Development of a safety impact estimation tool for advanced safety technologies

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ABSTRACT

In order to develop and deploy advanced safety technologies, it is important to estimate effectiveness based on the system function or performance. Although various types of safety impact methodology (SIM) have been proposed to date, few SIMs can be applicable for actual system effectiveness estimation. In this study, a universal SIM (T-SIM) was developed and its validity was confirmed against field data. T-SIM uses the number of fatalities and casualties (fatal and nonfatal injury) that are expected to be prevented by the technologies rather than just collision/avoidance ratio because some of the safety technologies, such as a collision mitigation system, can reduce the impact speed by brake application and thus may help reduce the number of fatalities and casualties. T-SIM consists of two parts: (1) accident pattern classification and (2) effectiveness estimation for each system. In the first part of the T-SIM, accident data from the National Automotive Sampling System - General Estimates System (NASS-GES) and Fatality Analysis Reporting System (FARS) were categorized by such variables as type of accident (e.g., head-on) and relation to the intersection. The categorized accident patterns enable users to choose the accidents for which the technologies may be effective. By using the same accident pattern database, users also can compare the effectiveness of different safety systems. In the second part of the T-SIM, accident patterns applicable to a particular safety system are selected from the categorized patterns. A driver-model and a vehicle-model can be applied, which allows users to examine the effect of system parameters and configurations. Through the validation process using a Electronic Stability Control (ESC) system as an example of advanced safety technologies, the estimated effectiveness by T-SIM was compared with that reported by a study based on field data [2]. Although the accident databases are different, statistical analysis showed the effectiveness estimated by T-SIM is not significantly different from that by the field study and it was confirmed that the T-SIM can be used to estimate the effectiveness of other advanced safety technologies. Then the T-SIM was applied for a Pre-Collision System for the effectiveness estimation and further improvement. It was estimated that a PCS has high potential for reducing fatalities and casualties of rear-end accidents. In addition, it was also estimated that the PCS could be improved by changing such system parameters as warning, brake-assist and automatic brake timings.

INTRODUCTION

Various kinds of safety technologies such as Electronic Stability Control (ESC) system and Pre-Collision System (PCS) have been developed in order to help reduce traffic accidents. It is important to estimate effectiveness for the development and deployment of a safety system. However, it could take at least several years to accumulate sufficient accident data in order to investigate the effectiveness of such systems in the field. Therefore, the development of a methodology that can estimate the effectiveness of a safety system in advance is useful.

A safety impact estimation methodology (SIM) is a tool to estimate the benefit of safety systems, for example, by the number of fatalities, casualties (fatal and non-fatal injuries), or accidents that may be prevented by introducing an active safety system into the market. Safety impacts can be measured in various ways (e.g., [1], [2], [4], [5], [8]); therefore, a wide variety of SIM tool designs may be possible. We believe, however, that such numbers as fatalities and casualties reduction should be used as the output of the SIM tools for active safety systems. Some recent safety systems can reduce the impact speed by utilization of the electronic throttle control and/or brake application. Therefore, a safety impact estimation methodology should also consider the estimated reduction in fatalities and injuries resulting from the

reduced impact speed, rather than only estimating a crash-avoidance ratio. If those numbers can be identified by a SIM tool, engineers and researchers can assess a system's effectiveness.

Before using a SIM tool to estimate the potential safety impact of an active safety system, the accuracy and reliability of the SIM tool should be confirmed with real field data. Accident databases such as FARS and NASS-GES are good examples of field data that can be used to confirm the validity of the SIM tool. However, as mentioned earlier, it may take more than 10 years to collect enough field data in order to have sufficient data for validation of the tool. In addition, even when some field data are available, it does not necessarily mean that the data from the field can be used for accurate validation of the SIM tool. Field data, which are collected based on past systems, may not include sufficient details of the crashes to allow for sufficient analysis into the applicability of the characteristics and configurations of the active safety systems that will be deployed in the future. Therefore, it is important to confirm the validity of the SIM tool by comparing the SIM output and the safety impact achieved by an active safety system that has already been available in the market for a long time. The SIM can be validated if the SIM output is confirmed to be similar to the findings from accident statistics.

It is also important to identify the users of a SIM tool when evaluating its usefulness. An effective SIM tool should provide good feedback to engineers and researchers who are responsible for the development of active safety systems and their deployment strategies by showing not only the effectiveness of a potential active safety system but also the changes in effectiveness when the system parameters are modified. Therefore, the SIM tool should allow users to modify system parameters, such as the system operating speed range, to examine the impact of those changes. In addition, it is important to design the SIM tool to be as user-friendly as possible to produce accurate and reliable outputs without requiring extensive user training.

SIM Development Approach

The goal of this study was to develop a universal SIM tool:

- That uses real field data (FARS and NASS-GES data) to estimate effectiveness of safety systems,
- Whose accuracy is validated by comparing the SIM outputs with the effectiveness achieved by an existing system in the field, and
- That allows engineers and researchers to examine the effect of modifying system parameters and configurations when developing an active safety system.

Therefore, our goal was to develop a systematic process to estimate the ratio (and the numbers) of fatalities and casualties expected to be prevented ("effectiveness") based on the data from FARS and NASS-GES databases. Although each accident is unique and an almost infinite number of accident types are possible, they are also usually classified into several categories. We believe that it would be helpful for engineers and researchers to provide such categories as "rear-end crashes" and "head-on crashes" and for the users to be allowed to select the categories when analyzing probable causes for an accident and considering the possible countermeasures. But this categorization should be done using a systematic methodology.

Toyota's SIM (T-SIM)

Figure 1 shows the comparison between typical SIMs and the T-SIM concept.

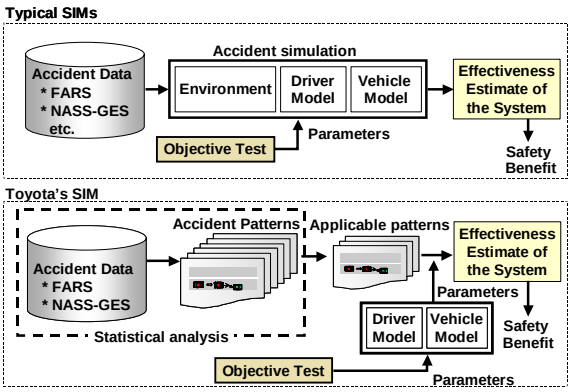

Figure 1. Comparison of T-SIM and typical SIMs

Typical SIMs are usually developed and tuned for a specific system, i.e., a SIM for Forward Collision Warning System (FCWS), a different SIM for ESC system, and so on. For each system, accident cases to which the system is applicable are selected from accident databases. Driver- and vehicle-model parameters are determined based on objective tests and detailed accident data (e.g., National Automotive Sampling System - Crashworthiness Data System

(NASS-CDS) and naturalistic driving data from driving recorders. System benefit is calculated from the accident simulation using the selected accident cases and the models.

However, there are some concerns associated with the approach. Firstly, it may result in creation of a number of complicated inflexible SIM tools. It is important for development engineers of active safety systems to have flexibility in adjusting parameters and system boundaries when designing effective systems. If multiple incompatible tools have to be used to compare two different systems, engineers will face a major challenge in designing integrated safety systems. Secondly, it is not easy to understand accident situations in such statistical data as NASS-GES and FARS and therefore it may be difficult to determine if a safety system can be effective for those accidents. Thirdly, such detailed data as NASS-CDS and naturalistic driving data can be used to determine if the system is applicable to those accidents; however, only a small number of detailed data are currently available and there is some uncertainty regarding whether the data are a good reflection of the national population. Fourthly, it is necessary for a better estimation to simulate accidents accurately; however, parameters for the simulation are given from small numbers of objective tests and/or detailed data. Finally, since this type of SIM is usually made for a specific system, users need to repeat nearly the entire process in order to build another SIM for each specific system.

On the other hand, our basic approach is to construct a universal SIM tool based on the standard sets of accident patterns with adjustable parameters. This type of SIM allows development engineers to select applicable accident patterns when creating a system concept. During the engineering exercise, engineers can adjust system boundaries, such as the operating speed range, to see the boundaries' impact on safety benefits.

The T-SIM consists of two parts: one part is the classification of accident patterns of NASS-GES and FARS database, which can be used for various kinds of systems. The other is the selection of the applicable patterns to a specific system from the categorized patterns and the application of a driver-model and a vehicle-model to estimate the system effectiveness.

The main benefits of the T-SIM are:

1. The classification will operate to allow the user to address a particular purpose; therefore, the T-SIM users can easily understand for what kind of accidents a safety system can be effective.
2. The T-SIM users do not need to conduct the accident analysis when they try to estimate effectiveness of a different safety system.
3. It is possible to compare the effectiveness of different systems in the same condition by using the same accident database of the T-SIM.

Accident Pattern Classification

Categorization of Data Elements

As the first step of developing standard sets of accident patterns, NASS-GES and FARS data were categorized into several groups. The "occupant" data set is used for both NASS-GES and FARS. Table 1 shows the results of these categorization efforts.

For multi-vehicle crashes, it is important to distinguish them into culpable party and counter party. A culpable party is the vehicle that has mainly contributed to the occurrence of a particular accident. For example, in a rear-end accident, if the driver of the following vehicle was inattentive and did not see the preceding vehicle slowing down, and collided into the preceding vehicle, the following vehicle is the culpable party because the contribution of this striking vehicle to the accident is greater than the preceding struck vehicle. To determine which vehicle was culpable we examined each vehicle's role (i.e. striking or struck), drivers' distraction, travel speed and vehicle maneuver prior to critical event.

The grouped vehicles are limited to three categories in order to reduce the number of combinations: automobiles, motored cycles, and other vehicles. Automobiles include all passenger vehicles (automobiles, automobile derivatives, utility vehicles, all kinds of trucks and buses).

Each item in the "grouped categories" can be considered one similar group of accidents (head-on collision between automobiles at an intersection with a traffic signal) therefore can be used as the basis for creating standard accident patterns. Their combinations (type of accident, culpable party, counter party, location, and traffic control) generate 486 sets of standardized accident patterns.

After minor cases (with less than 0.025% of all fatalities or less than 0.025% of all casualties) and unclear cases (vehicle involved in crashes and/or location of crash are unknown) are eliminated; only 98

patterns remain. In total, these 98 patterns can represent approximately 85% of all accident cases therefore it is reasonable to believe these 98 patterns can be used to represent a large percentage of the accident patterns in the United States (Table 2).

Table 1. Categorization of NASS-GES and FARS Accident Cases

	Grouped Categories	**2005 NASS-GES Variables**	**2005 FARS Variables**
Type of Accident	Multi-Vehicle Crashes Head-on; Angle; Rear-End; Sideswipe Same Direction; Sideswipe Opposite Direction; Rear-to-Rear Single Vehicle Crashes Pedestrian; Pedal Cyclist; Rollover/Overturn; Guardrail; Concrete Traffic Barrier; Post, Pole or Support; Culvert or Ditch; Curb; Embankment; Fence, Wall; Tree; Animal; Parked Motor Vehicle or Other Motor Vehicle not in Transport; Bridge Structure; Other Fixed Object; Other Object not Fixed; Other Non-Collision	#40 IMP Manner of Collision #37 IMP First Harmful Event	#25 Manner of Collision #24 First Harmful Event
Culpable Party	Automobile; Motored Cycle; Other Vehicle	#158 Imputed Body Type	#110 Body Type
Counter Party	Automobile; Motored Cycle; Other Vehicle	#158 IMP Body Type	#110 Body Type
Location	Intersection Related; Non-Junction; Other Location	#45 IMP Relation to Junction	#26 Relation to Junction
Traffic Control	Traffic Signal; Stop, Yield, School Zone Sign; No Controls	#48 IMP Traffic Control Device	#35 Traffic Control Device

* IMP: Imputed

Table 2. Coverage of Extracted 98 Standard Accident Patterns

Type of Accidents	**Number of Standard Accident Patterns**	**Coverage (Casualties, NASS-GES)**	**Coverage (Fatalities)**
Automobile x Automobile	22	86.3%	94.7%
Single Vehicle (excluding Pedestrian and Pedal Cyclist)	41	85.4%	91.7%
Automobile x Motorcycle	11	68.3%	82.6%
Motorcycle x Automobile	14	78.1%	82.6%
Automobile x Pedal Cyclist	5	81.9%	88.7%
Automobile x Pedestrian	5	93.1%	86.2%
Total	98	85.8%	83.5%

Selection of Parameters for Effectiveness Estimation

The next step was to examine the parameters (conditions) that can contribute to the number of accidents. The following NASS-GES and FARS data elements are identified as accident parameters (Table 3).

For each of these 98 patterns, the parameters and data counts are extracted from NASS-GES and FARS. The extracted data will be used as the database to calculate safety impacts. We are developing an interface tool to identify applicable accident patterns and adjustable accident parameters when estimating safety impacts of future active safety systems.

When examining NASS-GES and FARS databases, one would discover that there are many cases where vehicle travel speed is reported as “unknown.” We examined the linear correlation between “Posted Speed Limit” and “Vehicle Travel Speed.” After normal distributions were confirmed, linear regression models were created and applied to generate estimated vehicle travel speeds based on the posted speed limits (Figure 2).

Table 3. Categorization of NASS-GES and FARS Accident Cases

Parameters for Effectiveness Estimation	2005 NASS-GES Variables	2005 FARS Variables
Culpable Party's Travel Speed	#120: Travel Speed #46: Imputed Speed Limit	#127: Travel Speed #30: Speed Limit
Damage Area	#74: General Area Damage	#135: Impact Point – Initial
Traffic-Way Flow	#15: Trafficway Flow	#28: Trafficway Flow
Pre-Crash Vehicle Control	#138: Precrash Vehicle Control	-
Corrective Action Attempt	#137: Corrective Action Attempt	#151: Crash Avoidance Maneuver
Roadway Alignment	#36: Imputed Roadway Alignment	#31: Roadway Alignment
Roadway Surface Condition	#47: Imputed Roadway Surface Condition	#34: Roadway Surface Condition
Atmospheric Condition	#49: Imputed Atmospheric Condition	#39: Atmospheric Condition
Light Condition	#30: Imputed Light Condition	#38: Light Condition
Driver Distraction by #1	#182: Driver Distracted by #1	-
Driver Related Factors #1	-	#229: Driver Related Factors #1

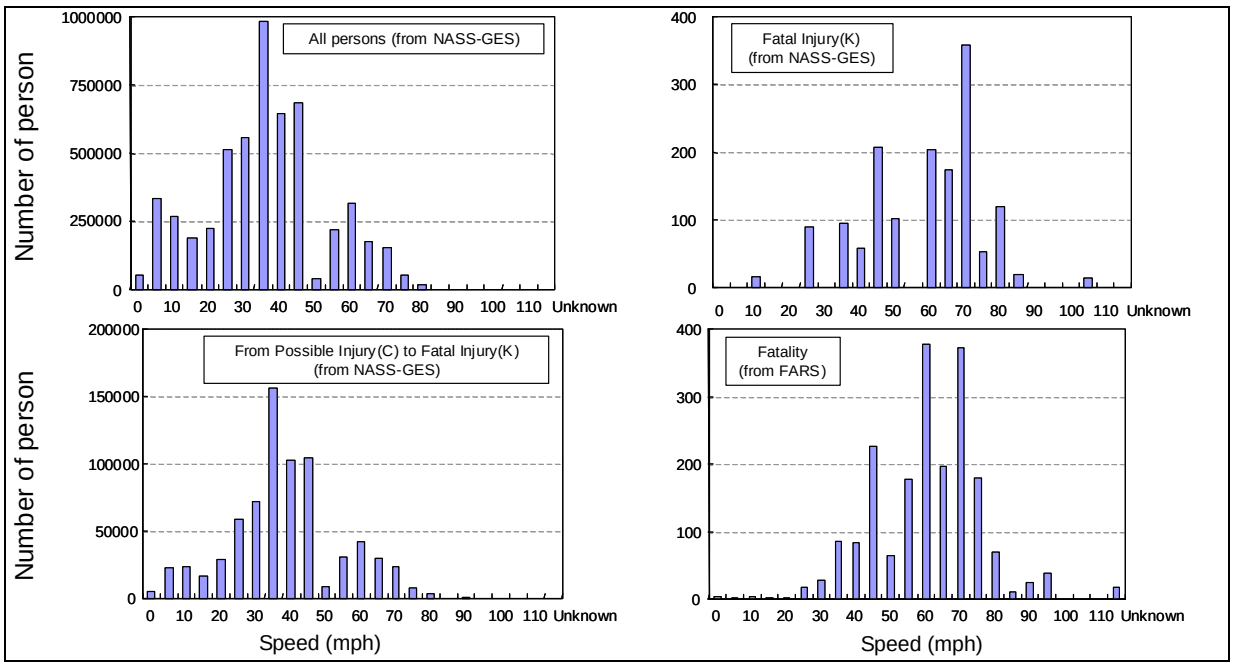

Figure 2. Estimated Vehicle Traveling Speeds

SIM Validation Approach

<u>T-SIM Application to ESC for its validation</u>

The validity of the T-SIM was examined with existing field data. There are sufficient accident data in the field for ESC systems because they were already introduced into the market for a wide range of vehicles for several years. One of the benefits of the T-SIM is that it can be used not only for a particular system but also for a wider range of active safety systems. Therefore, it was decided to validate the T-SIM concept by comparing the data produced by the T-SIM for ESC and the effectiveness of ESC identified in field studies conducted by NHTSA [2].

In the NHTSA report, it was identified that the effectiveness of ESC by comparing accident frequencies of identical and/or similar vehicle models with and without ESC.

In the report, analyses were conducted based on field data of FARS and state accident data from 1997 to 2004. We used the NASS-GES database to compare

the results with the state data files because those databases are thought to be comparable. Since the ranges of the years of the databases in the T-SIM and the NHTSA report are different, we compared the distributions of an accident type in those two ranges of years as a check for similarity and found that the databases are comparable.

Identification of Influential Parameters

To examine the validity of the T-SIM, we first identified the functionalities of a typical ESC system. A typical ESC system is designed to activate the vehicle chassis control system to help avoid vehicle loss of control and help allow the driver to regain control when s/he has lost control. There are two types of control loss: front-wheel skid (drift off) and rear-wheel skid (spin).

In this SIM validation step, two operating conditions for ESC were considered to estimate the effectiveness: (A) ESC works at the speed equal to or more than 10 mph, and (B) ESC works to help prevent skidding. The operating condition (A) is defined from the system setting, and the effect of ESC on preventing skidding in condition (B) is mentioned in the previous studies ([6], [11]) and was also confirmed by our ground test [10].

It is natural to consider that there may be some other factors that may affect ESC activation. The "roadway surface condition" is a good example. Table 4 shows the number of persons involved in accidents by "pre-crash vehicle control" and "roadway surface condition" categories. This table was made from the database with the 98 accident patterns. Although "skidding laterally" occurred more often (29%) in the "Snow or slush" condition than that in other conditions (3% in "Dry," 12% in "Wet," 23% in "Ice"), there are still a larger number of accidents that happened even when the vehicle was under a "tracking" condition (54% in "Snow or slush," 87% in "Dry," 70% in "Wet," 40% in "Ice"). In other words, even in the "Snow or slush" condition, a large amount of accidents occurred in the "tracking" condition. Similar phenomena are also observed in other roadway surface conditions. It indicates that the roadway surface condition may seem to have an association with the number of "skidding" accidents, however the influence is secondary. Since typical ESC systems are designed to function when the vehicle is "skidding," whether the vehicle is skidding or not is the primary effect on ESC activation. Therefore it is appropriate to use only the "pre-crash vehicle control" condition as the variable when examining the effectiveness of ESC.

Table 4. Number of persons involved in accidents by "Pre-crash Vehicle Control" and "Roadway Surface Condition" categories

Pre-crash Vehicle Control \ Roadway surface condition	Dry	Wet	Snow or slush	Ice	Other /Unkown	Total
Tracking	232806	52573	15315	5515	604	306815
Skidding longitudinally	14195	6729	4507	4660	19	30110
Skidding laterally	8552	8707	8092	3201	0	28551
Other	0	0	0	0	0	0
Other vehicle loss of control (specify)	0	591	0	0	0	591
Precrash stability unknown	11543	5944	299	552	0	18337
Total	267096	74545	28213	13928	623	384405

Estimated effectiveness by the T-SIM and the effectiveness reported by NHTSA

The NHTSA report estimated the effectiveness of ESC for passenger cars (PCs) and light trucks and vans (LTVs) separately. To examine the appropriateness of the T-SIM, however, we have divided our vehicle category into these two categories, PCs and LTVs, in order to match the NHTSA report. This was done solely for the purpose of examining the validity of the SIM tool.

The effectiveness of ESC estimated by the T-SIM and that by a previous report are shown in Figures 3 (for fatal crashes) and 4 (for various crashes). In these graphs, the bars on the left side of each accident type show the effectiveness of ESC for PCs, and the bars on the right side show that for LTVs, extracted from the NHTSA Technical Report [2].

The diamond (blue) dotted level lines indicate estimated results by the T-SIM calculated under the conditions of (A) ("culpable party's travel speed" is over 10 mph) and (B1) ("skidding laterally"), and the square (red) dotted level lines indicate estimated results calculated under the conditions of (A) and (B2) (both "skidding laterally and "skidding longitudinally").

In the NHTSA report, all crash involvements refer to all types of fatal crash involvements for the FARS database and not only fatal but also non-fatal crash involvements (i.e., property damage, possible injury, non-incapacitating and incapacitating injury) for the state data files (see page 19 of the NHTSA report). In the T-SIM, we used fatalities of the FARS database and "All Persons" data (Fatal injury (K), Incapacitating Injury (A), Nonincapacitating Evident Injury (B), Possible Injury (C), and No Injury (O)) in the NASS-GES database for the purpose of comparison.

In general, it can be said that the effectiveness values estimated by the T-SIM are reasonably comparable to

the effectiveness reported in the NHTSA report because most of the estimated effectiveness for preventing fatal accidents fit within the confidence bounds.

Then, chi-square statistics were applied for the estimated effectiveness of the crash types (e.g., "all run-off-road," rollover") by the T-SIM and that by the previous report. In this statistical analysis, the stated effectiveness in the NHTSA report was treated as the expected frequency and the effectiveness estimated by the T-SIM was treated as the observed frequency.

Overall, a significant difference was not seen when the confidence bounds in the NHTSA report are taken into account. Through the validation process of the effectiveness of ESC systems, it was confirmed that the T-SIM is able to estimate the effectiveness of the safety system. Therefore, the T-SIM can be used as a tool to estimate the effectiveness of other safety systems by modeling a driver-model and a vehicle-model for the systems.

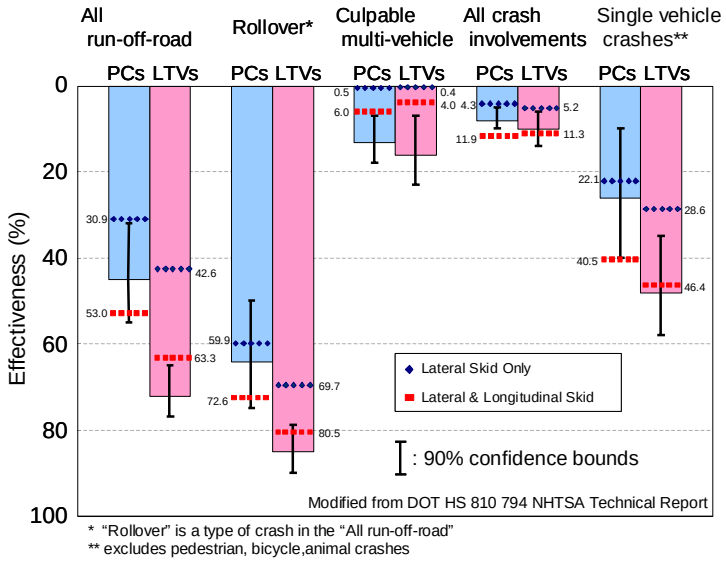

Figure 3. Effectiveness Estimation Results in Fatal Crashes by Vehicle Type

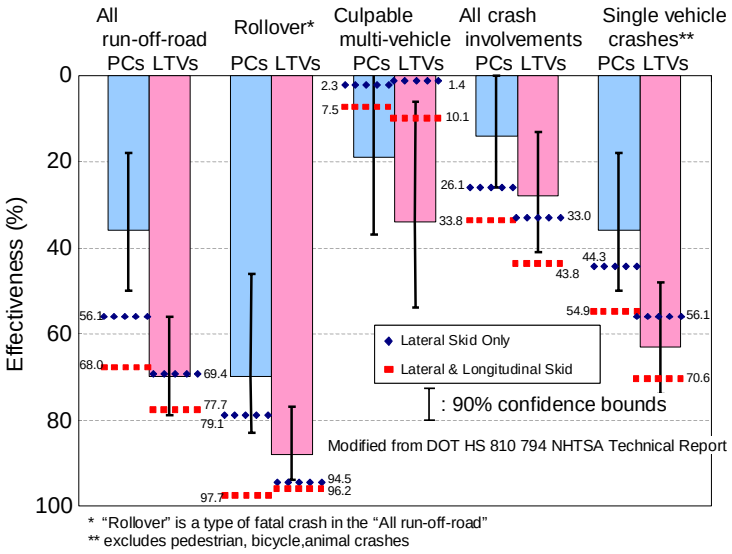

Figure 4. Effectiveness Estimation Results on Various Crashes by Vehicle Type

Effectiveness estimation of a Pre-Collision System

Among all accidents of light vehicle crashes, rear-end collisions is the most frequent, accounting for 29% of all crashes [8]. In order to reduce fatalities and casualties by the rear-end collisions, a Pre-Collision System (PCS) has been developed [3]. A PCS constantly monitors a vehicle and/or obstacle ahead with a front-mounted sensor (e.g. a millimeter-wave radar sensor), prepares the brake-assist for increased braking and finally applies automatic braking in order to mitigate the impact of collision when the system's computer determines that a frontal collision is unavoidable. Many countries are going to promote to spread the PCS.

For the effectiveness estimation and further improvement, the T-SIM was applied for a PCS. The driver model was developed from a driving simulator test. The driver-parameters such as subjects' response time to the warning, system response time, and reduction speed were collected using our driving simulator [7] from about 100 subjects. The vehicle model was made from objective tests using an actual vehicle.

It was estimated that a PCS has high potential for reducing fatalities and casualties caused by rear-end collision. In addition, the PCS system parameters such as warning, brake-assist and automatic brake timings were changed to study what parameter is the most effective and it was estimated that the PCS could be improved by modifying those parameters.

Conclusion

In this study, our goal was to develop a universal SIM tool (T-SIM) that is accurate and functional in estimating effectiveness of various safety systems.

The validity of the T-SIM was confirmed by comparing the estimated effectiveness using the T-SIM and an analysis reported by a previous study. Through the validation process of the effectiveness of ESC systems, it was confirmed that the T-SIM is able to estimate the effectiveness of the safety system.

One of the advantages of the T-SIM is that it can be used not only for ESC but also for a wider range of active safety systems. For the effectiveness estimation and further improvement, the T-SIM was applied for a PCS. The driver- and the vehicle-models were built from objective tests. It was estimated that a PCS has high potential for reducing fatalities and casualties of rear-end accidents. In addition, it was also estimated that the PCS could be improved by changing such system parameters as warning, brake-assist and automatic brake timings.

This is just the beginning of the study for the T-SIM and there is still a lot of work ahead of us; however, we believe that our T-SIM will be able to contribute to improve understanding of the effectiveness of advanced technology safety systems in helping to reduce crashes, and therefore, to improve vehicle safety.

Acknowledgement

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