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RESEARCH ARTICLE

Cost-Benefit Analysis to Assess the Effectiveness of an External Airbag and Autonomous Emergency Braking System

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ABSTRACT One of the recent developments in safety systems is an external airbag installed on the front bumper of a vehicle and autonomous emergency braking system. In this paper, we propose a framework for a cost-benefit analysis of the external airbag and autonomous emergency braking system in order to validate its commercialization. Road traffic crash data obtained from the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) was used, and three different crash types related to frontal damage in vehicles were extracted to estimate the safety performance of an external airbag. An ordinal logistic regression model was applied to estimate the safety performance in terms of the reduced maximum abbreviated injury scale (MAIS) based on a reduction in the total delta-v following the installation of an external airbag. Given the estimated safety performance of the external airbag, a cost-benefit analysis is conducted. According to the results, the external airbag system saves 46% of occupants with MAIS 3+ injuries and prevents 40% of fatalities. Moreover, the benefit/cost ratios of the external airbag system range from 0.496 to 0.509 depending on the scenario. Lastly, sensitivity analyses were performed with important parameters, including the initial and maximum market penetration ratio and the price of the system. This study aims to evaluate the technology of safety devices by analyzing the effectiveness of a new safety device using real-world vehicle accident data. We also statistically estimated its effectiveness and analyzed its societal value. We expect that our comprehensive findings will be helpful in evaluating the effectiveness of safety devices.

INDEX TERMS Cost-benefit analysis, external airbag, logistic regression, total delta V.

I. INTRODUCTION

Safety systems in vehicles can be divided into the two categories of primary and secondary safety systems. Primary safety systems will reduce the risk of crashes related to factors such as steering, brakes or lighting, while secondary safety system will minimize the risk of injury to those who are involved in vehicle crashes [1], [2]. Various secondary safety systems have been developed, of which the airbag system is one of the most representative. Numerous studies have assessed the safety performance of airbags for vehicle occupants [3], [4], [5], [6]. Recently, new types of airbag systems have been developed in order to reflect customers' needs for safer driving, to anticipate unexpected risks, and to minimize the cost of vehicle crashes. The external airbag (EAB) is one of these newly developed systems.

The EAB system is installed at the front bumper of a vehicle in order to absorb the impact energy from external collisions at the front of a vehicle by lessening the impact velocity. As a result of this process, the EAB is expected to reduce the severity of injuries suffered by the occupants of a vehicle. Although the operating environment and

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performance of EABs in terms of speed reduction are commonly defined by experimental collisions done by automakers, the socioeconomic performance with regard to reducing the risk of injury has not been investigated because this system has not been introduced in the actual market.

The goal of this paper is to investigate the socioeconomic impacts of the EAB system, a new safety system, as determined by injury reductions. We propose a framework for a cost-benefit analysis of the EAB system to assess socioeconomic effects of such a system. First, we apply an ordinal logistic regression model to predict the reduced Maximum Abbreviated Injury Scale (MAIS) in relation to the reduced speeds achieved by the EAB system to estimate the safety performance of the system. Based on the estimation of the safety performance, we calculate the benefit and cost borne by customers in a cost-benefit analysis. The resulting benefit of the system is related to reductions in social expenses, such as medical expenses incurred due to the reduced severity of injuries to occupants by the EAB system. Moreover, we consider discounts on insurance premiums caused by the installation of an EAB system as a benefit. Next, the cost in the analysis is defined as the setup cost of the system. Moreover, these benefits and costs of the system are directly related to the number of vehicle-installed safety systems and the number of causalities. In order to predict the number of vehicles which EAB systems installed, the number of registered vehicles and sales are forecasted via Holt's model, a method for estimating future trends with a reflection of trends with time-series data at the stage of the estimation of the benefit and the cost [7]. Through this procedure, safety performance levels and benefit/cost ratios of the EAB system are determined, and these results help us to comprehend the socioeconomic impacts of the EAB system. Moreover, a sensitivity analysis is conducted in an effort to understand the relationships between important variables and the benefit/cost ratio of the EAB system. The results can contribute to providing advantages of the commercialization of the system to decision makers.

This paper is organized as follows. Section II describes the related literature. Section III proposes a framework to estimate the performance of the AEB and AEB+EAB systems. In section IV, we conduct cost benefit analyses based on the safety performance of the AEB and AEB+EAB. Finally, in section V, we conclude this study and suggest possible directions for further studies.

II. LITERATURE REVIEW

In this section, we review the literature on safety performances of the EAB and AEB systems. Moreover, this section considers the literature related to the significant assumptions in this study surrounding the relationship between the speed of a vehicle and the injury severity levels in car crashes, and the collision direction. Lastly, we summarize the cost-benefit analysis process from previous studies.

A. EXTERNAL AIRBAG (EAB)

Stemming from the desire to guarantee the safety of occupants' who are involved in vehicle collisions, the EAB, which is an airbag made to reduce the direct impact of vehicle crashes on the outside of a vehicle, was introduced to the motor vehicle market. The EAB has already been installed on many different aerospace platforms [8]. Kellas et al. [9] measured the effectiveness of the DEA (deployable energy absorber), a type of EAB, for an MD-500 helicopter via collision experiments. They found that this system reduced the impact to the occupant's lumbar area, a part of spine which is related to a human's waist, from a crash by about 60-67% and reduced vertical pelvis acceleration by about 56-74%. Holnicki-Szulc et al. [10] confirmed that an adaptive EAB for the emergency landing of helicopters efficiently decreased the level of the arising acceleration of the vehicle. Moreover, the EAB was also introduced onto motor vehicles in order to enhance the safety of occupants in several studies which estimated the effectiveness of the EAB based on collision experiments. Pipkorn et al. [11] studied the effectiveness of a bumper bag and found that it reduced the velocity of an intrusion to the sides of other vehicles. Barbat et al. [12] estimated the effectiveness of the EAB as a bumper airbag in the event of side impact crashes via sled tests and computer simulations. According to their study, the EAB reduced the HIC (head injury criteria) by 24% and the TTI (thoracic trauma index) by 6% based on normalized dummy responses, the reaction of a man-like model, in the driver position of a target vehicle. Barbat et al. [13] estimated the effectiveness of two types of EABs, bumper airbags and grille airbags, for side impact crashes using sled tests. They indicated that a safety system which consisted of a bumper airbag and a grille airbag reduced the HIC by 73%, the TTI by 31% and the pelvis acceleration rate by 39% based on normalized dummy responses in the driver position of a target vehicle.

B. AUTONOMOUS EMERGENCY BRAKING (AEB) SYSTEM

The operation of AEB is one of the preconditions of the operation of EAB. Researchers created the AEB (autonomous emergency braking) system in order to avoid car crashes and to reduce the risk of injury to the occupants. Many investigators have made efforts to estimate the effectiveness of AEB on the safety of passengers. Kusano and Gabler [14] attempted to estimate the effectiveness of a pre-crash system including AEB based on the national automotive sampling system crashworthiness data system (NASS/CDS), which is a data collection system of the United States' National Highway Traffic Safety Administration (NHTSA). NASS/CDS contains detailed data regarding vehicle crashes. They represented the relationships between injury risk and other factors, including the delta-v and seatbelt use through a logistic regression. Moreover, they estimated the effectiveness of the pre-crash system by altering the velocity according to the effects of the system, finding that a pre-crash braking system prevents between 0% and 14% of collisions and reduces the proportion of injured drivers by 19% to 57%.

Georgi et al. [15] estimated the effectiveness of AEB by reflecting the behavioral characteristics of drivers based on the German In-Depth Accident Study (GIDAS) database via a case-by-case analysis and a logistic regression model. They estimated that 72% of crashes can be avoided by the AEB system when there is a realistic driver, i.e., a driver who performs adequate deceleration, during crashes. Balint et al. [16] investigated the effectiveness of AEB using the NASS/CDS database in three scenarios of car-to-car rear-end collisions: a stopped lead vehicle, a slower lead vehicle and a braking lead vehicle. In that study, the authors used the concepts of available points and scored points to quantify the effectiveness of the AEB system. "Available point" is a value which represents the distribution of crashes depending on the distribution of the crash velocities, and "scored point" is a value which expresses the reduced number of injuries by AEB. As a result, they found that AEB reduced the injury risk by 72%.

C. RELATIONSHIP BETWEEN INJURY RISK AND DELTA-V

Many researchers have investigated the relationship between velocity and the risk of injury to occupants and have posited numerous relationships between velocity and risk from the literature to their studies [17], [18], [19]. Gabauer and Gabler [20] studied the maximum injury and chest injuries of occupants according to the delta-v from event data recorders (EDRs) via a binary logistic regression for MAIS3+ injuries using the NHTSA EDR database. Hannawald [21] proposed three different occupant injury risk curves by injury level depending on the delta-v from a binary logistic regression based on the GIDAS database. Hampton and Gabler [22] constructed and compared three different injury risk functions depending on algorithms for delta-v reconstruction obtained from a binary logistic regression using NASS/CDS data. Richards and Cuerden [23] formulated the injury risk functions of fatal crashes and crashes resulting in serious injuries according to delta-v from a binary logistic regression using a cooperative crash injury study (CCIS), an on-the-spot study (OTS), and STATS 19 data, which is a data collection related to car crashes managed by police in Great Britain. Kusano and Gabler [14] created two risk functions for belted occupants and unbelted occupants through a logistic regression based on the NASS/CDS database. Viano and Parenteau [17] determined the discrete line-of-injury risk with the fraction of injured occupants according to the delta-v obtained from the NASS/CDS database. As shown above, the relationship between injury risks and relative velocities in crashes has been studied thoroughly. In our paper, we will identify the relationship between the relative velocity and the reduced relative velocity when adopting the AEB or the AEB+EAB system. When the AEB and EAB systems are operated, the vehicle can delay the time of collision [11], [22]. Therefore, the relative collision velocity is expected to be reduced significantly compared to that with the absence of such a system.

Generally, injury severity is classified into different categories according to their severity levels. So when the relationship between each injury severity and relative velocity is investigated, ordinal logistic regression is often used [24], [25]. With this model, the maximum likelihood estimation is used to estimate the probability of categorical membership. Therefore, we attempt to evaluate the effectiveness of an external airbag system by defining its reduction of the crash velocity. We use it as an explanatory variable for an ordinal logistic regression model for injury levels represented by MAIS where log odds ratio with respect to MAIS is assumed to have a linear relationship with the reduction of the crash velocity [26].

D. COST-BENEFIT ANALYSIS

The cost-benefit analysis is the comprehensive method of economic assessment which is used to compare contributions to stakeholders to what they paid [27] and it is frequently utilized in diverse fields [28], [29]. This analysis is a framework for evaluating the economic efficiency of a proposed product, or system. Theory of CBA is built on three key principles: economic efficiency, social welfare, and comparability [30]. Moreover, as various safety systems were developed to satisfy customers' needs for safety, researchers started to study the socioeconomic effects of these systems on society. Consequently, many investigators conducted cost-benefit analyses of various vehicle safety systems in order to confirm the feasibility of their development in terms of social and economic performance. In general, a benefit is defined as the cost saving from the reduced severity of injury to the occupants, and the cost is expressed as the installation cost of the system during the cost-benefit analysis process.

The European Commission [31] estimated the benefit/cost ratio of 18 different safety devices according to different scenarios based on different promotion conditions, such as the installation of a system in newly produced vehicles and in existing vehicles, and in newly produced vehicles only. In that study, the market share of vehicles featuring these types of safety systems varied by scenario according to the promotion plans of the respective safety systems. Therefore, more occupants can benefit from this system in vehicles with a high market share and the setup costs increase according to market share increases. Anderson et al. [32] analyzed the potential effectiveness of 15 types of new safety systems. In their paper, crash cases were divided into those which could be directly and indirectly affected by safety systems. Carsten and Tate [33] estimated the effectiveness of intelligent speed adaptation systems while reflecting the GDP growth rate of each nation in the increment of the vehicle fleet. Robinson et al. [34] conducted a cost-benefit analysis of AEB and the lane departure warning system (LDWS) based on STATS 19, which provides real crash data from the United Kingdom, determining the economic feasibility of these systems from the results of the cost-benefit analysis. In that study, the researchers suggested a range of benefit/cost ratio values based on the range of costs and of the performances of the components in the safety system. Buhne et al. [35] performed a cost-benefit analysis of pre-crash safety systems to prevent frontal crashes based on data from ProgTrans AG, a public company related to mobility and transport, to forecast passenger car fleet data. In addition, this study utilized data from eIMPACT, a project which assesses the socioeconomic effects of safety systems, to determine borrowing cost values caused by crashes with data from the NASS/CDS. The authors used the concepts of available points to express the distribution of injured occupants according to changes in the velocity, awarding points for the number of people who avoided injury. This study did not determine a benefit/cost ratio for the safety system but calculated a target breakeven cost which makes the benefits equal to the costs. The European Commission [31] also suggested breakeven costs for new safety systems which had no historical data, such as the collision warning system, fatigue detectors, and improved vehicle compatibility systems.

Although some investigators have studied the effectiveness of the EAB system in collision experiments [12], [13], no study has calculated its effectiveness based on statistical methods using crash statistics. Moreover, cost benefit analyses have not been conducted for the EAB system. In this study, we conduct a cost-benefit analysis for a safety system which includes EAB and AEB. The effectiveness of an external airbag was included as a benefit in the analysis procedure.

III. ANALYSIS FRAMEWORK AND SAFETY PERFORMANCE OF EAB AND AEB

In this section, we suggest a framework for the cost-benefit analysis of a safety system including both EAB and AEB systems. We used an empirical data set from the NASS/CDS, which is a well-known and detailed vehicle crash database which provides records of crash circumstances, internal and external damage to vehicles, injured people, and injury characteristics. Appendix A shows the overall framework, which contains the process used to estimate the safety performance of an EAB system and an outline of the cost-benefit analysis. The framework is divided into four main steps: 1) crash data extraction, which involves dividing the data into crash types and analyzing the relationship between the MAIS and total delta-v (DVTOTAL); 2) assessing the safety performance of the systems in terms of reduced injury levels according to the reduced DVTOTAL with AEB and EAB; 3) forecasting the numbers of registered vehicles, causalities and vehicle sales; and 4) conducting the cost-benefit analysis. DVTOTAL is the calculated delta-v from the damage algorithm in WinSMASH, accident reconstruction software. The National High Traffic Safety Administration (NHTSA) assumed the DVTOTAL score to be identical to the delta-v. Brief summaries of each step are described below.

Step 1: Extract the target data and find the relationship between DVTOTAL and MAIS.

First, we extracted crash data which satisfy specific properties of the systems and vehicles, such as the vehicle type, the width of the damage, and crash conditions. The extracted data represents a collection of crashes which can benefit from AEB and EAB systems.

Step 2: Assess performance levels of AEB and AEB+EAB systems.

Following the extraction of the target data, we determined the relationship between the MAIS and DVTOTAL values using a ordinal logistic regression model. We estimated the safety performance of the AEB and AEB+EAB systems based on reduced velocities. In this step, the reduced relative velocity by the AEB and AEB+EAB systems, as obtained through a simulation, was changed to the DVTOTAL value because the NASS/CDS did not offer relative velocity information; the detailed process used here is shown in section III-B. Based on both the ordinal logistic regression and the reduced DVTOTAL according to AEB and AEB+EAB, we created a modified MAIS distribution. Therefore, we estimated the safety performance, which was the reduction ratio of each class of MAIS. In addition, we confirmed both crash prevention cases and un-deployed cases of an internal airbag (driver or passenger airbag) through the operation of the AEB and AEB+EAB systems by means of binary logistic regression.

Step 3: Forecast the numbers of registered cars, car sales and casualties.

In order to calculate the benefits and costs for each stakeholder, i.e., passengers, the numbers of registered cars, car sales and casualties should be forecasted. We used Holt's model to obtain these values and forecasted the numbers for the United States.

Step 4: Calculate the benefit, cost and benefit/cost ratios.

The socioeconomic effects of the systems were evaluated in a cost-benefit analysis. We obtained the benefits and costs from the point of view of the occupants. Moreover, the benefits were divided into costs in order to obtain the benefit/cost ratios of the AEB and AEB+EAB systems.

A. TARGET POPULATION (STEP 1)

In the first step to analyze the performance of a safety system with AEB and AEB+EAB, we extracted an empirical data set which consisted of information on vehicle crashes from 2003 to 2011. Although the utilization of data over a long time period may not reflect the most recent characteristics of various conditions, such as vehicles, drivers or other circumstances, we use this empirical data here. Otherwise, we could not utilize crash data with MAIS 5 and 6, of which there are relatively few instances. Moreover, many studies utilize data of long time periods [36], [37], [14]. We extracted 10,282,239 instances of crash data involving injured people. This data represents the collection of crashes which may have been be influenced by a safety system. The extraction procedure, the related number of injured people, and the percentages are shown in Table 1.

Table 2 shows detailed information about the crash distribution by crash type, where a ratio inflation factor was applied to estimate the number of motor vehicle crashes occurring in the US involving passenger cars or light trucks that were towed due to damage. AEB and AEB+EAB are only operable

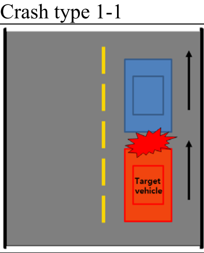
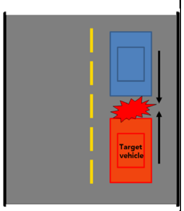
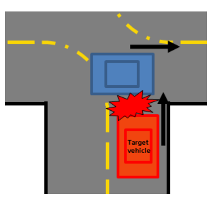
TABLE 1. Crash data extraction.

Condition	Number of injured people	Percentage
Raw data in NASS/CDS from 2009 to 2011	46,972,456	100.0%
If the un-deformed end width and direct damage width are unknown or missing, then delete.	31,600,821	67.3%
1) The MAIS level is one of 0, 1, 2, 3, 4, 5, or 6 2) If value of DVTOTAL is unknown or missing, then delete.	14,031,704	29.9%
1) Crash with another vehicle 2) Vehicle type is passenger vehicle or truck	11,104,260	23.6%
If crash type is unknown, then delete	11,073,918	23.6%
If crash is related to an intersection path and damage location is either missing or unknown, then delete.	10,333,548	22.0%
Crash type is one of 1) same traffic way and same direction, 2) same traffic way, opposite direction, or 3) intersecting paths	10,282,239	21.9%

TABLE 2. Percentage of each crash type.

Crash type	Condition	Number of injured people	Percentage
1-1	Same traffic way, and same direction (rear vehicle)	2,012,385	19.6%
1-2	Same traffic way, and same direction (front vehicle)	1,344,199	13.1%
2	Same traffic way, opposite direction	530,309	5.2%
3-1	Intersection path, deformation location is front	3,548,416	34.5%
3-2	Intersection path, deformation location is other	2,798,715	27.2%
4	Other types	48,186	0.5%
Total		10,282,239	100%

TABLE 3. Graphical description of crash types.

Crash type 1-1	Crash type 2	Crash type 3-1
		
Same traffic way, and same direction (rear vehicle)	Same traffic way, opposite direction	Intersection path, deformation location is front

in crash types in 1-1, 2, and 3-1 in Table 2 and this classification is based on the 2010 coding and editing manual from NASS/CDS 2011. A graphical explanation of three specific crash types is shown in Table 3. As a result, in this paper, we used the data set to extract a total of 6,091,110 injured people for the assessment of the safety system performance.

TABLE 4. Result of the ordinal logistic regression analysis (target = MAIS level).

Analysis of Maximum Likelihood Estimates						
Crash Type	Parameter	Level	Estimate	Standard Error	Wald χ^2	Pr > χ^2
Crash type 1-1	Intercept	MAIS 6	-11.3301	0.0985	13242.3147	<.0001
	Intercept	MAIS 5	-9.1999	0.0342	72228.6761	<.0001
	Intercept	MAIS 4	-8.5456	0.0249	117788.545	<.0001
	Intercept	MAIS 3	-6.143	0.00872	496421.535	<.0001
	Intercept	MAIS 2	-4.4998	0.00553	661285.227	<.0001
	Intercept	MAIS 1	-1.903	0.00403	223286.187	<.0001
	DVTOTAL		0.0638	0.000181	124848.35	<.0001
Crash type 2	Intercept	MAIS 6	-8.3166	0.0235	125184.202	<.0001
	Intercept	MAIS 5	-7.1363	0.0159	200952.737	<.0001
	Intercept	MAIS 4	-6.2017	0.0125	247032.732	<.0001
	Intercept	MAIS 3	-4.6875	0.00909	265920.792	<.0001
	Intercept	MAIS 2	-3.1537	0.00707	198721.139	<.0001
	Intercept	MAIS 1	-0.8345	0.00575	21033.03	<.0001
	DVTOTAL		0.0789	0.00022	128303.42	<.0001
Crash type 3-1	Intercept	MAIS 6	-12.0945	0.1062	12968.2525	<.0001
	Intercept	MAIS 5	-8.8597	0.0223	158340.344	<.0001
	Intercept	MAIS 4	-7.879	0.014	317560.98	<.0001
	Intercept	MAIS 3	-5.7043	0.00567	1012119.85	<.0001
	Intercept	MAIS 2	-4.1337	0.00387	1142131.44	<.0001
	Intercept	MAIS 1	-1.1246	0.00286	154687.646	<.0001
	DVTOTAL		0.0623	0.000135	213757	<.0001

B. ASSESS PERFORMANCE OF AEB AND AEB+EAB (STEP 2)

In this part, we evaluated the performance of the AEB and AEB+EAB systems to estimate the benefits to occupants given the relationship between the velocity and injury level. To investigate the relationships between MAIS and DVTOTAL, we applied an ordinal logistic regression analysis. Table 4 shows the results of the ordinal logistic regression analysis. We note that DVTOTAL is significantly related to MAIS in all crash types.

The AEB and EAB systems were assessed with all crash data in which the percentage of offset exceeded 50%. It was found that 3,753,910 data instances benefited from the performance of the AEB system (1,426,989 data instances for crash type 1-1, 277,800 data instances for crash type 2, and 2,049,121 data instances for crash type 3-1). Additionally, the operating condition of the EAB depended on the relative velocity after the use of the AEB. Unfortunately, information on the relative velocity of each vehicle was not offered by the NASS/CDS. Therefore, we needed to calculate the relative velocity for each crash type. To calculate the relative velocity, several assumptions are required depending on the crash type.

In order to utilize the speed values in the NASS/CDS database, it was necessary to define the relative velocity, which directly influences the occupants' injury severity levels. The relative velocity should be expressed in terms of DVTOTAL. In crash type 1-1, we assumed that the relative velocity could be defined as the travel speed of the rear vehicle minus the travel speed of the front vehicle. In crash type 2, the relative velocity could be calculated as the summation of the travel speeds of the two vehicles. In crash type 3-1, we assumed that the relative velocity was equivalent to the travel speed of the vehicle which received frontal damage. These assumptions were defined by specialists of automaker A. Automaker A, which developed the EAB, defined the EAB deployment velocity as 80kmph in terms of the relative velocity.

Within the assumptions regarding the relative velocity for the three crash types, we calculate the mathematical relationship between the relative velocity and a target vehicle's travel speed. Next, we finally consider the relationships between the relative velocity and a target vehicle's DVTOTAL to simplify the analysis. The mathematical relationships are shown in Table 5.

TABLE 5. Assumptions applied to the relative velocity and DVTOTAL.

Crash type 1-1	Crash type 2	Crash type 3-1
Relative velocity = target vehicle's travel speed – front vehicle's travel speed DVTOTAL = 0.39873 * Relative velocity	Relative velocity = left vehicle's travel speed - target vehicle's travel speed ➔Relative velocity = 2.03024 * target vehicle's travel speed DVTOTAL = 0.17679 * Relative velocity	Relative velocity = target vehicle's travel speed DVTOTAL = 0.30599 * Relative velocity

Based on the above assumptions, we found the following operation speeds of the EAB in DVTOTAL: 32kmph (crash type 1-1), 14kmph (crash type 2), and 24kmph (crash type 3-1). As a result, 1,009,923 data instances were considered in light of the performance of the AEB+EAB system (111,305 data instances for crash type 1-1, 257,243 data instances for crash type 2, and 641,375 data instances for crash type 3-1).

Next, we identified the relationship between DVTOTAL and the reduced DVTOTAL when adopting the AEB or the AEB+EAB system. When the AEB and EAB systems are operated, the vehicle will delay the time of collision. Therefore, DVTOTAL is significantly reduced compared to the absence of a system.

In the previous studies, the investigators applied the reduction of crash speed to estimate the effect of a safety system. Gupta et al. [38] estimated the reduction of relative velocity based on the various scenario of pedestrian impacts on to EAB. Schoeneburg et al. [39] studied the reduction of MAIS using EAB, passenger airbag and restraint system. In this paper, the effect of safety system was estimated to be a reduction of impact speed. Based on the result of a simulation which investigated the reduced DVTOTALAEB, we developed the following Equation (1) that was estimated based on MADYMO. It is a simulation program for understanding the conditions of the vehicle accident [40]:

$$\begin{aligned} \text{ReducedDVTOTAL}_{\text{AEB}} = \alpha + \beta_1 \times \text{DVTOTAL}^1 \\ + \beta_2 \times \text{DVTOTAL}^2 \\ + \beta_3 \times \text{DVTOTAL}^3. \end{aligned} \tag{1}$$

Table 6 shows the coefficient estimated for the reduced DVTOTALAEB depending on the crash type.

AEB operation is a precondition when using EAB during crashes. The relationship found between the reduced

TABLE 6. Estimated coefficients for reduced DVTOTAL (AEB).

Parameter	Crash type 1-1	Crash type 2	Crash type 3-1
Intercept	-29.478	-13.07	-22.621
First order term	3.2599	3.2599	3.2599
Second order term	-0.0776	-0.1751	-0.1012
Third order term	0.0009	0.0044	0.0015

$\text{DVTOTAL}_{\text{EAB}}$ and reduced $\text{DVTOTAL}_{\text{AEB}}$ for each crash type is as follows:

$$\begin{aligned} &\text{Reduced DVTOTAL}_{\text{EAB}}\ (\text{crash type } 1-1) \\ &\quad = 5.113931429 - 0.394285714 \\ &\qquad \times \text{Reduced BESDVTOTAL}_{\text{AEB}} \\ &\qquad + 0.018197589 \times \text{Reduced BESDVTOTAL}^2_{\text{AEB}}; \\ &\text{Reduced DVTOTAL}_{\text{EAB}}(\text{crash type2}) \\ &\quad = 5.910954286 - 0.394285714 \\ &\qquad \times \text{Reduced BESDVTOTAL}_{\text{AEB}} \\ &\qquad + 0.015743858 \times \text{Reduced BESDVTOTAL}^2_{\text{AEB}}; \\ &\text{Reduced DVTOTAL}_{\text{EAB}}\ (\text{crash type } 3-1) \\ &\quad = 5.11024 - 0.394285714 \\ &\qquad \times \text{Reduced BESDVTOTAL}_{\text{AEB}} \\ &\qquad + 0.018210735 \times \text{Reduced BESDVTOTAL}^2_{\text{AEB}}. \end{aligned} \tag{2}$$

In addition, we classified the data into each of the crash types, 1-1, 2, and 3-1, as shown in Table 2, into two sub-types based on the percentage of offset, i.e., more than 50% or less than 50%. AEB and EAB were operated when the percentage of offset exceeded 50%.

Additionally, we conducted a binary logistic regression analysis to analyze the performance in terms of driver and passenger airbag deployment. In general, when the DVTOTAL was reduced, the probability of airbag deployment was also reduced; this is related to the severity of the occupants' injuries. We compared the average percentage of airbag deployment in the actual crash data with the percentage in the simulated data that accounted for the effect of the AEB or EAB based on the result of the logistic regression model.

In a similar manner, we analyzed the performances of the systems in terms of fatalities. The NASS/CDS data included information on the time of death. In this paper, we considered data as fatal cases when occupants died within 30 days of the crash; otherwise, we consider the data to be non-fatal. Based on Table 6 and on equations (1) and (2), we analyzed the distribution of injured people in each crash type. These distributions are shown in Table 7.

Based on the modified data pertaining to injured people in Table 7 and the result of the ordinal logistic regression

TABLE 7. Population of each sub-type.

Crash type 1-1					
Technology		AEB		AEB+EAB	
Sub-type		Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%
Population	AEB	1,426,989			
	AEB+EAB			1,426,989	
	Present		585.396		585,396
	Airbag deployment	425,995		389,835	
	Crash prevention	45,717		45,717	
	Modified injured person	1,381,272		1,381,272	
Crash type 2					
Technology		AEB		AEB+EAB	
Sub-type		Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%
Population	AEB	277,800			
	AEB+EAB			277,800	
	Present		252,509		252,509
	Airbag deployment	163,835		124,773	
	Crash prevention				
	Modified injured person	277,799		277,800	
Crash type 3-1					
Technology		AEB		AEB+EAB	
Sub-type		Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%
Population	AEB	2,049,121			
	AEB+EAB			2,049,121	
	Present		1,499,295		1,499,295
	Airbag deployment	1,080,577		650,667	
	Crash prevention	12,428		12,428	
	Modified injured person	2,036,693		2,036,693	

TABLE 8. Performance of the new safety system (injuries to people).

Crash type	Crash type 1-1					
Technology	Present		AEB		AEB+EAB	
Sub-type	Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%
Crash prevention (V)			45,717		45,717	
MAIS0	873,947	425,437	977,168	425,437	1,012,623	425,437
MAIS1	482,608	142,854	355,576	142,854	329,580	142,854
MAIS2	56,460	13,034	38,878	13,034	31,459	13,034
MAIS3	12,992	3,365	8,971	3,365	7,077	3,365
MAIS4	566	243	392	243	308	243
MAIS5	322	452	223	452	175	452
MAIS6	94	10	65	10	51	10
Crash type	Crash type 2					
Technology	Present		AEB		AEB+EAB	
Sub-type	Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%
Crash prevention (V)						
MAIS0	59,027	90,664	61,465	90,664	111,478	90,664
MAIS1	124,365	119,415	123,442	119,415	97,455	119,415
MAIS2	66,524	22,256	65,342	22,256	46,230	22,256
MAIS3	20,735	12,694	20,462	12,694	16,449	12,694
MAIS4	3,997	4,118	3,959	4,118	3,401	4,118
MAIS5	2,140	2,164	2,123	2,164	1,875	2,164
MAIS6	1,013	1,198	1,006	1,198	911	1,198
Crash type	Crash type 3-1					
Technology	Present		AEB		AEB+EAB	
Sub-type	Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%	Offset % is more than 50%	Offset % is less than 50%
Crash prevention (V)			12,428		12,428	
MAIS0	956,945	727,838	1,082,776	727,838	1,269,753	727,838
MAIS1	947,727	708,959	834,239	708,959	695,027	708,959
MAIS2	115,118	45,698	95,369	45,698	57,784	45,698
MAIS3	26,686	14,076	22,107	14,076	12,835	14,076
MAIS4	2,022	1,330	1,678	1,330	976	1,330
MAIS5	579	1,359	486	1,359	295	1,359
MAIS6	44	35	38	35	25	35

model, we estimated the number of injured people who benefited from AEB and AEB+EAB according to injury level, as shown in Table 8. The number of injured people with MAIS level j after the installation of the AEB or AEB+EAB system, (Z_j), was calculated as follows:

$$Z_j = \frac{Y_j \times O_j}{\sum_{j=0}^{6} Y_j \times O_j} \sum_{j=0}^{6} Y_j; \tag{3}$$

where $O_j = \frac{M_j}{P_j}$;

O_j is the average increase in the ratio of the MAIS level j after the installation of the AEB or AEB+EAB;

M_j is the average injury probability of the MAIS level j before the installation of the AEB or AEB+EAB;

P_j is the average injury probability of the MAIS level j after the installation of the AEB or AEB+EAB; and

Y_j represents injuries to people at MAIS level j before the installation of the AEB or AEB+EAB.

We also calculated the performances of AEB and AEB+EAB, which are defined in terms of number of people with reduced injury severity levels. These results are shown in Table 9. Table 10 summarizes the effects of the AEB+EAB and AEB systems.

IV. COST-BENEFIT ANALYSIS

A. FORECASTING THE NUMBERS OF REGISTERED VEHICLES, VEHICLE SALES AND CASUALTIES (STEP 3)

In the cost-benefit analysis, the costs and benefits to passengers are directly related to the number of registered vehicles, vehicle sales and casualties. The benefit of the vehicle safety system is the sum of the reduced costs of traffic crashes by preventing injuries or reducing their severity levels using the safety system and the discounted amounts of insurance premiums after installing the AEB or AEB+EAB system. The installation of the safety system of the vehicle is subject to premium discounts of insurance. This is considered as a benefit in CBA process. Many previous studies have been adopted this approach [40], [41], [42]. In terms of the cost savings from the reduction of injury severity levels, injury severity is expressed in terms of MAIS. Moreover, the cost of the vehicle safety system represents the buying cost for consumers. Therefore, we needed to forecast these numbers in order to calculate the benefit and cost of the safety systems. This could be done by applying Holt's model [7], which

TABLE 9. Performance of the new safety system (reduction ratio).

Crash type	Crash type 1-1			Crash type 2		
Comparison	AEB/ Present	AEB+ EAB/ present	AEB+ EAB/ AEB	AEB/ Present	AEB+ EAB/ present	AEB+ EAB/ AEB
MAIS0	1.170	1.211	1.035	1.041	1.889	1.814
MAIS1	0.737	0.683	0.927	0.993	0.784	0.789
MAIS2	0.689	0.557	0.809	0.982	0.695	0.708
MAIS3	0.691	0.545	0.789	0.987	0.793	0.804
MAIS4	0.692	0.543	0.785	0.990	0.851	0.859
MAIS5	0.692	0.543	0.785	0.992	0.876	0.883
MAIS6	0.692	0.543	0.785	0.994	0.900	0.905
Crash type	Crash type 3-1					
Comparison	AEB/ Present	AEB+ EAB/ present	AEB+ EAB/ AEB			
MAIS0	1.144	1.340	1.171			
MAIS1	0.880	0.733	0.833			
MAIS2	0.828	0.502	0.606			
MAIS3	0.828	0.481	0.581			
MAIS4	0.830	0.483	0.581			
MAIS5	0.839	0.508	0.606			
MAIS6	0.855	0.557	0.651			

TABLE 10. Summary of safety performance levels for AEB and AEB+EAB.

Crash type	Crash type 1-1			
Category	Sub-category	Present	AEB	AEB+EAB
Operation rate	AEB	0%	71%	71%
	AEB+EAB	0%	0%	7.8%
	Driver or Passenger airbag	44%	30%	27%
Analysis of occupant's injury (person)	MAIS 2+	70,434	48,529	39,069
	MAIS 3+	13,975	9,652	7,611
Fatality (person)		549	429	331
Crash type	Crash type 2			
Category	Sub-category	Present	AEB	AEB+EAB
Operation rate	AEB	0%	52%	52%
	AEB+EAB	0%	0%	92.6%
	Driver or Passenger airbag	59.5	58.9	44.91
Analysis of occupant's injury (person)	MAIS 2+	94,408	92,892	68,866
	MAIS 3+	27,884	27,551	22,636
Fatality (person)		3,245	3,239	3,189
Crash type	Crash type 3-1			
Category	Sub-category	Present	AEB	AEB+EAB
Operation rate	AEB	0%	57.75%	57.75%
	AEB+EAB	0%	0%	59
	Driver or Passenger airbag	52.73%	43.13%	24.19%
Analysis of occupant's injury (person)	MAIS 2+	144,449	119,678	57,870
	MAIS 3+	29,331	24,309	11,341
Fatality (person)		413	365	202

reflected the trends in actual data for regarding the numbers of registered vehicles, vehicle sales and casualties. Holt's method is used when the data shows a trend for a time series. In other words, a recent observation is given relatively more weight for forecasting than older observations. The numbers of registered passenger cars, vehicle sales and casualties for the target period were estimated using Holt's method, as described below:

$$\begin{aligned} &F_t = L_{t-1} + T_{t-1}, \quad t \geq 3; \\ &L_t = \omega_1 \times D_t + (1-\omega_1) \times (L_{t-1} + T_{t-1}); \\ &T_t = \omega_2 \times (L_t - L_{t-1}) + (1-\omega_2) \times T_{t-1}; \\ &L_1 = D_1; \quad T_1 = 0; \; t \geq 2; \; 0 < \omega_1, \; \omega_2 < 1; \end{aligned} \tag{4}$$

TABLE 11. Smoothing parameters in Holt's model.

	Registered vehicles	Vehicle sales	Casualties
ω_1	0.91	0.95	0.95
ω_2	0.95	0.05	0.68
MAPE	0.70%	6.70%	2.70%

where

ω_1 is the smoothing parameter for updating the mean level;
ω_2 is the smoothing parameter for updating the trend;
L_t is the mean level at time t;
D_t is the observed (or actual) value at time t;
T_t is the trend at time t;
F_t is the newly forecasted value at time t.

We used the parameters of ω_1 and ω_2 to minimize the mean absolute percentage error (MAPE):

$$MAPE = \frac{\sum_{t=3}^{n} |D_t - F_t|/D_t}{n-2}. \tag{5}$$

In this study, the MAPEs were lower than 10%, which confirmed the relatively high accuracy of forecasting in this case [40].

In the forecasting process, we used historical data of the numbers of registered passenger cars (from 1972 to 2011) and vehicle sales (from 1991 to 2012) and actual data of the number of casualties (from 1988 to 2011) in the United States. The applied smoothing parameters are shown in Table 11, and the forecasted those numbers are shown in Appendix B. In order to find the coefficient of Holt's model, we used information provided by the Bureau of Transportation Statistics (BTS) from the United States Department of Transportation.

Based on the results of Holt's model, we applied market penetration rates to the number of vehicle sales with safety systems considering two scenarios. In this study, the market penetration rate represents the proportion of vehicles with the safety system out of each year's total vehicle sales. The initial market penetration rates for both safety systems in the two scenarios were 5% and the maximum values of the market penetration rates for the AEB and AEB+EAB systems were 30% and 15%, respectively. Scenario 1 represents a situation in which the market penetration rate of AEB and AEB+EAB vehicles reached the maximum level (30% and 15%, respectively) 10 years after the introduction of these systems into the market. In scenario 2, the market penetration rates of AEB and AEB+EAB vehicles reached the maximum levels (30% and 15%, respectively) 20 years after their release. These scenarios and values referred to the cost benefit analysis of a new vehicle safety system, the frontal center curtain airbag [40]. To derive the market penetration rate of the AEB and AEB+EAB systems for the target period, we assumed that the AEB and AEB+EAB penetration rates had a tendency to increase in the manner of an S curve depending on the elapsed time. In addition, the S curve for the market penetration rate was expressed by a logistic function. The applied values of α and β in each scenario are shown in Table 12. Two parameters, α and β, are defined according

TABLE 12. Parameters used in the logistic function for the market penetration rate.

Technology	AEB		EAB	
Scenario	1	2	1	2
A	-3.18	-3.05	-3.08	-3.01
B	0.23	0.11	0.13	0.06

to the initial and maximum market penetration rates in the logistic function:

$$\text{penetration rate}(t) = \frac{\exp(\alpha+\beta t)}{1+\exp(\alpha+\beta t)}; \quad (6)$$

where α is the intercept, and
β is the penetration growth rate.

We also estimated the number of registered vehicles (H(t)), the number of vehicle sales and the number of casualties among the occupants of passenger vehicles for the target years using the Holt's model. The numbers of vehicle sales with AEB and AEB+EAB (S(t)) were obtained by multiplying the market penetration rates for each year by the number of vehicle sales for each year. On the other hand, the numbers of casualties were calculated by multiplying the cumulated market penetration rate for each year by the number of casualties for each year. The results of the estimated values are shown in Appendices A and B. Next, we introduce a benefit and a cost model in order to evaluate the economic effects with respect to passengers, after which we conduct a cost-benefit analysis.

B. ESTIMATED COSTS AND BENEFITS (STEP 4)

In this section, we propose a benefit model in relation to vehicle occupants based on the results discussed in the previous section. We define the first generation as AEB and the second generation as AEB+EAB. The benefits to occupants can be represented as the reduced cost of a traffic crash in terms of the reduced severity of injuries from crash crashes. Moreover, the discounted amounts of insurance premiums are an additional benefit to the passenger after their installation of the AEB or AEB+EAB system. Meanwhile, the cost incurred by the occupant is directly equivalent to the purchase price of the AEB or AEB+EAB system. The benefit and cost incurred by the occupant from the AEB+EAB and AEB system according to crash type at time t and the total benefit were calculated as follows:

$$\text{TotalBenefit} = \frac{\sum_{t=1}^{2}(\text{Benefit}_{i=1}(t)\,\text{PVBenefit}_{i=1}(t))}{(1+r)^t} + \frac{\sum_{t=3}^{20}(\text{Benefit}_{i=2}(t)+\text{PVBenefit}_{i=2}(t))}{(1+r)^t}; \quad (7)$$

$$\text{Totalcosts} = \frac{\sum_{t=1}^{20}\text{Cost}_i(t)}{(1+r)^t}; \quad (8)$$

where $N_i(t) = F(t)\times\left[\frac{\sum_{a=1}^{t} S_i(a)}{H(t)}\right]$;

$$\text{Benefit}_{i,h}(t) = \frac{\sum_{j=0}^{6}\sum_{k=1}^{3} N_i(t)\times DF_{i,j,k}\times CT_j(t)}{TC} + \sum_{k=1}^{3}\Big(\sum_{a=1}^{t} S(a)\times H(t)\div F(t) \times ATR_k\times(CT_{j=0}(t)+CT_{j=1}(t)) + S_i(t)\times DP_i;$$

$$\text{PVBenefit}_{i,h}(t) = \sum_{k=1}^{3}\Big(\sum_{a=1}^{t} S_i(a)\times OCCU \times \frac{F(t)}{H(t)\times OCCU}\times PVR_k\Big);$$

$$\text{Cost}_i(t) = S_i(t)\times PA_i;$$

i: Safety system generation, i∈ {1: AEB, 2: AEB and EAB};
j: MAIS class of the passenger's injury severity, j∈{0: uninjured, 1: minor, 2: moderate, 3: serious, 4: severe, 5: critical, 6: maximum};
k: Crash type, k∈ {1: same traffic way and same direction, 2: same traffic way, opposite direction, 3: intersection paths, deformation location at the front};
h: Type of safety system, h ∈ {0: AEB, 1: AEB and EAB deploying at 44kmph, 2: AEB and EAB deploying at 80kmph};
t: Elapsed time since the launch of EAB and AEB (unit: year), $t = 1, 2, \cdots, 20$;
N (t) : Number of forecasted casualties who were occupants of passenger vehicles with AEB or AEB+EAB at time t;
$DF_{i,j,k}$: Difference between the distributions of casualties before AEB or AEB+EAB were applied and after AEB or AEB+EAB was applied in the k crash type;
TC: Number of total casualties;
$CT_j(t)$: Related costs of the j injury level at time t;
F(t) : Number of crash casualties at time t;
$S_i(t)$: Sales volume of vehicles set up with AEB or AEB+EAB at time t;
H(t) : Number of registered vehicles at time t;
DP_i : Discounted amounts of insurance premium;
ATR_k : Crash occurrence ratio for each crash type;
r : Discount rate reflecting the GDP growth rate;
PA_i : Purchase price of the ith generation's safety system;
OCCU: Number of passengers per car, OCCU = 2; and
PVR_k : Proportion of prevented crashes for each crash type.

In the cost-benefit analysis, the benefit was divided by the cost in order to obtain the benefit/cost ratios from the customer's point of view and benefit/cost ratios that could support commercialization decisions. We represented the calculated result of the cost and benefit according to each crash type: crash type 1-1 (same traffic way and same direction), 2 (same traffic way), and 3-1 (intersection paths, deformation location at the front).

The sales volume for vehicles featuring the safety systems (S(t)) was estimated from the results of Holt's forecasting method and by multiplying the market penetration rates in

TABLE 13. Assumptions used in the cost-benefit analysis.

Items	Specific Items	Descriptions
Price	AEB	$600 / vehicle
	AEB+EAB	$1,500 / vehicle
Discount amounts of insurance premium	AEB	$22.78 / vehicle
	AEB+EAB	$ 45.56 / vehicle
GDP growth rate	United States	2.01%

the S curves in Section IV-A. The differences between the distributions of casualties which stemmed from the safety systems ($DF_{i,j,k}$) before and after the installation of the safety systems were derived from the empirical data set provided by the NASS/CDS in order to calculate the benefits of both the AEB and AEB+EAB systems. The total number of casualties (TC) was used to change the scale of the reduced numbers of casualties from the sample to all crashes. According to each crash type, the changed distributions of casualties over injury levels caused by the installation of an AEB or an AEB+EAB system and the performance of each technology are given in section V. In order to calculate the benefits with respect to passengers, we used the ratio between the changed distribution of each injury level and the total number of casualties.

In addition, we considered the causality cost ($CT_j(t)$) to calculate the benefits from the reduced severity of occupants' injuries. These values were reported by the NHTSA [44]. To forecast the future value of the benefits, we applied an exponentially weighted moving average (EWMA) method based on the GDP growth rate of the United States during the period from 2000 to 2012 to the causality costs according to the injury level. The EWMA method represents the estimated level at time t, and this method gives more weight to recent information. The weight in the EWMA method was assigned as 0.7. The estimated costs in the United States are displayed in Appendix C. Moreover, information regarding the pricing of the systems was provided by automaker A, and the discounted amounts of insurance premiums stemming from the installation of the AEB or the AEB+EAB system referred to insurance premium discounts for installing an antilock braking system (ABS). Our assumptions regarding the price, the discounted insurance premiums and the GDP growth rate are shown in Table 13.

For a socioeconomic evaluation of the AEB+EAB and AEB systems, we calculated the net present value (NPV) of the benefits and costs using a discount rate which reflected the GDP growth rate in the United States. The results of the benefit/cost ratio with respect to scenarios 1 and 2 in the United States are displayed in Table 14.

With respect to the occupants, the benefit/cost ratios of AEB were 0.553 and 0.509 in scenarios 1 and 2, while the benefit/cost ratios of AEB+EAB were 0.509 and 0.496 for scenarios 1 and 2, respectively.

TABLE 14. Benefit/cost ratios for safety system scenarios 1 and 2 in the United States.

Scenarios	AEB		AEB+EAB	
	1 (t=10)	2 (t=20)	1 (t=10)	2 (t=20)
NPV (Benefit)	8,454,748,653	5,038,554,329	10,332,522,308	7,539,192,400
NPV (Cost)	15,295,704,240	9,899,726,324	20,299,153,274	15,211,827,378
Benefit/cost ratio	0.553	0.509	0.509	0.496

TABLE 15. Breakeven costs of the safety systems in scenario1.

	AEB	AEB+EAB
Breakeven costs	$305.4	$763.5

TABLE 16. Sensitivity analysis with initial market penetration ratio for AEB and AEB+EAB (United states).

Initial market penetration ratio					Maximum market penetration ratio			Prices				
Condition	AEB		AEB+EAB		Condition	AEB+EAB		Condition (AEB, AEB+EAB)	AEB		AEB+EAB	
	t=10	t=20	t=10	t=20		t=10	t=20		t=10	t=20	t=10	t=20
1%	0.50	0.40	0.44	0.37	11%	0.53	0.52	$500, $1250	0.66	0.61	0.61	0.59
3%	0.53	0.47	0.48	0.45	13%	0.52	0.51	$550, $1375	0.60	0.56	0.56	0.54
5%	0.55	0.51	0.51	0.50	15%	0.51	0.50	$600, $1500	0.55	0.51	0.51	0.50
7%	0.57	0.54	0.53	0.53	17%	0.50	0.48	$650, $1625	0.51	0.47	0.47	0.46
9%	0.58	0.56	0.55	0.55	19%	0.50	0.48	$700, $1750	0.47	0.44	0.44	0.42

C. ESTIMATED COSTS AND BENEFITS (STEP 4)

The breakeven cost is the AEB or AEB+EAB cost, where the sum of these costs is equal to the sum of the benefits from the customer's point of view. The breakeven cost can provide directions with regard to a system's cost in relation to its benefits for vehicle occupants. In this section, we determined the breakeven costs for AEB and AEB+EAB by changing the costs of these systems in the same proportion when the market conditions in scenario 1 had the maximum market penetration rates achieved during the tenth period. The breakeven costs of the safety systems in the United States are shown in Table 15.

To determine the variation in the benefit/cost ratio depending on the market condition, we also conducted a sensitivity analysis with the three parameters of the initial market penetration ratio, the maximum market penetration ratio and the price of the AEB or AEB+EAB system. Considering the maximum market penetration rates, because AEB and AEB+EAB systems have different maximum market penetration rates, we only conducted the sensitivity analysis using the rates for the AEB+EAB system. This result is shown in Table 16. The initial market penetration rates for both the AEB and AEB+EAB systems ranged from 1% to 9%, and the maximum market penetration rate for AEB+EAB ranged from 11% to 19%. Moreover, the prices of the AEB and AEB+EAB systems ranged from $500 to $700 and from $1250 to $1750, respectively. The results of the sensitivity analysis are shown below.

First, in both scenarios in general, the benefit/cost ratio gradually increased with the initial market penetration rate. Second, considering the sensitivity analysis with the

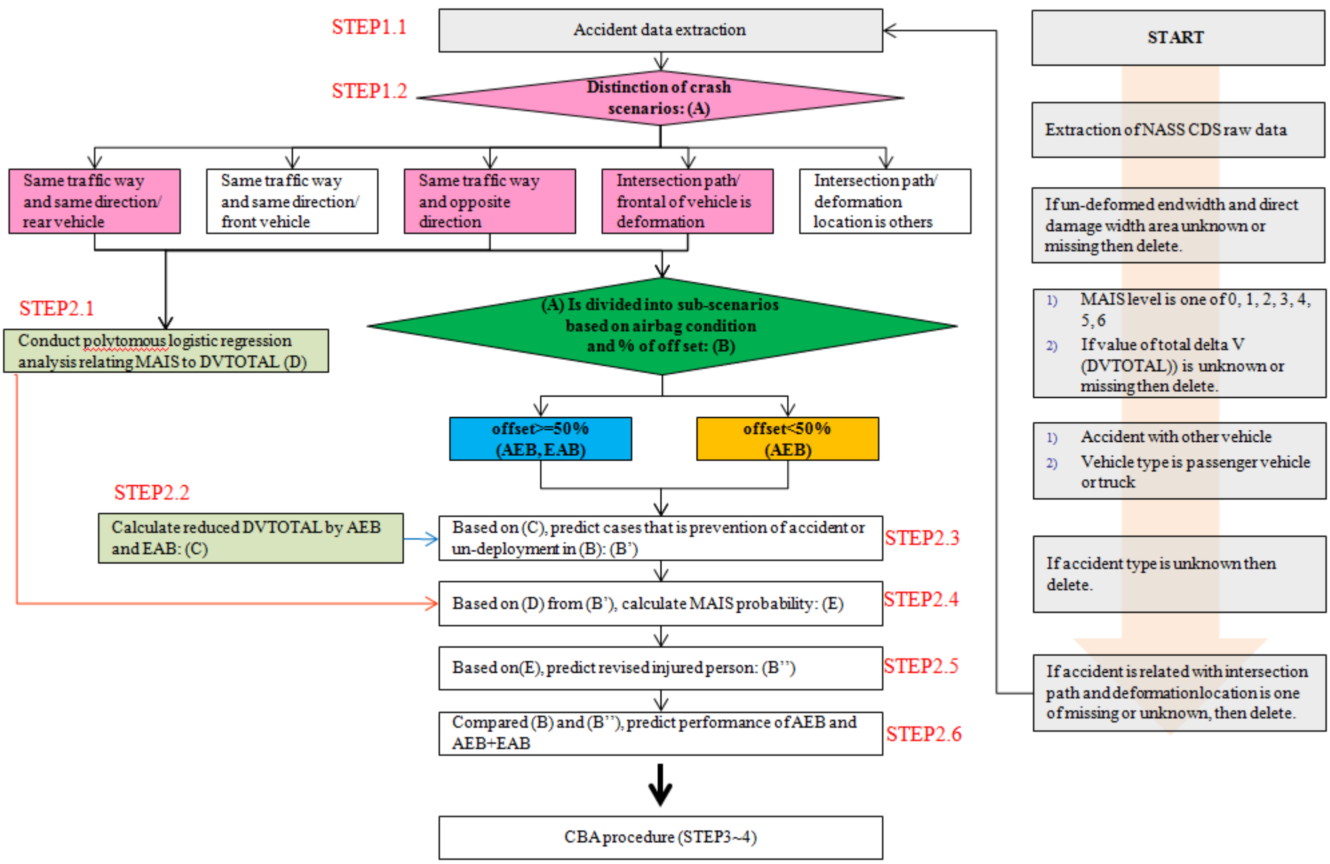


FIGURE 1. Framework for the estimation of the AEB and AEB+EAB performance levels.

maximum market penetration rate, the benefit/cost ratio for passengers decreased as the maximum market penetration rate increased. Lastly, in the sensitivity analysis with the prices of the AEB and AEB+EAB systems, the benefit/cost ratio for passengers decreased when the AEB and AEB+EAB prices increased.

V. CONCLUSION

Vehicle safety systems have led to a reduction in the severity of injuries suffered by occupants of vehicles involved in crashes. The airbag system, which is one of the main safety systems used at present, can prevent serious injuries and reduce mortality rates during collisions. Recently, a new type of airbag system, the external airbag (EAB), was developed for installation onto the front bumpers of vehicles. In this paper, we conducted a cost-benefit analysis of these EAB systems, which have not yet been introduced into the market. With respect to automobile companies, effective decision-making has been emphasized for the introduction of new safety systems. Thus, we proposed a framework for a performance estimation of the autonomous emergency braking (AEB) system and the EAB system and then analyzed the effectiveness of the safety system with a socioeconomic evaluation of the EAB system.

To determine the effectiveness of a new safety system including both EAB and AEB devices, we extracted empirical data which consisted of information related to crash crashes from the NASS/CDS and applied ordinal logistic regression by MAIS in order to analyze the safety performance levels of AEB and AEB+EAB based on injuries to people in each crash type. Furthermore, using the performance estimation results for AEB and AEB+EAB, we conducted a cost-benefit analysis to support decision-making processes. In our cost-benefit analysis model, we calculated the benefits and costs from the perspective of passengers. We employed the Holt's method to forecast the number of registered vehicles, the number of vehicles sold, and the number of causalities. We then applied the proposed cost-benefit analysis model to the AEB and AEB+EAB cases in the United States market to assess the viability of the commercialization of these systems. The benefit/cost ratios for AEB are 0.553 and 0.509 in scenarios 1 and 2, and the benefit/cost ratios for AEB+EAB are 0.509 and 0.496 for scenarios 1 and 2, respectively.

When an automaker decides whether to commercialize a system, they should consider not only the benefit/cost ratios but also the performance of the system in relevant crashes and the socioeconomic effectiveness of the system. Although the benefit/cost ratio was less than 1, AEB+EAB showed a performance rate of 46% in terms of reducing injury risks for

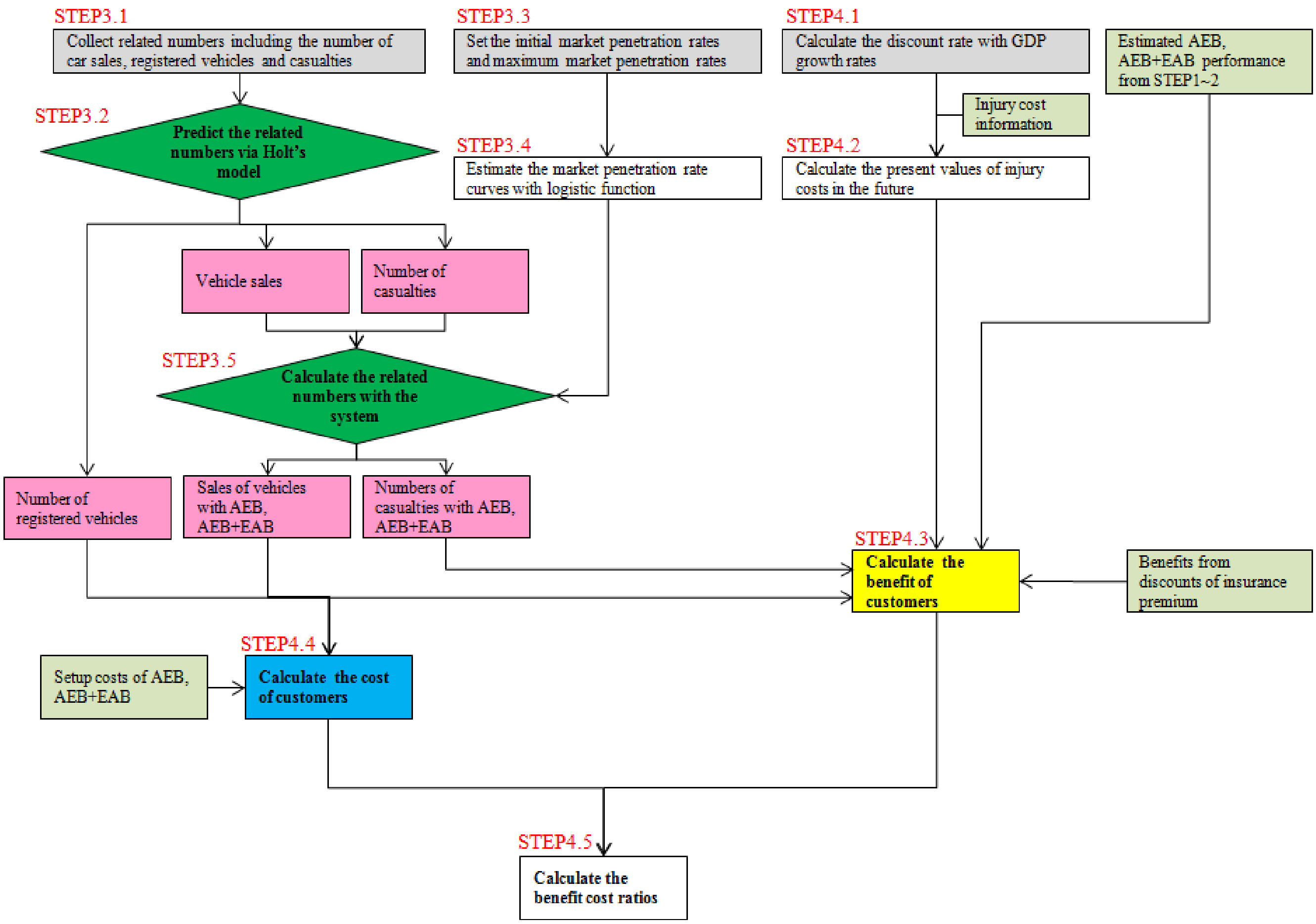


FIGURE 2. Framework for the cost-benefit analysis of the AEB and AEB+EAB systems.

MAIS3+ and good socioeconomic effectiveness in that led to savings of half a billion dollars on average per year. Moreover, according to Paine [43], other safety systems which are commercialized, such as the side airbag (BCR = 0.2) and the front passenger airbag (BCR = 0.19), were reasonably commercialized, meaning that the EAB system, whose benefit/cost ratio exceeds 0.2, is also adequate for commercialization. Moreover, in order to suggest the direction of the system's cost, we calculated the breakeven costs of the systems. The breakeven cost for the AEB device is \$305.4 and the cost of the AEB+EAB system is \$763.5.

Next, we conducted a sensitivity analysis to consider various factors, such as market circumstances and price conditions. In the sensitivity analysis, considering the initial market penetration rate and maximum market penetration rate, the benefit/cost ratio for customers increased with those rates.

Our study has proposed an approach not only to estimate the performance based on reduced injury severity levels but also to evaluate the socioeconomic effect of a new safety system featuring both EAB and AEB devices. This research focused on estimating the effectiveness of AEB/EAB using real-world vehicle accident data. Additionally, we suggested a CBA of the effectiveness of AEB+EAB for vehicles by combining its MAIS reduction effects, which is a novel approach that has not been previously reported. We expect that the proposed framework will help decision-makers to reach more effective decisions related to new safety systems.

Nevertheless, this study has a number of limitations. First, the proposed benefit and cost model includes parameters that are influenced by external environmental factors. Therefore, in further research, the accident types should be divided in detailed scenarios and the effects of various environmental factors need to be included. Second, we applied traditional methods to calculate future costs and benefits based on the GDP growth rate. This method does not reflect non-economic values related to environmental factors or macroeconomic factors. However, the proposed framework is expected to be applicable for examining the potential commercialization of new products. Third, we only conducted a cost-benefit analysis for AEB and AEB+EAB in the United States. Comparisons of the benefit/cost ratios of these types of safety systems in other nations are left for future work. Additionally, in order to operate EAB, AEB must be activated. In the future, a system that evaluates the information related to the severity of accidents along with AEB needs to be developed to determine the deployment of EAB.

TABLE 17. Forecasted number of registered vehicles, casualties and sales of vehicles with AEB and AEB+EAB systems.

Years	Registered vehicles	Vehicle sales						Casualties					
	Vehicles	AEB			AEB+EAB			AEB			AEB+EAB		
	H(t)_United States	The forecasted number of vehicle sales (US)	S(t)_United States		The forecasted number of vehicle sales (US)	S(t)_United States		The forecasted number of casualties (US)	F(t)_United States		The forecasted number of casualties (US)	F(t)_United States	
			t=10	t=20		t=10	t=20		t=10	t=20		t=10	t=20
2015	130,434,284	7,165,854	358,293	358,293	7,165,854	358,293	358,293	1,222,547	3,358	3,358	1,222,547	3,358	3,358
2016	129,434,829	7,175,965	447,082	398,345	7,175,965	407,491	381,135	1,215,188	7,561	7,104	1,215,188	7,189	6,942
2017	128,435,374	7,186,076	556,100	442,590	7,186,076	462,995	405,350	1,207,829	12,804	11,278	1,207,829	11,556	10,766
2018	127,435,919	7,196,187	689,018	491,403	7,196,187	525,485	431,010	1,200,471	19,316	15,926	1,200,471	16,525	14,844
2019	126,436,463	7,206,298	849,692	545,175	7,206,298	595,678	458,189	1,193,112	27,367	21,098	1,193,112	22,175	19,194
2020	125,437,008	7,216,409	1,041,920	604,315	7,216,409	674,320	486,963	1,185,754	37,265	26,848	1,185,754	28,588	23,830
2021	124,437,553	7,226,520	1,269,084	669,243	7,226,520	762,175	517,411	1,178,395	49,349	33,233	1,178,395	35,857	28,772
2022	123,438,098	7,236,631	1,533,661	740,386	7,236,631	860,007	549,613	1,171,036	63,987	40,317	1,171,036	44,080	34,038
2023	122,438,643	7,246,742	1,836,663	818,174	7,246,742	968,558	583,652	1,163,678	81,560	48,166	1,163,678	53,366	39,648
2024	121,439,187	7,256,854	2,177,056	903,030	7,256,854	1,088,528	619,612	1,156,319	102,441	56,854	1,156,319	63,830	45,621
2025	120,439,732	7,266,965	2,180,089	995,362	7,266,965	1,090,045	657,578	1,148,960	123,431	66,457	1,148,960	74,348	51,980
2026	119,440,277	7,277,076	2,183,123	1,095,554	7,277,076	1,091,561	697,637	1,141,602	144,533	77,055	1,141,602	84,924	58,747
2027	118,440,822	7,287,187	2,186,156	1,203,950	7,287,187	1,093,078	739,874	1,134,243	165,749	88,734	1,134,243	95,556	65,946
2028	117,441,366	7,297,298	2,189,189	1,320,848	7,297,298	1,094,595	784,376	1,126,885	187,081	101,582	1,126,885	106,247	73,603
2029	116,441,911	7,307,409	2,192,223	1,446,478	7,307,409	1,096,111	831,230	1,119,526	208,531	115,692	1,119,526	116,998	81,741
2030	115,442,456	7,317,520	2,195,256	1,580,993	7,317,520	1,097,628	880,521	1,112,167	230,103	131,158	1,112,167	127,809	90,390
2031	114,443,001	7,327,631	2,198,289	1,724,451	7,327,631	1,099,145	932,333	1,104,809	251,799	148,076	1,104,809	138,683	99,577
2032	113,443,546	7,337,742	2,201,323	1,876,805	7,337,742	1,100,661	986,748	1,097,450	273,621	166,541	1,097,450	149,621	109,331
2033	112,444,090	7,347,853	2,204,356	2,037,884	7,347,853	1,102,178	1,043,843	1,090,092	295,572	186,651	1,090,092	160,624	119,682
2034	111,444,635	7,357,964	2,207,389	2,207,389	7,357,964	1,103,695	1,103,695	1,082,733	317,655	208,500	1,082,733	171,693	130,663

TABLE 18. Casualty cost in the united states (in U.S. Dollars).

Injury Severity	United States	
	Total costs2000	Total costs2015
MAIS 0	$1,962	$2,646
MAIS 1	$10,562	$14,244
MAIS 2	$66,820	$90,111
MAIS 3	$186,097	$250,965
MAIS 4	$348,133	$469,481
MAIS 5	$1,096,161	$1,478,249
MAIS 6	$977,208	$1,317,833

*Source: NHTSA, The Economic Cost of Motor Vehicle Crashes, Washington DC: NHTSA, 2000

APPENDIX A
FRAMEWORKS FOR THE COST-BENEFIT ANALYSIS OF EAB AND AEB SYSTEMS

See Figures 1 and 2.

APPENDIX B
FORECASTED NUMBER OF REGISTERED PASSENGER VEHICLES, VEHICLE SALES AND CASUALTIES IN THE UNITED STATES

See Table 17.

APPENDIX C
CASUALTY COST IN THE UNITED STATES

See Table 18.

REFERENCES

[1] P. M. Wilks, "Safety in car design," *Proc. Roy. Soc. Med.*, vol. 60, no. 10, p. 955, 1967.

[2] F. Mo, X. Jiang, S. Duan, Z. Xiao, S. Xiao, and W. Shi, "Parametric analysis of occupant ankle and tibia injuries in frontal impact," *PLoS ONE*, vol. 12, no. 9, 2017, Art. no. e0184521.

[3] P. L. Zador and M. A. Ciccone, "Automobile driver fatalities in frontal impacts: Air bags compared with manual belts," *Amer. J. Public Health*, vol. 83, no. 5, pp. 661–666, 1993.

[4] H. A. Deery, A. P. Morris, B. N. Fildes, and S. V. Newstead, "Airbag technology in Australian passenger cars: Preliminary results from real world crash investigations," *J. Crash Prevention Injury Control*, vol. 1, no. 2, pp. 121–128, 1999.

[5] F. A. Pintar, N. Yoganandan, and T. A. Gennarelli, "Airbag effectiveness on brain trauma in frontal crashes," in *Proc. Annu. Assoc. Advancement Automot. Med.*, vol. 44, no. 1, 2000, p. 149.

[6] M. Segui-Gomez, "Driver airbag effectiveness by severity of the crash," *Amer. J. Public Health*, vol. 90, no. 10, pp. 1575–1581, 2000.

[7] C. C. Holt, "Forecasting seasonals and trends by exponentially weighted moving averages," *Int. J. Forecasting*, vol. 20, no. 1, pp. 5–10, 2004.

[8] J. S. Shane, "Design and testing of an energy-absorbing crewseat for the F/FB-111 aircraft," Nat. Aeronaut. Space Admin., Washington, DC, USA, Tech. Rep. NASACR-3916, 1985.

[9] S. Kellas, K. E. Jackson, and J. D. Littell, "Full-scale crash test of a MD-500 helicopter with deployable energy absorbers," in *Proc. 66th AHS Annu. Forum*, Phoenix, AZ, USA, 2010, pp. 1–12.

[10] J. Holnicki-Szulc, P. Pawlowski, M. Mikulowski, and C. Graczykowski, "Adaptive impact absorption and applications to landing devices," *Adv. Sci. Technol.*, vol. 56, pp. 609–613, Feb. 2008.

[11] B. Pipkorn, R. Fredriksson, and J. Olsson, "Bumper bag for SUV to passenger vehicle compatibility and pedestrian protection," in *Proc. Exp. Saf. Vehicles Conf.*, 2007, pp. 1–12.

[12] S. Barbat, X. Li, and P. Prasad, "Bumper and grille airbags concept for improved vehicle compatibility in side impact: Phase I," in *Proc. 23rd Int. Tech. Conf. Enhanced Saf. Vehicles*, 2013, pp. 27–30.

[13] S. Barbat, X. Li, and P. Prasad, "Bumper and grille airbags concept for enhanced vehicle compatibility in side impact: Phase II," *Traffic Injury Prevention*, vol. 14, no. 1, pp. S30–S39, 2013.

[14] K. D. Kusano and H. C. Gabler, "Potential occupant injury reduction in pre-crash system equipped vehicles in the striking vehicle of rear-end crashes," *Accident Anal. Prevention*, vol. 42, no. 6, pp. 1949–1957, 2010.

[15] A. Georgi, M. Zimmermann, T. Lich, L. Blank, N. Kickler, and R. Marchthaler, "New approach of accident benefit analysis for rear end collision avoidance and mitigation systems," in *Proc. 21st Int. Tech. Conf. Enhanced Saf. Vehicles*, Stuttgart, Germany, 2009, pp. 1–8.

[16] A. Balint, H. Fagerlind, and A. Kullgren, "A test-based method for the assessment of pre-crash warning and braking systems," *Accident Anal. Prevention*, vol. 59, no. 1, pp. 192–199, 2013.

[17] D. C. Viano and C. S. Parenteau, "Injury risks in frontal crashes by delta V and body region with focus on head injuries in low-speed collisions," *Traffic Injury Prevention*, vol. 11, no. 4, pp. 382–390, 2010.

[18] T. Lieutaud, B. Gadegbeku, A. Ndiaye, M. Chiron, and V. Viallon, "The decrease in traumatic brain injury epidemics deriving from road traffic collision following strengthened legislative measures in France," *PLoS ONE*, vol. 11, no. 11, 2016, Art. no. e0167082.

[19] Y. H. Ju and S. Y. Sohn, "Time to death analysis of road traffic accidents in relation to delta V, drunk driving, and restraint systems," *Traffic Injury Prevention*, vol. 15, no. 8, pp. 771–777, 2014.

[20] D. J. Gabauer and H. C. Gabler, "Comparison of delta-V and occupant impact velocity crash severity metrics using event data recorders," in *Proc. Annu. Assoc. Adv. Automot. Med.*, vol. 50. Association for the Advancement of Automotive Medicine, 2006, p. 57.

[21] L. Hannawald, *Multivariate Bewertung Zukünftiger Fahrzeugsicherheit*. Dresden, Germany: Technische Universität Dresden, 2008.

[22] C. E. Hampton and H. C. Gabler, "Influence on the missing vehicle and CDC-only delta-V reconstruction algorithms for prediction of occupant injury risk," *Biomed. Sci. Instrum.*, vol. 45, no. 1, pp. 238–243, 2009.

[23] D. Richards and R. Cuerden, "The relationship between speed and car driver injury severity," Dept. Transp., London, U.K., Tech. Rep. Road Safety Web Publication 9, 2009.

[24] M. Detwiller and H. C. Gabler, "Potential reduction in pedestrian collisions with an autonomous vehicle," in *Proc. 25th Int. Tech. Conf. Enhanced Saf. Vehicles (ESV)*, Detroit, MI, USA, Jun. 2017, pp. 5–8.

[25] J. Zhang, Z. Li, Z. Pu, and C. Xu, "Comparing prediction performance for crash injury severity among various machine learning and statistical methods," *IEEE Access*, vol. 6, pp. 60079–60087, 2018.

[26] R. Bender and U. Grouven, "Ordinal logistic regression in medical research," *J. Roy. College Phys. London*, vol. 31, no. 5, p. 546, 1997.

[27] R. Robinson, "Cost-benefit analysis," *Brit. Med. J.*, vol. 307, no. 6909, pp. 924–926, 1993.

[28] H. Mohring, "Maximizing, measuring, and not double counting transportation-improvement benefits: A primer on closed-and open-economy cost-benefit analysis," *Res. B, Methodol.*, vol. 27, no. 6, pp. 413–424, 1993.

[29] H. J. Kim, S. J. Jee, and S. Y. Sohn, "Cost-benefit model for multi-generational high-technology products to compare sequential innovation strategy with quality strategy," *PLoS ONE*, vol. 16, no. 4, 2021, Art. no. e0249124.

[30] A. E. Boardman, D. H. Greenberg, A. R. Vining, and D. L. Weimer, *Cost-Benefit Analysis: Concepts and Practice*. Cambridge, U.K.: Cambridge Univ. Press, 2017.

[31] European Commission-DT RGD, European Commission Directorate General Energy and Transport. (2006). *Cost-Benefit Assessment and Prioritization of Vehicle Safety Technologies*. [Online]. Available: http://ec.europa.eu/transport/roadsafety_library/publications/vehicle_safety_technologies_final_report.pdf

[32] R. W. G. Anderson, T. P. Hutchinson, B. Linke, and G. Ponte, "Analysis of crash data to estimate the benefits of emerging vehicle technology," Centre Automot. Saf. Res., Univ. Adelaide, Adelaide SA, Australia, Tech. Rep. CASR094, 2011.

[33] O. M. J. Carsten and F. N. Tate, "Intelligent speed adaptation: Accident savings and cost-benefit analysis," *Accident Anal. Prevention*, vol. 37, no. 3, pp. 407–416, 2005.

[34] B. Robinson, W. Hulshof, R. Cookson, R. Cuerden, R. Hutchins, and E. Delmonte, "Cost benefit evaluation of advanced primary safety systems-final report," Transp. Res. Lab., Wokingham, U.K., TRL Rep. PPR 586, 2011, pp. 1–68, vol. 1, no. 1.

[35] J. Buhne, A. Ludeke, S. Schonebeck, J. Dobberstein, H. Fagerlind, A. Balint, and M. McCarthy, "Assessment of integrated vehicle safety systems for improved vehicle safety," *Proc.-Social Behav. Sci.*, vol. 48, no. 1, pp. 1632–1641, 2012.

[36] J. Padmanaban and M. Davis, "Re-evaluation of rear seat restraint system effectiveness in preventing fatalities, using recent fatal accident data," in *Proc. Annu. Assoc. Advancement Automot. Med.*, vol. 43, 1999, p. 399.

[37] K. Bohman, E. Rosén, C. Sunnevang, and O. Boström, "Rear seat occupant thorax protection in near side impacts," in *Proc. Ann. Adv. Automot. Med./Annu. Sci. Conf.*, vol. 53, 2009, p. 3.

[38] A. Gupta, F. Alvarez, T. Daniel, and D. Larner, "Investigating the use of adhesively-coated external airbag to reduce post-impact kinematics," in *Proc. IRCOBI Conf.*, 2017, pp. 1–10.

[39] R. Schoeneburg, K. H. Baumann, M. Fehring, D. Ag, and M. Cars, "The efficiency of PRE-SAFE systems in pre-braked frontal collision situations," in *Proc. 22nd ESV Conf.*, Jun. 2011, pp. 1–11, Paper 11-0207.

[40] B. K. Lee, E. J. Han, S. Y. Sohn, Y. S. Kim, J. Y. Yoon, and J. Y. Choi, "A cost-benefit analysis to assess the effectiveness of frontal center curtain airbag," *Sustainability*, vol. 9, no. 10, p. 1745, 2017.

[41] M. Distner, M. Bengtsson, T. Broberg, and L. Jakobsson, "City safety—A system addressing rear-end collisions at low speeds," in *Proc. 21st Int. Tech. Conf. Enhanced Saf. Vehicles*, Jun. 2009, pp. 1–7, Paper 09-0371.

[42] H. Lahrmann, N. Agerholm, N. Tradisauskas, T. Næss, J. Juhl, and L. Harms, "Pay as you speed, ISA with incentives for not speeding: A case of test driver recruitment," *Accident Anal. Prevention*, vol. 48, pp. 10–16, Sep. 2012.

[43] M. Paine, "Encouraging the purchase of safer vehicles—Part A (benefits and costs of vehicle safety features)," Vehicle Des. Res. Pty Ltd., Beacon Hill, NSW, Australia, Tech. Rep. G227A, 2002.

[44] L. J. Blincoe, A. G. Seay, E. Zaloshnja, T. R. Miller, E. O. Romano, S. Luchter, and R. S. Spicer, "The economic impact of motor vehicle crashes, 2000," Nat. Highway Traffic Saf. Admin., Washington, DC, USA, Tech. Rep. DOT-HS-809-446, 2002.

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