AN EMPIRICALLY BASED PROCESS FOR ESTIMATING SAFETY BENEFITS

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ABSTRACT

The advent of new crash prevention technologies has made it necessary to develop new methodologies capable of estimating safety benefits before they are introduced in the market. This paper describes the development of one such empirically based methodology for estimating safety benefits.

The developed methodology uses detailed engineering descriptions of the crash prevention system performance, in conjunction with a universal description of crash causal factors and resulting relevant crash types. This study also establishes objective tests to evaluate systems; a brake-assist system is used to describe the process.

Crash data files such as the General Estimate System (GES) and the Fatality Analysis Reporting System (FARS) are used to develop Measures of Performance (MOP) and are used as the basis for objective tests. Naturalistic driving data are used to estimate Exposure Ratio and to refine elements of the objective tests. Finally data from the objective tests are used to estimate benefits of the crash prevention system.

The process developed here has not been applied to a specific system. For that reason a hypothetical system is used as an example to demonstrate the data processing required to convert test outcomes to number of crashes that would be prevented. A generic brake-assist system is used as an example. This hypothetical example suggests that such a system could prevent 50% of rear-end crashes in which the following vehicle brakes to avoid crashing into a decelerating lead vehicle.

The new process developed here has not been applied at this time. Challenges that will arise during application are not addressed in detail in this paper.

INTRODUCTION

In 2004, more than 10 million drivers were involved in a police-reported-crash. Each of these crashes began with a critical event, defined as a causal factor of the crash. The drivers who were confronted with these events responded by braking, steering or both; or by taking no action. The distribution of critical events and driver responses from the 2004 GES [1] are shown in Tables 1 and 2, respectively. It is the combination of critical event and driver response that occasionally (one crash for every 450,000 miles of travel) results in a crash.

A basic foundation for assessments of crash avoidance systems is the distribution of these critical events for each crash related vehicle and driver responses associated with crashes.

Table 1
Distribution of critical events for all vehicles involved in crashes (rounded to nearest thousands)

Critical Event	Total
Subject vehicle loss of control	671,000
Action by subject vehicle	3,082,000
Action by another vehicle in subject vehicle‘s lane	4,114,000
Encroachment by another vehicle in subject vehicle’s lane	2,510,000
Pedestrian and other non-motorist	113,000
Object or animal	455,000
Total	**10,945,000**

The complete timeline of the chain of events for each vehicle in the GES file (critical event, driver response, first harmful event) is summarized in Table 3. This Universal Description provides a high-level, but complete, picture of each vehicle experience. A focused analysis of the underlying details of the Universal Description provides a solid foundation for developing test procedures and

estimating benefits for either crashworthiness or crash avoidance systems.

Table 2.
Distribution of avoidance maneuvers for all vehicles involved in crashes (rounded to nearest thousands)

Avoidance maneuver	Total
No maneuver	7,684,000
Braking	1,753,000
Steering	1,220,000
Braking and steering	221,000
Accelerating/Others	67,000
Total	**10,945,000**

This paper is derived from the report "A Process for Estimating Safety Benefits for Pre-production Driver Assistance Systems"[2]. This paper summarizes sections from this reference that address the basic process, the benefits estimation process, objective tests and conversion from Measure of Performance to Measure of Effectiveness. The latter section includes an example of assessment of a hypothetical Brake-Assist system.

THE BASIC PROCESS

The methodology for estimating the expected effectiveness of driver assistance systems before they are brought to the market combines the statistical descriptions from representative data files (both crash files and naturalistic driving files) and the engineering description of system performance. For each system that is studied, there will be a series of activities. The diagram in Figure 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 leftmost rectangle in the diagram. The intermediate steps or activities create a database that is then used in the final activity to estimate the safety benefits (reductions in the number of crashes, injuries and fatalities)
As the sequence of activities progresses it may be beneficial to use output from an activity as a basis for revisiting an earlier activity.

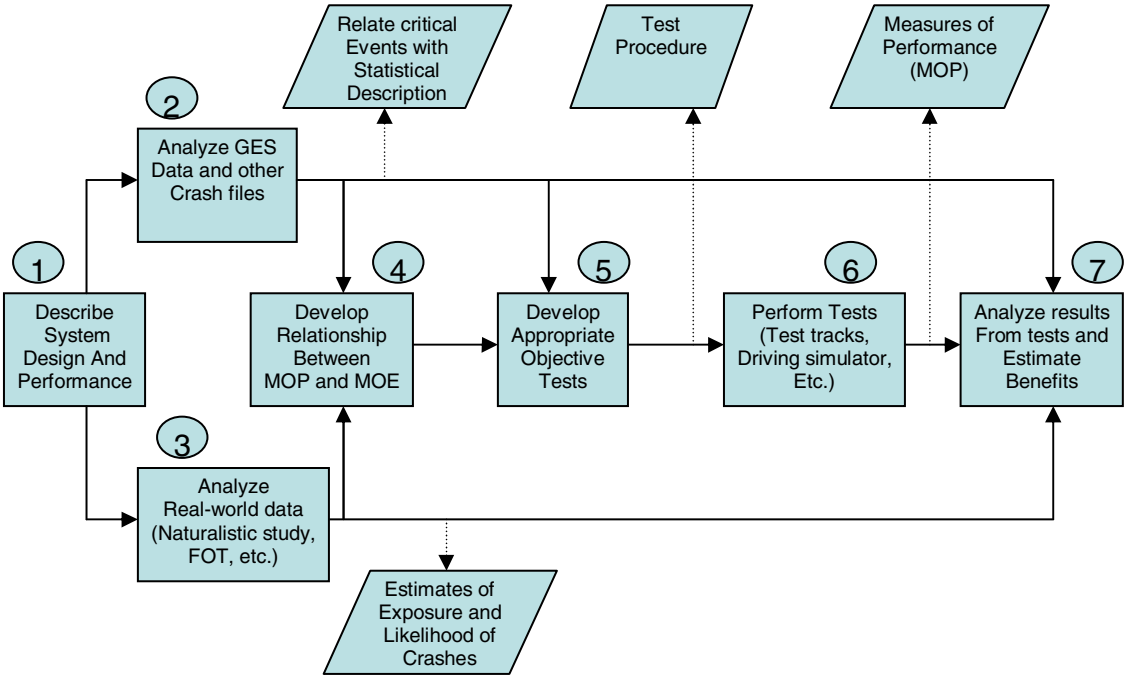

Figure 1. Process for assessing the safety impact of driver assistance systems.

Table 3.
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) (rounded to nearest thousands)

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 non-motorist	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**

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.

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 events shown in Table 3, and includes defining the relevant crash problem size.

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

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 in exposure rate that are provided by the system. As seen in the next section on the benefits estimation process, the exposure ratio is a key component of the benefits estimation process

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 situation that a driver faces, this performance determines whether or not a crash occurs. 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 situations 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 summarized in the next section are the Exposure Ratio and the Prevention Ratio[3]. The Exposure Ratio is the ratio between rate of exposure (the rate at which drivers encounter a specific risky situation) with the system and the rate of exposure to the same situation without the system. Similarly, the Prevention Ratio is the ratio between the probability of having a crash in the specific situation with the system and the probability of having a crash without the system in the same specific situation. A major link in the benefits estimation process is the connection of objective test results to estimates of Prevention Ratio or Exposure Ratio.

Activity 5. Develop Appropriate Objective Tests

In this activity, test conditions for the system are developed. This activity is tightly coupled with Activity 2; and in practice, these two activities will probably be done simultaneously.

Activity 6. Perform tests

In this activity, the tests developed in Activity 5 will be performed. These tests will be run on test tracks, driving simulators or in other laboratory environments. The outcomes from these tests will include the Measures of Performance that are identified in Activity 4.

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 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.

BENEFITS ESTIMATION PROCESS

The central step in the process for estimating safety benefits is the actual calculation of estimated benefits. This step combines results from the objective tests with crash data (example. GES) and other data to produce the estimates. Although there are many formulations, they all are based on the fundamental definition of benefits[4]:

$$B = N_{WO} - N_W \quad (1)$$

Where,
B = benefits, (can be number of crashes, number of fatalities, "harm," or other such measures.)
N_{wo} = value of this measure, (for example, number of crashes) that occurs without the system.
N_w = value of the measure with the system fully deployed.

The value of N_{wo} is usually known from crash data files, but N_w is not known for pre-production or early-production systems. Thus, it is necessary to estimate the effectiveness of a countermeasure and combine it with the known value of N_{wo}, as shown in the following equation[5]:

$$B = N_{WO} \times SE \quad (2)$$

Where,
SE = effectiveness of the system
N_{wo} = size of the problem.

An extension of this idea is that the overall benefits consist of the benefits in a number of specific situations

$$B = \sum B_i = \sum N_{WOi} \times E_i \quad (3)$$

Where,
"i" = individual situations.
E_i = effectiveness of the system in reducing the number of crashes in a specific crash-related situation
N_{woi} = baseline number of crashes in individual situation "i".
B_i = the benefits in each of the individual situations.

From expressions (2) and (3), system effectiveness can be written as:

$$SE = \frac{\sum N_{WOi} \times E_i}{N_{WO}} \quad (4)$$

Many advanced technology systems change the rate of exposure to situations. To accommodate this feature of crash avoidance systems, the expression for effectiveness can be separated into the effect on preventing the situation and the effect on preventing a crash when the situation occurs. In this form, the expression for effectiveness is written as:

$$E_i = \left(1 - ER_i \times PR_i\right) \quad (5)$$

Where,
ER_i = Exposure Ratio for the specific situation "i".
PR_i = Prevention Ratio for the specific situation "i".

The expression for system effectiveness then is:

$$SE = \frac{\sum N_{WOi} \times \left(1 - ER_i \times PR_i\right)}{N_{WO}} \quad (6)$$

The purpose of the analysis of crash data files and objective tests is to generate the input values for the terms in these effectiveness expressions.

OBJECTIVE TESTS

There are two aspects to the development of objective tests. The first is the use of crash data to establish the basic test conditions. This is accomplished as part of Activity 2. An example of this step is provided in a companion paper at this conference[6]. The second aspect, the test protocol itself, is discussed here.

The purpose of each objective test is to provide data that can be used to estimate safety benefits for the system. The tests must not only be objective but they must also reflect the variability of driver performance. The following outline of seven test procedures 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 system inactive and will utilize a sample of volunteer drivers. A total of 16 drivers will be recruited for each test. For each test, one male and one female representative will be used from the age groups defined in NHTSA's 2003 Traffic Safety Facts[7] as shown in Table 4.

Table 4.
Choice of 16 test subjects based on age/sex categories from Traffic Safety Facts.

AGE	Sex	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

- 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.

- 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. The controller will faithfully replicate the input from each of the drivers in the first subset of test runs.

- Data that is adequate for use in estimating benefits will be collected during each test run.

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 is the bridge between the quantitative description of safety performance that is obtained from objective tests described and calculation of benefits.

The purpose of each objective test is to provide data that can be used to estimate safety benefits for the system. The formulations for estimating benefits are summarized in the earlier section of this paper

The following six steps are necessary for mapping the results of objective tests into estimates of the Prevention Ratio. A similar discussion for Exposure Ratio is not included in this paper.

1. Determine the distribution of baseline driver performance (e.g. time of initiation of response and level of effort of response) without the system 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[8,9] (ECA). The ECA, as the name suggests, is an approximation of how close to each other the 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.
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 Estimated Closest Approach.
5. Use these intermediate measures to estimate the probability of a crash, a basic measure of effectiveness
6. Combine the probabilities of a crash to compute the Prevention Ratio and estimate benefits.

In the following example, a hypothetical brake-assist system is analyzed 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 the applies

brake pedal at a rate greater than a panic brake threshold

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

Level of braking--- The brake-assist system will produce maximum deceleration for 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.

The test condition used for this 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. 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 test 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 host vehicle effective 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 2.

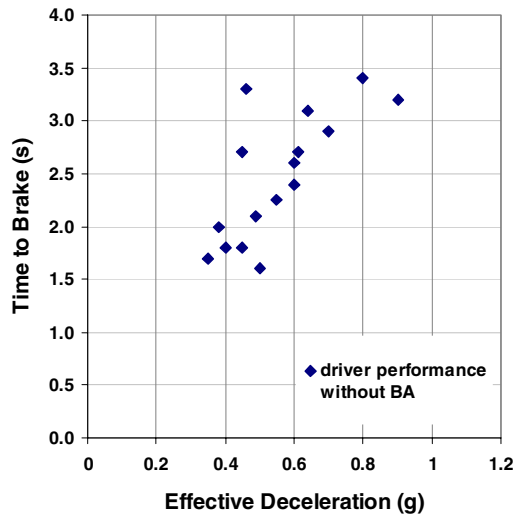

Figure 2. Hypothetical driver performance in terms of effective deceleration level and time to brake in order to avoid collision with lead vehicle, no brake-assist available for the subject vehicle.

The location of these descriptors for each driver can be compared to the crash/no-crash performance boundary for the test situation. This boundary is called the Crash Prevention Boundary or CPB[10]. The CPB delineates the region of driver performance that is adequate to prevent a crash from the region of performance that will not be adequate to 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 individual descriptions of performance to the CPB for this decelerating lead-vehicle situation is shown in Figure 3. In this figure the eleven drivers to the right of the boundary did not have a crash; and the five drivers to the left of the boundary did have a crash.

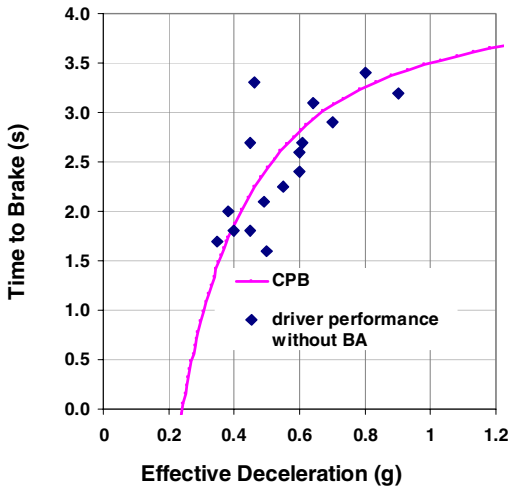

Figure 3. Comparison of driver performance to the Crash Prevention Boundary for baseline driving conditions

The distance between the location of the performance descriptors and the CPB in Figure 3 is indicative of the value of the Estimated Closest Approach. The values of performance by each baseline driver and the corresponding value of Estimated Closest Approach are summarized in Table 5.

Table 5.
Summary of driver performance in baseline conditions for decelerating lead vehicle example.

Age	Sex	Time to Brake (s)	Effective deceleration level (g)	Estimated Closest Approach (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

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 the 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 brake at brake pedal rate less than the threshold. This effect is seen in the Figure 4, where the performance of the 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

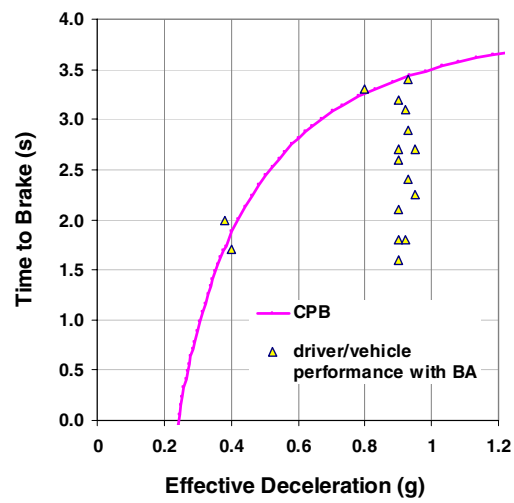

Figure 4. Comparison of driver performance to the Crash Prevention Boundary for brake-assist system activated driving conditions.

A summary of "equivalent" driver performance with brake-assist is shown in Table 6.

Table 6.
Summary of "equivalent" driver performance with the brake-assist system activated for decelerating lead vehicle example.

AGE	Sex	Time to Brake (s)	Effective deceleration level (g)	Estimated Closest Approach (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

The next step is to convert the values of Estimated Closest Approach to estimates of the probability of a crash for baseline conditions and for equivalent driving with the brake-assist system active. Keeping in mind that each subject is a representative of their age and sex, each value of Estimated Closest Approach is weighted by the appropriate fraction of crash-involved drivers as shown in Table 4 and the cumulative distributions of Estimated Closest Approach are produced for the tests without the brake-assist system and for the tests with the brake-assist system. The values of Estimated Closest Approach are shown in Tables 5 and 6. The cumulative distributions are shown in Figure 5.

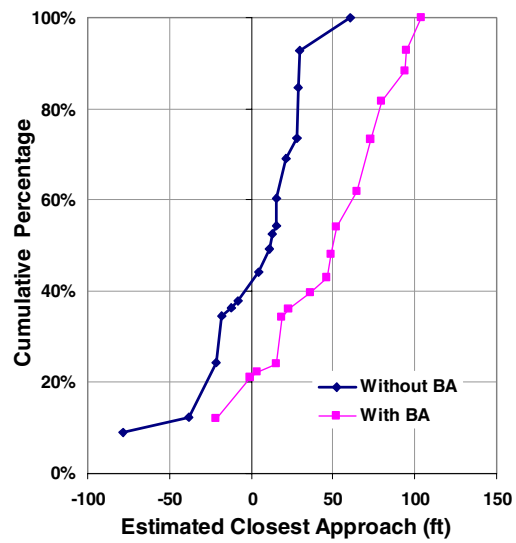

Figure 5. Cumulative distribution of Estimated Closest Approach, with and without the brake-assist system active.

Noting that positive values of Estimated Closest Approach correspond to situations where there was not a 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 activated = 0.21. Additional replications of this process may be necessary to produce representative samples and statistically valid results.

The estimate of effectiveness for this decelerating vehicle scenario is calculated by using Expression (5); assuming exposure ratio (ER) is equal to one.

$$E = 1 - \frac{P_w}{P_{wo}} = 1 - \frac{0.21}{0.42} = 0.5 \qquad (6)$$

Where,

$PR = P_w / P_{wo}$

P_w = probability of crash with brake-assist

P_{wo} = probability of crash without brake-system.

It then follows that the estimated benefits of the hypothetical brake-assist system for this crash type are:

$$B = 0.5 \times 216{,}000^{\otimes} \times 0.83^{\oplus} = 89{,}640$$

$\otimes$ Of the total 10,945,000 crashes from 2004 GES, 1,848,800 (Table 3) had brake and brake-and-steer as crash avoidance maneuver. Of these 1,848,800 crashes, 216,000 were rear-end crashes in which the lead vehicle was decelerating.

$\oplus$ Based on the assumed 50 mph speed for this example, 83% of the crashes of decelerating lead vehicles are at travel speeds of 50mph or less and are included in possible benefits.

In summary, this section includes an example of a hypothetical brake-assist system, using a test procedure that is based on analysis of GES data. It is estimated that such a system could eliminate 50% of the crashes caused by a decelerating lead vehicle and in which the following driver brakes to avoid a crash. This corresponds to 89,640 crashes.

CONCLUSIONS

The advent of new crash prevention technologies has made it necessary to develop new methodologies capable of estimating safety benefits before they are introduced in the market. This paper describes the development of one such empirically based methodology for estimating safety benefits.

The developed methodology uses detailed engineering descriptions of the crash prevention system performance, in conjunction with a universal description of crash causal factors and resulting relevant crash types. This study also establishes objective tests to evaluate systems; a hypothetical brake-assist system is used as an example to describe the process.

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