestrian/Pedalcyclist/Animal/Object."

Due to the presence of many unknowns for travel speed in GES data for multivehicle crashes, other approaches for determining travel speed could be derived. One such method is by correlating travel speed with speed limits to provide a suitable model that represents travel speeds.

APPENDIX D

The objective of this analysis is to determine the approach angle with respect to the lane line. The analysis uses data from a recent naturalistic driving study.[12] This study provides details on 200,000 vehicle miles of travel. The data was generated by 241 participants driving for 43,000 hours over a span of 23 months.

There are 828 event files in the data base used for this analysis. Each event is a *Crash* or a *Near-Crash*. Of these, 762 files were *Near-Crashes*. Each file includes real time video of five views: frontal, rear, left side, right side, and driver's hand position; variables such as lane offset, lane width, delta time frame, vehicle speed, lateral and longitudinal acceleration.

The process of estimation of the approach angle involves identification of relevant variables and their denotation. The following variables were identified and used:

Lane offset, X (in): Distance between vehicle's longitudinal center and the lane center.
Delta Frame, δt (Sec): Time increment between current step and preceding step of data collection.
Lane Width, W (in): Lateral distance across current lane.
Vehicle Speed, V (mph): Vehicle travel speed.

Figure D-1 shows the signature of offset in inches, during a right-to-left and left-to-right lane change maneuver. In these two examples the Right-to-left lane change took about 5 seconds while left-to-right lane change took 3.5 seconds.

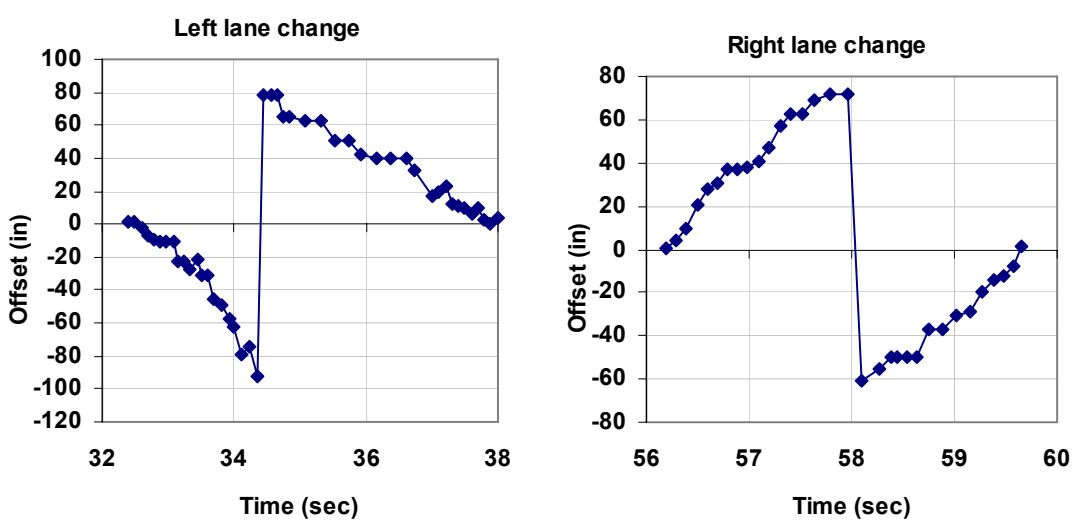

Figure D-1: Offset channel signature during a lane change maneuver.

Once the variables and their values are established, the approach angle is calculated:
where

The approach angle is:

$$\theta = Sin^{-1}\left(\frac{V_L}{V}\right)$$

where V_L is the estimated lateral velocity of the vehicle and V is the vehicle travel speed. The angle θ is determined for each time frame by substituting values for V_L and V. If the vehicle's longitudinal center line is in the left of the lane center then the offset has a negative value while it has a positive value on the right side.

Estimation of lateral velocity at each step uses the expression:

$$V_L = \frac{X_n - X_{n-1}}{\delta t_n}$$

where n is the frame number. These relationships are summarized in Figure D-2.

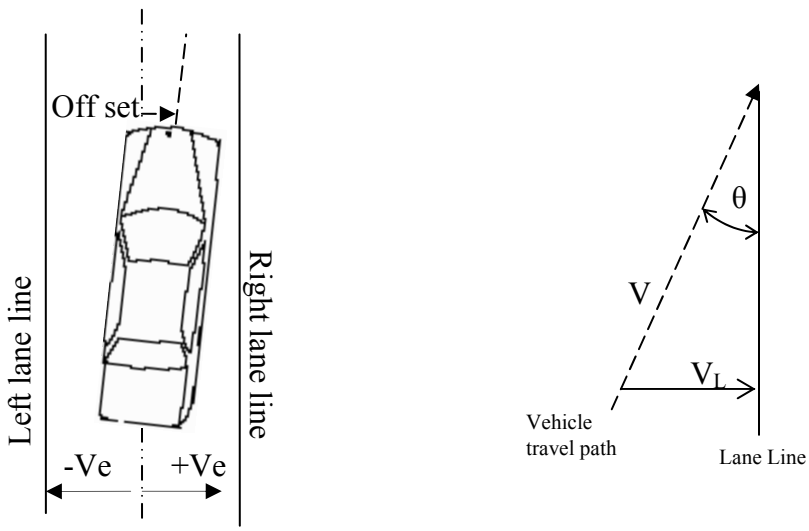

Figure D-2: Offset, and angle of approach θ

The time at which the vehicle crosses the lane, T_{lc}, is the time when $Offset + \frac{1}{2} car\ width \geq \frac{1}{2} lane\ width$. The approach angle θ at this instant is the vehicle's approach angle at the lane change event.

First step in locating a lane change maneuver is to find the offset signature shown in Figure D-1. Next, calculate the value $Offset + 1/2(car\ width)$ for each time step till it becomes equal or greater than the value $1/2(lane\ width)$, from the beginning to the offset signature. Finally, at this juncture calculate the value of the angle θ, which is the approach angle for this lane change maneuver, θ_{lc}.

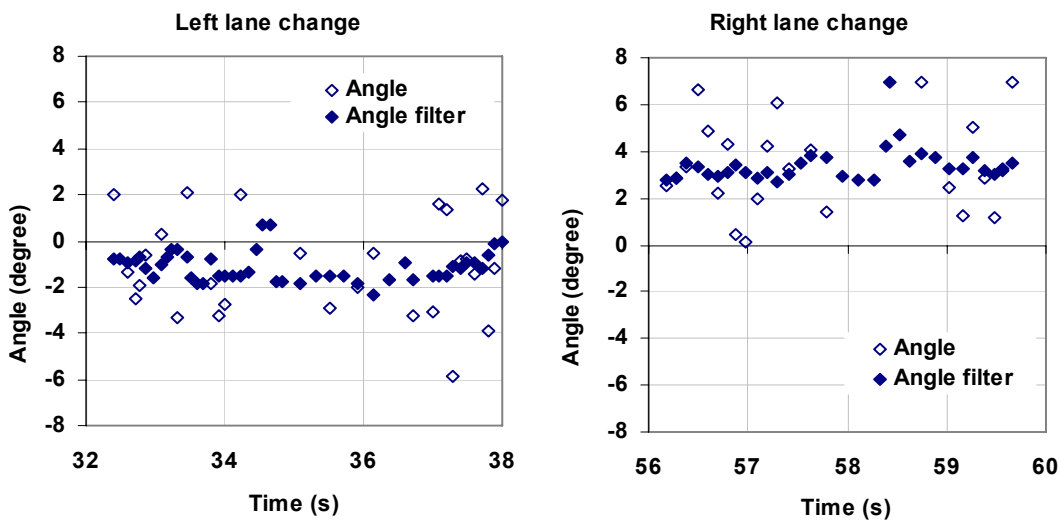

Figure D-3: Estimated angle θ

Figure D-3 shows the estimated values of θ for the same two examples in Figure D-1. An eight point moving average filter is used to reduce the noise in the data collection/calculation process. The filtered value of θ is also shown in the Figure D-3 and is used in estimating the value for θ_{lc}

The lane change signature described in Figure D-1 was applied to the data in each of the 762 near crashes. A total of 223 lane change maneuvers were identified by the algorithm. These selected lane change maneuvers had a minimum speed of 10 mph. Distribution of road alignment and road type is shown in Table D-1. Of 223 lane changes, 30 were completed on curved roads while the rest were completed on straight roads. Fifty-three of the lane changes took place on undivided trafficways, of which 19 had only two lanes.

Number of lane changes		Road alignment				
Traffic_Flow	# of Travel Lanes	Curve Grade	Curve level	Straight grade	Straight level	Grand Total
Divided (median strip or barrier)	1		3		3	6
	2		5	4	37	46
	3	1	10	7	68	86
	4				27	27
	5		2		2	4
Not divided	2		2	1	16	19
	3		4		9	13
	4		1		9	10
	5				6	6
	6				1	1
One-way traffic	1	1	1		1	3
	2				1	1
	4				1	1
Grand Total		2	28	12	181	223

Table D-1: Distribution of road alignment and road type

Figures D-4 to D-9 give the distribution of absolute value of lane change angles for velocities 10-20, 20-30, 30-40, 40-50, 50-60, and 60 or greater mph. The plots also include cumulative distribution of lane change angles.

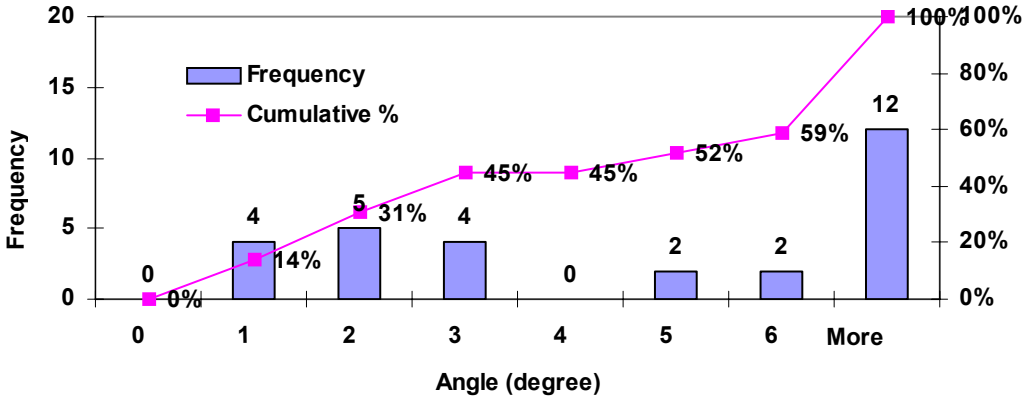

Figure D-4: Distribution of lane change angles for velocities between 10 and 20 mph.

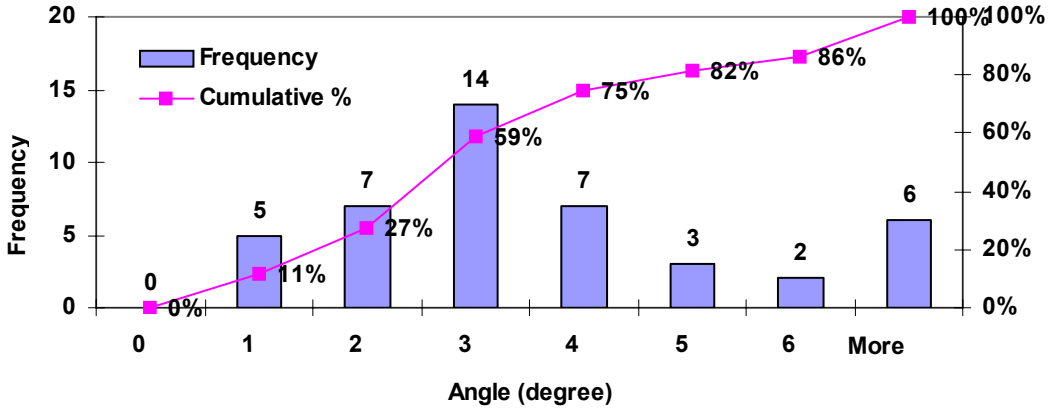

Figure D-5: Distribution of lane change angles for velocities between 20 and 30 mph

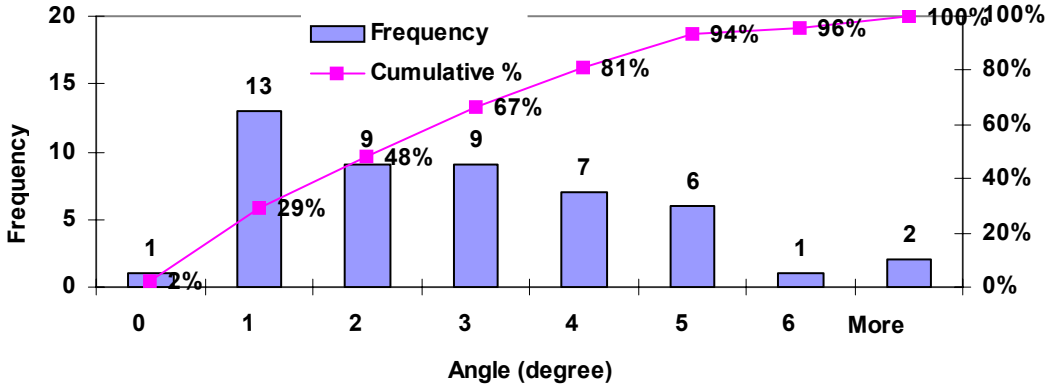

Figure D-6: Distribution of lane change angles for velocities between 30 and 40 mph

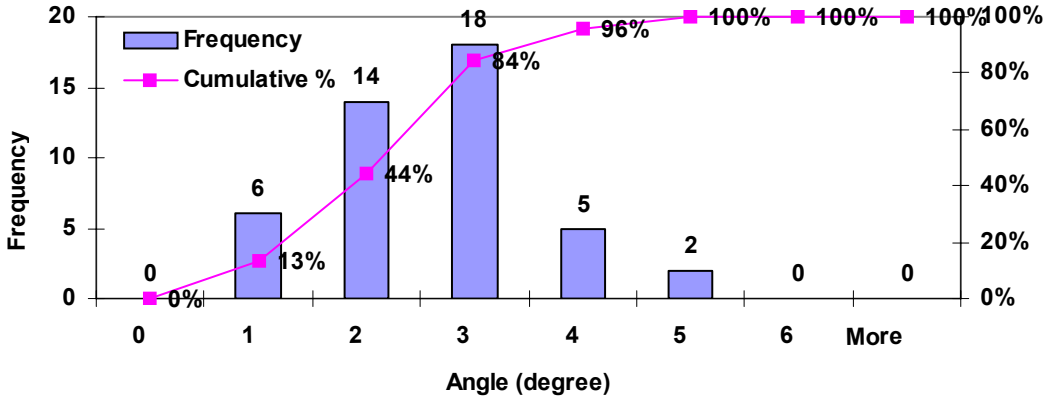

Figure D-7: Distribution of lane change angles for velocities between 40 and 50 mph

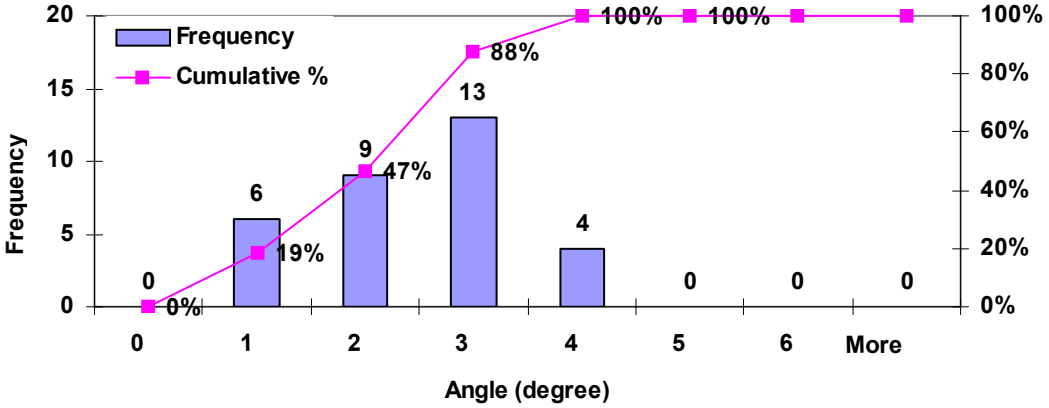

Figure D-8: Distribution of lane change angles for velocities between 50 and 60 mph

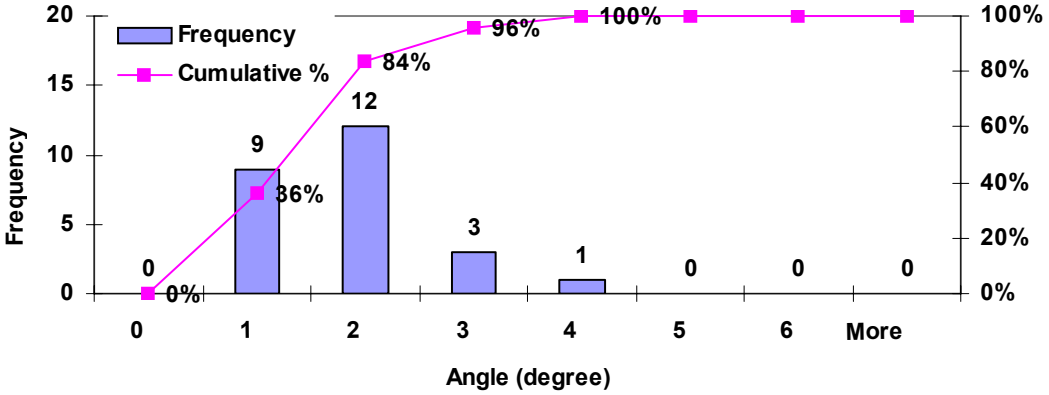

Figure D-9: Distribution of lane change angles for velocities greater than 60 mph

Summary

As expected, the magnitude of lane change angles decrease with the increase in vehicle velocities. This can be seen in the summary shown in Figure D-10. From this figure it is seen that at higher speeds (greater than 50 mph), there are essentially no events with a lane change angle greater than 3 degree. This leads to the conclusion that 3 degree is an appropriate approach angle for testing lane-keeping and road departure systems.

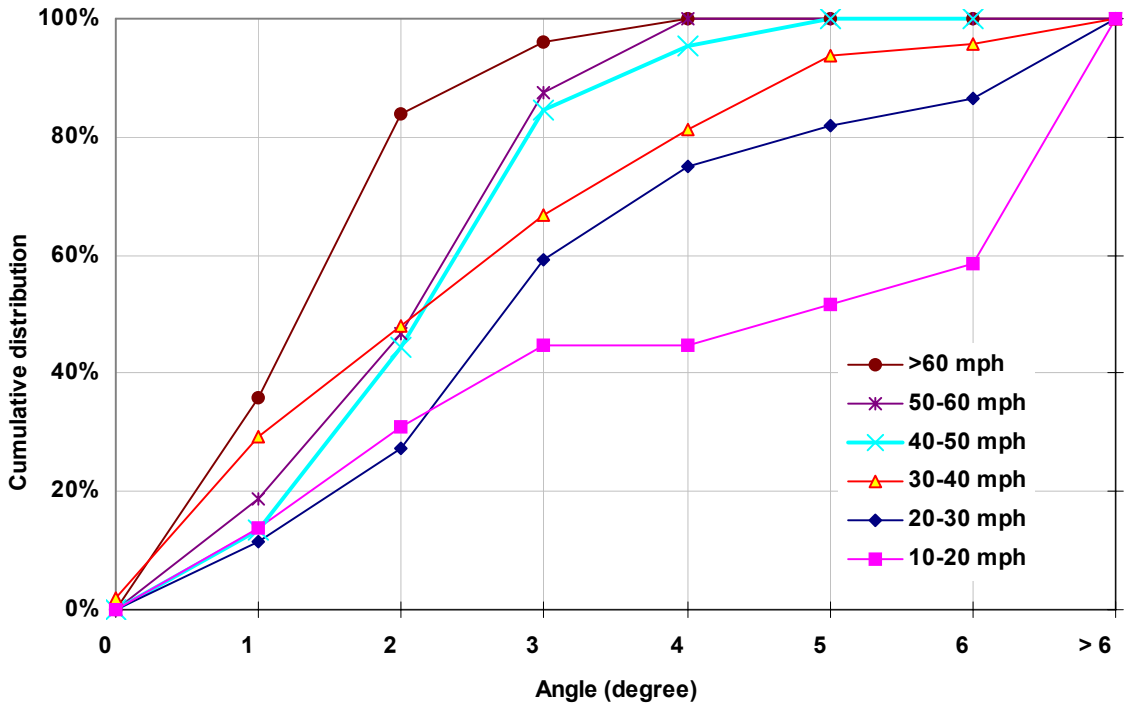

Figure D-10: Cumulative distributions of approach angles during a lane change maneuver.

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