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A Cost–Benefit Analysis to Assess the Effectiveness of Frontal Center Curtain Airbag

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Abstract: Several new varieties of airbags are under consideration for development. However, their commercialization decision must be backed by a positive Cost–Benefit Analysis (CBA) outcome. In this study, we propose a CBA framework for the frontal center curtain airbag, a newly designed safety system intended to reduce the injury risk of rear-seat passengers. The proposed CBA covers not only economic benefits of the producer but also the effectiveness in sustainable reduction of the fatal and injury rate. In this context, with accumulated field data on road traffic accidents, a forecasting method reflecting the reduced casualties and the market share of vehicle sales associated with frontal center curtain airbag is utilized. Our results suggest that the use of frontal center curtain airbags helps to reduce the number of casualties with a Maximum Abbreviated Injury Scale (MAIS) of 3 or above by 87.4%. Furthermore, both the initial market penetration rate and price of the frontal center curtain airbag significantly influence its socioeconomic benefits. By evaluating the effectiveness of the frontal center curtain airbag, our study can contribute to the decision making for its commercialization.

Keywords: frontal center curtain airbag; vehicle safety system; Cost–Benefit Analysis

1. Introduction

The launch of a new type of safety system in a market requires the estimation of its socioeconomic effects, which is necessary for the sustainable management of technology [1–3]. In this context, some previous works developed the Cost–Benefit Analysis (CBA) framework, which has generally been used to assess the effectiveness of safety systems quantitatively. However, these works primarily rely on field accident cases. Thus, the application of the established CBA framework is limited for a new safety system that has not been installed in a fleet. To fill this gap, this study proposes a CBA framework with a forecasting model for a newly-developed safety system that has not been launched in the market yet. Herein, we consider the case of the frontal center curtain airbag.

In the proposed framework, we predict the injury severity reduction of potential passengers based on the functionality of a safety system using data from the National Automotive Sampling System—Crashworthiness Data System (NASS-CDS). This study focuses on the role of the safety system in sustainable reduction in fatal and injury rate with considering the monetary value of injury severity reduction as the benefits of the safety system installation [4]. Additionally, to estimate the potential passengers who will benefit from the safety system, we forecast the future sales of vehicles that include this system as a basic option. We utilize the past sales records of the automaker that developed a safety system. Then, for sensitivity analysis, we conduct multiple CBAs by adjusting the parameters of market saturation periods and the cumulative market penetration rate.

Subsequently, we apply the proposed framework to the frontal center curtain airbag, a new type of safety system. Airbags have been considered as safety systems that can reduce the severity of injuries by preventing direct crashes into the interior parts of the vehicle. Many previous studies have investigated the effectiveness of airbags according to their types [5–8]. However, these studies solely focused on the protection of the front-seat passengers.

On the other hand, the frontal center curtain airbag is designed to protect rear-seat passengers from direct collisions with various injury sources at the front side. As shown in Figure 1, this airbag is installed inside the headlining, and horizontally in the roof between the front and the rear seats. The frontal center curtain airbag is expected to be deployed between the front seat and the rear seat right after the deployment of the frontal airbag in the first row to prevent frontal crash, side crash, or roll-over accident.

We consider such distinctive features of the new safety system in the proposed CBA framework.

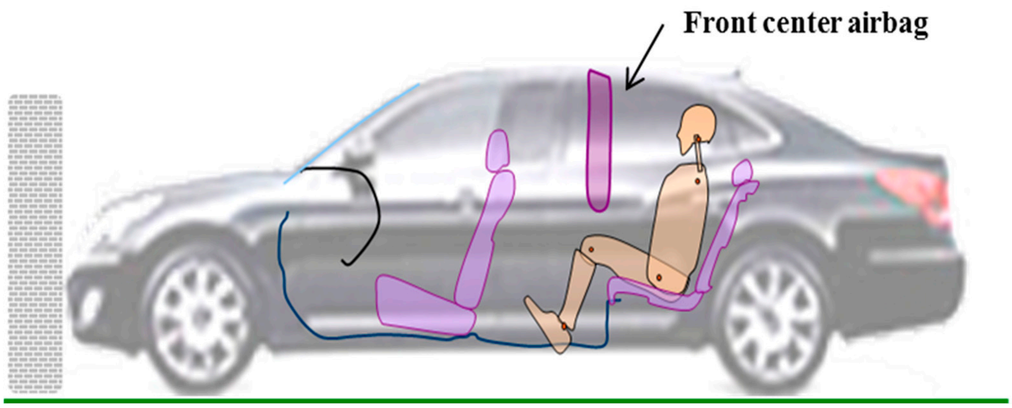

Figure 1. Concept of frontal center curtain airbag.

The remainder of the paper is organized as follows. Section 2 presents related studies and Section 3 describes the steps of the proposed framework. Section 4 analyzes the case of the frontal center curtain airbag. Finally, Section 5 concludes the study and discusses future research directions.

2. Literature Review

2.1. Cost–Benefit Analysis of Safety Systems

Many previous studies have attempted to investigate the socioeconomic effects of vehicle safety systems by CBA [9]. Previous studies on the effectiveness of safety systems are summarized in Table 1.

Most studies utilized traffic accident data and considered accident reduction as the benefit of safety systems. In terms of benefit, the expected injury reductions of safety systems are assessed by experts [10] based on previous studies [11] or on traffic accident data or test data.

Fildes et al. [10] conducted CBA for full-size driver airbags and facebags and compared their effectiveness. The authors considered harm reduction for front-seat occupants to analyze the effectiveness of these devices. Since airbags play an important role in protecting passengers from frontal impacts, the authors utilized frontal crash data from Australia. Similarly, Evans [12] studied the effectiveness of front airbags using the Fatality Analysis Reporting System (FARS) and NASS-CDS data. The author extracted two Maximum Abbreviated Injury Scale (MAIS) distributions for the accident cases in these databases: one where the front airbag was deployed and the other where it was not deployed. Thereafter, two injury risk probabilities are compared in terms of the MAIS, and the reduced MAIS is considered for the effectiveness of the airbags.

Table 1. Summary of previous studies on the effectiveness of safety systems.

Fildes et al. [10]	Safety system	Full size Airbag, Facebag
	Data	Australian database (Crashed Vehicle File)
	Benefit	Harm reduction (The expected injury reductions of facebag is assessed by experts)
	Cost	Airbag and facebag costs
	BCR	Full size Airbag = 1.17, Facebag (Maximum) = 0.98, Facebag (Intermediate) = 0.69, Facebag (Minimum) = 0.58
	Characteristic	The different benefit scenarios for facebag (Maximum, Intermediate, Minimum)
COWI [11]	Safety system	21 vehicle safety technologies
	Data	EU CARE database
	Benefit	A reduced number of fatalities/injuries × Accident costs
	Cost	The installment costs
	BCR	0.04–8.2
	Characteristic	Promotion (Do-nothing, Do-something scenarios)
Evans [12]	Safety system	Frontal airbag
	Data	Fatality Analysis Reporting System (FARS) data, NASS-CDS
	Benefit	The net annual benefit (Injury reduction - replacement costs)
	Cost	The initial total purchase costs ÷ a 10 year life of the car
	BCR	For drivers, net annual benefit = \$1.14 billion, net annual cost = \$3.00 billion For passengers, net annual benefit = -\$0.13 billion, net annual cost = \$2.42 billion
	Characteristic	-
Robinson et al. [13]	Safety system	AEBS (Advanced Emergency Brake Systems), LDWS (Lane Departure Warning Systems), Youth key
	Data	STATS19 data
	Benefit	Annual casualty savings
	Cost	System costs
	BCR	AEBS for passenger = 0.07–2.78, AEBS for pedestrian = 0.19–1.04, LDWS = 0.25–2.12, Youth key = 0.69–11.2
	Characteristic	Reductions in serious and slight casualties
ASSESS [14]	Safety system	Pre-crash safety system (Emergency Braking System)
	Data	NASS CDS, eIMPACT's ProgTrans data
	Benefit	Annual system cost × Fleet penetration rate × Car fleet
	Cost	Break even costs
	BCR	-
	Characteristic	Market penetration, Accident trend

As seen in Table 1, CBA has been utilized to assess the effectiveness of not only airbags but also several safety systems. The COWI [11] performed a CBA on 18 different safety devices based on different market share scenarios. It estimated the effectiveness of 21 different safety devices across European countries, and each nation's Gross Domestic Product (GDP) per capita was reflected to correct the differences in the economic wealth of the countries. Particularly, the casualty costs-unit rates are controlled according to the national GDP per capita.

In addition, Robinson et al. [13] conducted a CBA on an advanced emergency braking system (AEBS) and a lane-departure warning (LDW) system with data from the STATS 19 database. Their study suggested Benefit–Cost Ratio (BCR) values with regard to the cost and performance levels of these systems.

Similar to COWI [11], ASSESS [14] estimated the effectiveness of pre-crash safety systems across European countries with reflecting each nation's GDP per capita to consider economic wealth of the countries. This study shows the comparisons of effectiveness for pre-crash safety systems across European countries in 2020 and 2030, with the estimation of fatality rates based on the ProgTrans World Transport Report 2010/2011 data on vehicle mileage and Eurostat data on fatalities during 2000–2009.

Although most of the CBA research recognized the necessity of forecasting steps to predict future beneficiaries, to the best of our knowledge, a proper forecasting model, such as the Holt model, to predict the market diffusion trends of new systems/products, has not yet been employed.

Furthermore, the CBA is based on many assumptions. For example, Mendivil et al. [15] investigated the benefits of installation of speed cameras on the beltways of Barcelona; they also performed sensitivity analysis by considering both the minimum and maximum number of people who avoided injury. The sensitivity analysis results suggest that the benefits range from 5.6 to 23.1 million Euros. In this context, a CBA framework should include sensitivity analysis with a range of parameters for not only estimating the effectiveness of new systems/technologies but also forecasting the number of potential beneficiaries.

2.2. Rear-Seat Passenger Safety Systems

Various studies have been conducted to analyze the effectiveness of airbags to reduce the risk of injury to passengers. However, most of these studies have focused on the injury levels of the front-seat passengers from the frontal or side airbags [5–8,16–18]. Moreover, studies on safety systems for rear-seat passengers have been conducted to analyze the benefits of seatbelts during accidents. For example, Evans [19] estimated the effectiveness of a rear-restraint system in the form of a lap belt, using a double-pair comparison method based on data from the Fatality Analysis Reporting System (FARS). The average effectiveness of the restraint system for two outboard rear-seating positions was estimated, showing that 18 ± 9% of fatalities can be reduced. In addition, Shimamura et al. [20] estimated the effectiveness of seatbelts for rear-seat passengers by applying a logistic regression to national accident data in Japan. The result shows that the number of rear-seat passengers killed or seriously injured can be reduced by 45% if seatbelts are worn. Moreover, a notable finding of the study is that wearing seatbelts has a positive influence, in that it reduces the risk of injury for not only rear-seat passengers but also frontal occupants. Kuppa et al. [21] examined NASS-CDS and FARS data, and engaged in controlled collisions using an experimental dummy. They confirmed the positive influence of seatbelts on reducing injury levels for rear-seat passengers, and suggested longer distances between rear and front seats to reduce the probability of injury to rear-seat passengers. Further, Zhu et al. [22] applied a matched-set cohort design to estimate the association of rear-seat safety belt use in car accidents. The authors employed FARS data between 2000 and 2004, and found that the mortality rate from traffic crashes of rear-seat passengers can be reduced by 55–75% when seatbelts are used.

Although numerous studies have been conducted on seatbelts, only a few studies have dealt with the benefits of airbag-type safety systems for rear-seat passengers. McCartt and Kyrychenko [23] studied the efficacy of side airbags in reducing driver death through a regression model, and concluded that head-protecting airbags and torso-only side airbags reduced driver death risk by 37% and 26%, respectively. Bohman et al. [24] investigated the effectiveness of thoracic side airbags for rear-seat occupants, and showed that thoracic side airbags reduce rib deflection of occupants.

3. Model: The Cost–Benefit Analysis Framework

Given that the frontal center airbag is a new safety system, evaluation of its socioeconomic effectiveness is necessary. The evaluation process is shown in Figure 2.

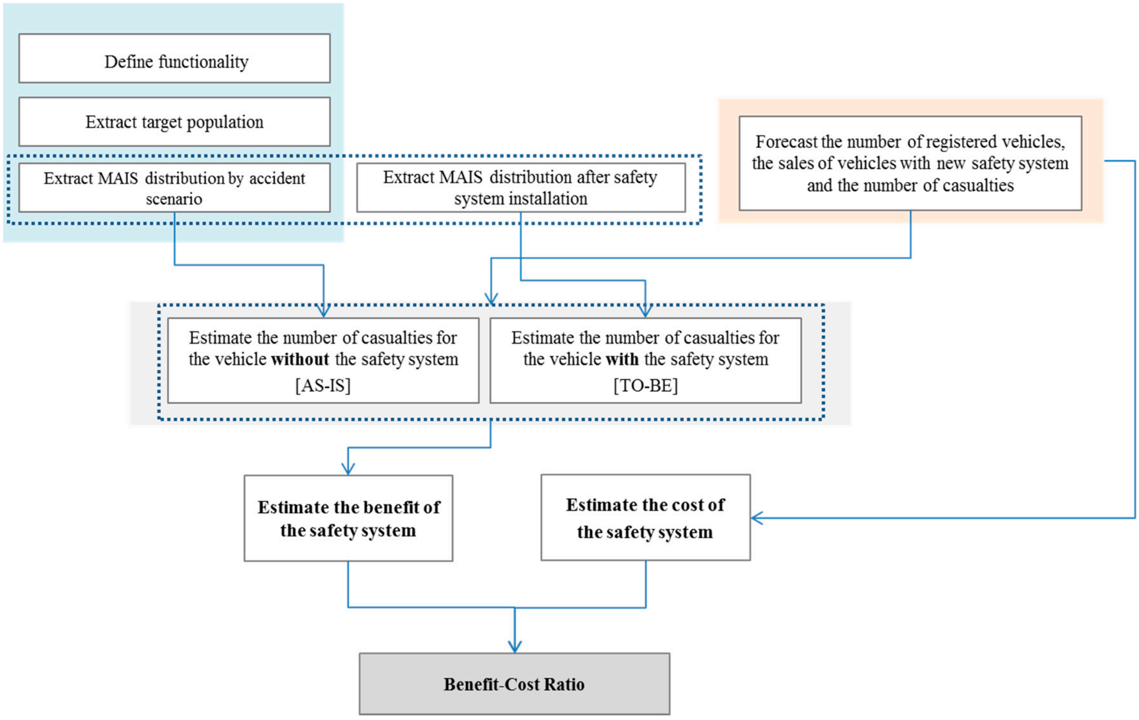

Figure 2. Economic evaluation process for a safety system.

Step 1. Target data and distribution of MAIS from NASS-CDS

Step 1-1. Define functionality

First, we define the functionality of the safety system to draw the distribution of injury risk. Based on the specifications of the safety system, the target population and accident scenarios are identified.

Step 1-2. Extract target population

Thereafter, we define the target population, which refers to occupants who could be influenced by the function of the safety system in a group of accidents. Of many accident datasets available, we use the NASS-CDS dataset, which contains rich information about accident situations. From NASS-CDS, data on accidents that meet certain conditions related to the vehicle and the passenger, including the vehicle type, accident mode, seat position, injured body region, and injury source, are extracted.

Step 1-3. MAIS distribution by accident scenario

The accident scenario is analyzed through the combination of certain conditions, including the injured body region, accident mode, Barrier Equivalent Speed (BES), and passenger's age. Since the effectiveness of the safety system may differ depending on the accident scenarios, investigating the distribution of injury risk according to these conditions is necessary. In this study, we present injury risk with the MAIS, similar to most previous works. The MAIS is an injury severity scale, which ranges from 1 (minor) to 6 (maximum). The data were obtained from the medical records of the accidents.

Step 2. Distribution of the MAIS from MADYMO

Since the CBA framework is proposed for a new safety system that has not yet been launched in the market, we compare the injury risks between the vehicles with safety systems installed and those without it. Thus, we simulate using the mathematical dynamical model program, MADYMO, which is useful to understand the situation of the vehicle accident [25]. The result of the simulation shows the probability of the MAIS level after the installation of the safety system.

Step 3. Forecast of the number of potential passengers

To estimate the socioeconomic benefits after launching the safety system, it is necessary to forecast the number of potential passengers who will benefit from the safety system installation. Therefore, in Step 3, we forecast the sales of vehicles having the safety system by using the Holt model.

Since a new type of safety system is developed by a specific automaker, the parameters of the Holt model, which are used to forecast future sales, can be defined based on the automaker's past sales record: the total number of registered passenger vehicles at time t; the sales of passenger vehicles with the new safety system at time t; and the number of casualties, who are occupants of passenger vehicles with the safety system, at time t. These values are derived by applying the Holt model, which reflects the trends in the passenger vehicle sales and casualties. In this study, we omit the Holt model function.

Furthermore, we set the maximum penetration rate of the safety system to derive a realistic number of potential passengers who will benefit from the safety system installation, by reflecting the diffusion of the safety system. We considered two cases according to the time required to achieve the maximum penetration rate of the new safety system. Case A indicates the market penetration rate in 10 years, and Case B indicates that in 20 years. In addition, we assumed that the penetration rate of the new safety system has a tendency to gradually increase over time, following an S-curve. In order to derive information on the passengers and vehicles that would benefit from the installation of the new safety system, the penetration rate of safety systems at time t is calculated by applying a logistic function, using the initial and maximum penetration rates of the new safety system, as shown below:

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

where α is the intercept; and β is the growth ratio of the penetration rate with time.

The maximum penetration rate can be obtained from the technical and market experts in firms that manufacture safety systems, or related automobile firms. Finally, to forecast the number of casualties for the occupants of passenger vehicles with the new safety system, we apply the concept of cumulative market penetration rate to total casualty. The cumulative market penetration rate at time t indicates the proportion of passenger vehicles with the safety system among the entire registered passenger vehicles at time t. This can reflect the percentage of all passenger vehicles that benefit from a new safety system.

The cumulative market penetration rate at time t is derived by the following function:

$$\text{CMP (t)} = {FS(1) + \cdots + FS(t)} \Big/ {H(t)}, \quad (2)$$

where $\text{FS}(t)(= \text{passenger vehicle sales } (t) \times \text{penetration rate } (t))$ indicates the sales of passenger vehicles with the safety system at time *t*; *t* represents the elapsed years after releasing the safety system ($t = 1, \ldots, 20$); and H(t) denotes the total number of registered passenger vehicles at time *t*.

Step 4. Estimation of the benefit of the safety system

In this step, we calculate the benefit of the safety system based on the expected injury reduction by the installation of the safety system. We apply the MAIS distribution from Step 1 to the number of future casualties from Step 3, to predict the number of injured rear-seat passengers when the safety system is not installed (AS-IS). In a similar context, we apply the MAIS distribution from Step 2 to the forecasted number of casualties from accidents involving vehicles with the safety system (TO-BE).

The benefit for passengers (P) from the frontal center curtain airbag is measured by the reduced costs of traffic accidents, due to a decrease in the severity of the injuries incurred in crash accidents ($Benefit\ 1_p$), and to the discounted car insurance from installing the safety system ($Benefit\ 2_p$). $Benefit\ 1_p$ is derived from comparing the number of casualties in AS-IS with those of TO-BE. The benefit for passengers at time t and the $Total\ Benefit_p$ are given as follows:

$$\text{Benefit } 1_p(t) = \sum_{m=1}^{3}\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{2}\sum_{l=1}^{6}[N(t) \times PT_{mijkl} \times CT_l(t)]$$

$$- \sum_{m=1}^{3}\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{2}\sum_{l=0}^{6}[N(t) \times PT'_{mijkl} \times CT_l(t)] \quad (3)$$

$$\text{Benefit } 2_p(t) = \sum_{a=1}^{t} FS(a) \times DP \quad (4)$$

$$Total\ Benefit_p = \sum_{t=1}^{20}[\text{Benefit } 1_p(t) + \text{Benefit } 2_p(t)] \times (1+r)^{-t} \quad (5)$$

where $N(t)$ is the number of forecast casualties who are occupants of a passenger vehicle with the safety system at time t; PT_{mijkl} is the probability of the injury severity level for the accident scenario, as defined by the accident mode (m), BES (i), injured body region (j), and age of the casualty (k); PT'_{mijkl} is the probability of the injury severity level for the accident scenario, after the passenger uses the safety system; $CT_l(t)$ is the total cost associated with the MAIS class l, as a result of a traffic accident; DP is the discounted car insurance due to the presence of the safety system; and and r is the discount rate, considering the GDP growth rate.

Step 5. Estimation of the cost of the safety system

We consider the purchase costs of the safety system as the cost in the CBA process. The values for the total cost of traffic accidents ($Total\ Costs_p$) are forecasted using the exponentially weighted moving average (EWMA), considering the GDP growth rate. The cost incurred by the passengers (P) at time t and the total costs are considered as follows:

$$Cost_p(t) = FS(t) \times PA \quad (6)$$

$$Total\ Costs_p = \sum_{t=1}^{20} Cost_p(t) \times (1+r)^{-t} \quad (7)$$

where PA is the price of the safety system.

Step 6. Cost-benefit ratio and sensitivity analysis

Based on the results of the previous step, we calculate the benefit–cost ratio (BCR). The BCR is sensitive to certain variables; consequently, sensitivity analysis must be conducted with regard to the important variables [26,27].

4. Results: A Case Study of the Frontal Center Curtain Airbag

In this section, the proposed CBA procedure is applied to the case of the frontal center curtain airbag, which has not been launched in the market yet. In addition, we calculate the BCR of this new safety system considering the US market.

Step 1. Target data and distribution of the MAIS from NASS-CDS

Step 1-1. Define functionality

First, we define the functionality of the frontal center curtain airbag, which is intended to protect rear-seat passengers from direct collision injury sources. This airbag is installed between the front and rear seats to reduce the impact on rear-seat passengers. The detailed description is shown in Table 2.

The frontal center curtain airbag would be installed in passenger vehicles to protect rear-seat passengers. This safety system is expected to prevent or reduce the head and chest injuries from the collision with interior sources in vehicles, as shown in Table 2. The frontal center airbag would be effectively deployed for front crash, side crash and roll-over protection. Furthermore, the effectiveness of this safety system is expected to differ based on the age of passengers due to the size of the body.

Table 2. Functionality of the frontal center curtain airbag.

Condition	Description	
Vehicle type	Passenger vehicle (Sedan, Hatchback, Station wagon, Auto base panel, Large limousine, Compact utility, or Large utility)	
Seat position	Rear seat (Passengers in second row rear seat)	
Injured body region	Head (face or head) Chest (chest, abdomen, back, arm, forearm, shoulder, wrist/hand, or upper limbs)	
Injury source	Seat, A-pillar, B-pillar, C-pillar, seatbelt, CRS, roof, windshield, side window glass, floor, center console, C/PAD, door trim, interior trim, outside part, exterior, and cargo in vehicle	
Accident mode	Front crash, side crash, and roll over	
Age	Adult/Child	Adult (Over 14 years old), Child (Under 14 years old)
Deployment Condition	Front crash	When one of the airbags located at the driver and front passenger seats is deployed
	Side crash	When one of the airbags located at the driver and front passenger seats is deployed
	Roll over	More than one quarter roll

Step 1-2. Extract target population

Based on the functionality of the frontal center curtain airbag, as shown in Table 2, we select the proper target population dataset from the NASS-CDS data. According to this functionality, the effectiveness of this safety system differs depending on the accident scenario. Therefore, we propose a total of 54 (3 × 3 × 3 × 2) scenarios based on the conditions at the time of the accident; there are three accident modes (front crash, side crash, and roll over), three injured body regions (head, chest, and both head and chest), three levels of BES (low, intermediate, and high), and two age groups (child and adult). Among all possible accident situations, these 54 accident scenarios are the cases in which the frontal center curtain airbag can have an effect on protecting the rear-seat passenger.

The BES presents the change in velocity due to the impact from the crash. The WinSmash software calculates this speed, considering the size, weight, and body type of the passenger vehicle. Thus, to measure the effectiveness of airbag-type safety systems, it is more appropriate to use BES, rather than travel speed, for the speed index. In this study, we define the speed interval based on the BES as follows: low (less than 17 kph); intermediate (between 17 and 33 kph); and high (over 33 kph). The speed intervals are set by the developing company of the safety system, according to its internal crash experimental criterion. The child condition refers to an age of less than 14, while the adult condition refers to an age equal to or greater than 14.

We extracted accident cases from NASS-CDS according to the above-mentioned 54 accident scenarios defined by the combination of various conditions. From 2003 to 2011, the number of passengers involved in our accident scenarios is 111,373, out of 2,697,054 total passengers. The number of injured passengers for the three accident modes is presented in Figure 3. These numbers are obtained by applying the Ratio Inflation Factor in order to adjust for the difference between the sample and actual accident data.

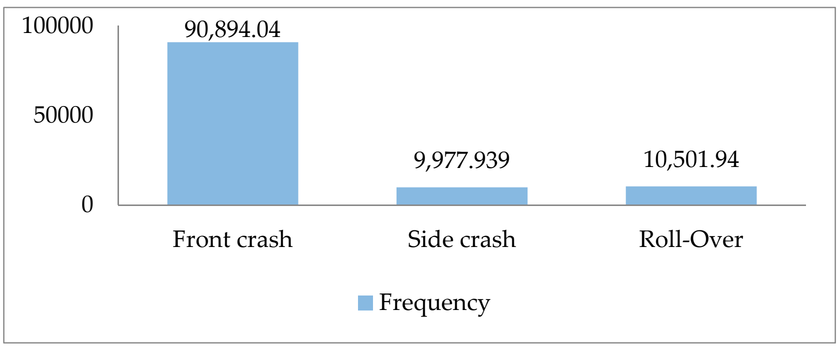

Figure 3. The number of injured passengers for each accident mode.

Step 1-3. MAIS distribution by accident scenario

With the extracted data in Step 1-2, we could derive the MAIS distribution according to the accident scenarios. The probability for an accident scenario is as follows:

$$PT_{mijkl} = \frac{Number\ of\ casualties\ between\ 2003\ and\ 2011_{mijkl}}{\sum_{m=1}^{3}\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{2}\sum_{l=1}^{6}[Number\ of\ casualties\ between\ 2003\ and\ 2011_{mijkl}]} \quad (8)$$

where m is the accident mode, $m \in$ {1: front crash; 2: side crash; 3: roll-over}; i is the BES, $i \in$ {1: low; 2: intermediate; 3: high}; j is the injured body region, $j \in$ {1: head; 2: chest; 3: head and chest}; and k is the age of the casualty, $k \in$ {1: adult; 2: child}; and l is the MAIS level.

An example of the MAIS distribution is shown in Table 3. For instance, among all casualties reported in NASS-CDS, the ratio of a head-injured adult involved in a frontal-crash accident at a low speed is 0.0008. This probability is derived from the ratio of the number of injured passengers with head injuries at frontal crash accident in low BES (2157) to the total number of passengers (2,697,054). Furthermore, the head-injured adult occupant who experienced the front crash with low BES would have an MAIS score of 1 with a probability of 0.97848. All distributions for each accident scenario are shown in Appendix A. This probability distribution is employed to determine the effectiveness of the frontal center curtain airbag in Step 4 in order to estimate the benefits of the safety system.

Table 3. Probability distribution of injury risk without the frontal center curtain airbag.

	BES	Age	Probability	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
Front crash for head injuries	Low	Adult	0.0008	0.97848	0.005695	0.015825	0	0	0
		Child	0.000721	0.707148	0.292852	0	0	0	0
	Intermediate	Adult	0.004081	0.868695	0.096161	0.006777	0.024634	0.003733	0
		Child	0.001567	0.85896	0.008454	0.015126	0.11746	0	0
	High	Adult	0.000849	0.643303	0.128293	0.017863	0.206867	0.003675	0
		Child	0.000706	0.965394	0.015562	0.017659	0	0.001385	0

Notes: BES = Barrier Equivalent Speed, MAIS = Maximum Abbreviated Injury Scale.

Step 2. Distribution of the MAIS from MADYMO

As mentioned previously, MADYMO is a simulation program that is useful for understanding the conditions of the vehicle and the passenger [25]. This program simulates multi-body dynamics through a mathematical dynamical model. From MADYMO, we obtain the Head Injury Criterion (HIC)—a predictor of the risk of head injury, developed from cadaver studies—and Chest G (or chest acceleration)—an index for chest injury risk, measured by g at the center of gravity of the thoracic region. Both HIC and Chest G are most widely used for measuring a safety system's effectiveness tests.

As the HIC and Chest G values can be different, depending on the weight or height of the passengers, we assess this difference by using both adult-size and child-size unbelted dummies. These dummies were located in outboard seats, according to Federal Motor Vehicle Safety Standards (FMVSS) 208 specifications, and the simulation experiments were carried out at 16, 32, and 40 kph, for different BES levels—low, intermediate, and high, respectively. In addition, the different crash directions, which present the accident modes, are simulated. Thus, we can obtain HIC and Chest G values for each accident scenario using the result of the MADYMO simulation. Next, we convert the HIC and Chest G values to MAIS levels for head and chest, respectively. We employed the conversion formulae from the expanded Prasad/Mertz curves for head MAIS, and used the data for 55 cadaver sled tests, provided by the National Highway Traffic Safety Administration (NHTSA), for chest MAIS.

By comparing the casualties between the MAIS distribution from NASS-CDS and those from MADYMO, we are able to identify the effectiveness of the safety system in terms of injury reduction.

Table 4 shows these results. These probabilities will be used to determine the effectiveness of the frontal center curtain airbag in the future. For example, after the installation of the frontal center curtain airbag, the probability of a Child will get head injury at the AIS 1 level from a front crash with intermediate speed is 0.02. All distributions for each accident scenario with the frontal center curtain airbag are shown in Appendix B.

Table 4. Probabilities of injury risk with the frontal center curtain airbag.

	BES	Age	AIS 0	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6
Front crash for Head injuries	Low	Adult	1						
		Child	1						
	Intermediate	Adult	0.93	0.05	0.01	0.01			
		Child	0.97	0.02	0.01				
	High	Adult	0.89	0.06	0.03	0.02			
		Child	0.46	0.34	0.13	0.06	0.01		

Notes: BES = Barrier Equivalent Speed, AIS = Abbreviated Injury Scale.

Step 3. Forecasting

We assumed the initial and maximum penetration rates (5.0% and 20.7%, respectively) of the frontal center curtain airbag. The maximum penetration rate was obtained from the technical and market experts at H* Motors. Moreover, the front safety system can be diffused differently according to the consumer's preference; we set two different cases according to the market's saturation periods: 10 years (Case A) and 20 years (Case B).

In the Holt model, the smoothing parameters for updating the local mean level (ω_1) and local trend (ω_2) are set up to minimize Mean Absolute Percentage Error (MAPE), and these values are displayed in Appendix C. All MAPE values are less than 10%, which indicate that the forecasting is reliable.

The total number of registered passenger vehicles, at time t ($H(t)$); the sales of passenger vehicles with frontal center curtain airbag, at time t ($FS(t)$); and the number of casualties who are occupants of passenger vehicles with frontal center curtain airbag, at time t ($N(t)$), in the US, are shown in Table 5.

Table 5. $H(t)$, $FS(t)$, and $N(t)$ in the US.

t	$H(t)$	$FS(t)$		$N(t)$	
		Case A (10 years)	Case B (20 years)	Case A (10 years)	Case B (20 years)
1	130,434,284	358,293	358,293	3358	3358
2	129,434,829	424,536	388,640	7350	7013
3	128,435,374	502,138	421,404	12,084	10,987
4	127,435,919	592,702	456,749	17,688	15,309
5	126,436,463	697,924	494,850	24,304	20,005
6	125,437,008	819,549	535,884	32,094	25,105
7	124,437,553	959,301	580,035	41,236	30,643
8	123,438,098	1,118,795	627,494	51,924	36,651
9	122,438,643	1,299,412	678,453	64,368	43,166
10	121,439,187	1,502,169	733,107	78,791	50,227
11	120,439,732	1,504,262	791,651	93,290	57,873
12	119,440,277	1,506,355	854,279	107,865	66,149
13	118,440,822	1,508,448	921,182	122,520	75,099
14	117,441,366	1,510,541	992,543	137,255	84,770
15	116,441,911	1,512,634	1,068,538	152,072	95,213
16	115,442,456	1,514,727	1,149,329	166,974	106,479
17	114,443,001	1,516,820	1,235,064	181,960	118,621
18	113,443,546	1,518,913	1,325,872	197,035	131,695
19	112,444,090	1,521,006	1,421,857	212,199	145,759
20	111,444,635	1,523,099	1,523,099	227,454	160,871

Notes: $H(t)$ = number of registered passenger vehicles, at time t; $FS(t)$ = sales of luxury passenger vehicles with frontal center curtain airbag, at time t; and $N(t)$ = number of casualties who are occupants of luxury passenger vehicles with frontal center curtain airbag, at time t.

Step 4. Estimation of the benefit of the safety system

To obtain the benefit of injury reduction by installing the frontal center curtain airbag, we apply each probability of the injury severity, from Steps 1 and 2, to the $N(t)$ from Step 3. By comparing the number of casualties in both cases, we consider their difference as the effectiveness of the safety system. Table 6 presents the predicted number of injured passengers, with and without the safety system, in the US market. By using the frontal center curtain airbag, the number of casualties with MAIS level 3 or above reduced by 87.4%.

Table 6. Number of casualties with and without the safety system.

MAIS	Case A (10 years)		Case B (20 years)	
	Casualties without the Safety System	Casualties with the Safety System	Casualties without the Safety System	Casualties with the Safety System
0 and 1	69,171	63,133	46,011	41,994
2	6112	16,076	4066	10,693
3	2067	467	1,375	310
4	2003	98	1,332	65
5	333	0	222	0
6	87	0	58	0
Total	79,774	79,774	53,063	53,063

Notes: MAIS = Maximum Abbreviated Injury Scale.

To transform injury reduction into a monetary benefit, we use the cost according to MAIS level l (CT_l), from an NHTSA report in 2000. We estimate CT_l for 2015 using EWMA with the GDP growth rate in the US from 2000 to 2012. The weight value is set to 0.7 and, consequently, the discount rate, considering the GDP growth rate (r), is 2.01%. The annual GDP growth data were obtained from the World Bank. Table 7 presents the CT_l values of 2000 along with the estimated values for 2015.

Table 7. The costs of traffic accidents in the US.

Injury Severity (l) \ Classification	CT_l (2000)	CT_l (2015)
MAIS 0	$1962	$2644
MAIS 1	$10,562	$14,236
MAIS 2	$66,820	$90,063
MAIS 3	$186,097	$250,831
MAIS 4	$348,133	$469,231
MAIS 5	$1,096,161	$1,477,459
MAIS 6	$977,208	$1,317,129

Notes: CT_l = cost according to MAIS level l.

This study sets the discounted car insurance benefit (DP) value as $22. Moreover, the information related to the DP (per vehicle in one year) is obtained from the websites of car insurance companies.

Step 5. Estimation of the cost of the safety system

The cost of the frontal center curtain airbag (PA) is $600; this value was obtained from a car manufacturer, and is derived by considering the cost of R&D, commercialization, and production of the airbag.

Step 6. Benefit–cost ratio and sensitivity analysis

Based on the estimated benefit and cost of frontal center curtain airbag, we calculate the BCR. These results are shown in Table 8.

Table 8. Benefit–cost ratio for the US by scenario.

	Case A (10 years)	Case B (20 years)
Benefit	$5,973,979,316	$3,974,155,672
Cost	$11,027,777,826	$7,727,474,206
BCR	0.542	0.514

Notes: BCR = benefit–cost ratio.

The BCR is sensitive to certain variables; consequently, a sensitivity analysis must be conducted with regard to the important variables [15]. We examine the BCR values for the US, as well as how they are affected when the initial market penetration rate, maximum market penetration rate, and price of the safety system are changed. The price of the frontal center curtain airbag is high, and most customers would be sensitive to price. Accordingly, we perform a sensitivity analysis of the price of the safety system. The results are shown in Figure 4 and Appendix D. When the product penetrates the target market rapidly—high initial and maximum market penetration rates—the BCR of the frontal center curtain airbag increases. Conversely, the BCR decreases when the price of the frontal center curtain airbag increases. Thus, firms need to consider higher penetration rates and lower price strategies.

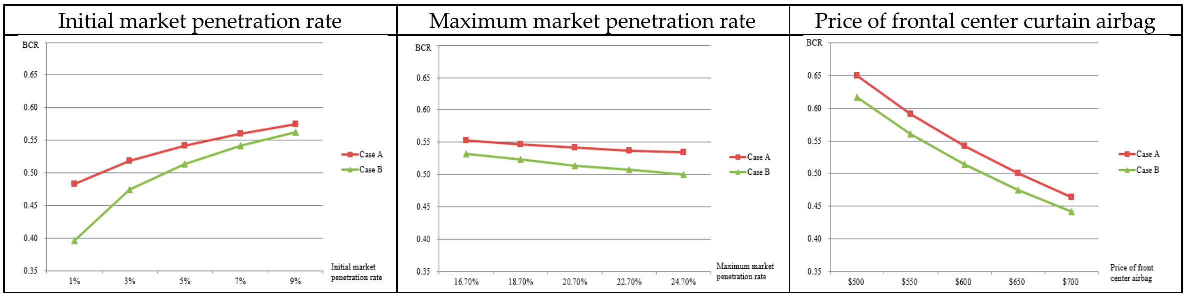

Figure 4. Sensitivity analysis.

5. Discussion

This study developed a CBA framework, including a forecasting model, to a new type of safety system that has not been applied in a vehicle so far. The established literature has attempted to estimate the potential benefits and costs of safety system installation. However, the inclusion of a forecasting method in a CBA framework has not been suggested so far. Furthermore, we performed sensitivity analyses in order to adjust to a wide variety of market situations. Our results, especially those focusing on the socioeconomic effects, can help in the commercialization decision and eventually encourage sustainable automotive innovation.

We applied the proposed CBA framework to frontal center curtain airbag, a new type of airbag developed to prevent collisions between front-and rear-seat passengers by separating the two areas with an airbag. The BCR turned out to be lower than 1, but exceeded the expectation of the developer in terms of societal contribution. This is because unlike commercial purposed product/service which is focused to be economically sustainable, a safety system is critical in risk management to reach sustainable mobility society. In this context, to maximize the effectiveness of the frontal center curtain airbag, we proposed a high rate of initial market penetration and a relatively low price for the frontal center curtain airbag.

It would be interesting to apply the suggested procedure to estimate the effect of the safety system in different markets by considering each market's characteristics, when detailed information concerning traffic accidents by country is obtained. Future research must consider this possibility.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Probability Distributions of Injury Risk without the Frontal Center Curtain Airbag

Table A1. Frontal crash case.

Front	BES	Age	Probability	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
Head	Low	Adult	0.0008	0.978480	0.005695	0.015825	0	0	0
		Child	0.000721	0.707148	0.292852	0	0	0	0
	Intermediate	Adult	0.004081	0.868695	0.096161	0.006777	0.024634	0.003733	0
		Child	0.001567	0.85896	0.008454	0.015126	0.11746	0	0
	High	Adult	0.000849	0.643303	0.128293	0.017863	0.206867	0.003675	0
		Child	0.000706	0.965394	0.015562	0.017659	0	0.001385	0
Chest	Low	Adult	0.002856	0.922822	0.051723	0.025455	0	0	0
		Child	0.002117	0.879672	0.105034	0	0.015294	0	0
	Intermediate	Adult	0.011559	0.869521	0.11589	0.013011	0.001578	0	0
		Child	0.004346	0.932944	0.035068	0.031988	0	0	0
	High	Adult	0.001464	0.648819	0.061984	0.076112	0.173142	0.021627	0.018316
		Child	0.001037	0.751564	0.124795	0.123641	0	0	0
Head & Chest	Low	Adult	0.0000553	1	0	0	0	0	0
		Child	0.000291	1	0	0	0	0	0
	Intermediate	Adult	0.000203	0	0	0	0	0	0
		Child	0.000759	0.914224	0.023696	0.062080	0	0	0
	High	Adult	0.000214	1	0	0	0	0	0
		Child	0.0000767	0	0	0	0	0	0

Table A2. Side crash case.

Side	BES	Age	Probability	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
Head	Low	Adult	0.0000993	0	0	0	0	0	0
		Child	0.00000765	0	0	0	0	0	0
	Intermediate	Adult	0.00032	0	0	0	0	0	0
		Child	0.000584	0	0	0	0	0	0
	High	Adult	0.000144	0.585361	0.124921	0	0.139566	0.129301	0.02085
		Child	0.000115	0.881770	0.086447	0	0.031783	0	0
Chest	Low	Adult	0.0000121	0.252440	0.252440	0.495120	0	0	0
		Child	0.000199	1	0	0	0	0	0
	Intermediate	Adult	0.000446	0.613055	0.082824	0.013431	0.29069	0	0
		Child	0.000469	0.651176	0.145095	0.203728	0	0	0
	High	Adult	0.000182	0.214195	0.010478	0.468165	0.128001	0.179161	0
		Child	0.00033	0.868084	0.032621	0.099294	0	0	0
Head & Chest	Low	Adult	0.000575	1	0	0	0	0	0
		Child	0	0	0	0	0	0	0
	Intermediate	Adult	0.0000524	1	0	0	0	0	0
		Child	0.0000119	1	0	0	0	0	0
	High	Adult	0.000095	0.980113	0	0.019887	0	0	0
		Child	0.0000573	0.790995	0	0.047491	0.161515	0	0

Table A3. Roll-over case.

Roll-over	BES	Age	Probability	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
Head	Low	Adult	0.000152	0.799551	0	0	0.200449	0	0
		Child	0.0000118	1	0	0	0	0	0
	Intermediate	Adult	0.000018	0	1	0	0	0	0
		Child	0.001287	0.995884	0	0	0	0	0.004116
	High	Adult	0.000306	0.956308	0	0.011917	0	0	0.031775
		Child	0.00000805	0	0	1	0	0	0
Chest	Low	Adult	0.0000484	0	0	1	0	0	0
		Child	0	0	0	0	0	0	0
	Intermediate	Adult	0.001321	0.894255	0.088180	0.017566	0	0	0
		Child	0.000226	1	0	0	0	0	0
	High	Adult	0.000268	0.846942	0.053165	0.099893	0	0	0
		Child	0	0	0	0	0	0	0
Head & Chest	Low	Adult	0	0	0	0	0	0	0
		Child	0	0	0	0	0	0	0
	Intermediate	Adult	0.000244	1	0	0	0	0	0
		Child	0.00000362	1	0	0	0	0	0
	High	Adult	0	0.976209	0.023791	0	0	0	0
		Child	0	1	0	0	0	0	0

Notes: BES = Barrier Equivalent Speed, MAIS = Maximum Abbreviated Injury Scale.

Appendix B

Table A4. Probability of Injury Risk with the Frontal Center Curtain Airbag.

	BES	Age	MAIS 0	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
Front crash for head injury	Low	Adult	1						
		Child	1						
	Intermediate	Adult	0.93	0.05	0.01	0.01			
		Child	0.97	0.02	0.01				
	High	Adult	0.89	0.06	0.03	0.02			
		Child	0.46	0.34	0.13	0.06	0.01		
Front crash for chest injury	Low	Adult	1						
		Child	1						
	Intermediate	Adult	0.47		0.53				
		Child	1						
	High	Adult	0.39		0.61				
		Child	1						
Front crash for head and chest injury	Low	Adult	0.7		0.3				
		Child	1						
	Intermediate	Adult	0.47		0.53				
		Child	1						
	High	Adult	1						
		Child	0.44		0.32	0.18	0.06		
	BES	Age	MAIS 0	MAIS1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
Side crash for head injury	Low	Adult	1						
		Child	1						
	Intermediate	Adult	0.93	0.05	0.01	0.01			
		Child	0.97	0.02	0.01				
	High	Adult	0.89	0.06	0.03	0.02			
		Child	0.46	0.34	0.13	0.06	0.01		
Side crash for chest injury	Low	Adult	0.7		0.3				
		Child	1						
	Intermediate	Adult	1						
		Child	1						
	High	Adult	0.39		0.32	0.21	0.08		
		Child	0.44		0.32	0.18	0.06		
Side crash for head and chest injury	Low	Adult	1						
		Child	1						
	Intermediate	Adult	0.47		0.53				

		Child	1						
	High	Adult	1						
		Child	0.44		0.32	0.18	0.06		
	BES	Age	MAIS 0	MAIS1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
Roll over for head injury	Low	Adult	1						
		Child	1						
	Intermediate	Adult	0.93	0.05	0.01	0.01			
		Child	0.97	0.02	0.01				
	High	Adult	0.89	0.06	0.03	0.02			
		Child	0.46	0.34	0.13	0.06	0.01		
Roll over for Chest injury	Low	Adult	0.7		0.3				
		Child	1						
	Intermediate	Adult	0.47		0.53				
		Child	1						
	High	Adult	1						
		Child	1						
Roll over for head and chest injury	Low	Adult	1						
		Child	1						
	Intermediate	Adult	1						
		Child	1						
	High	Adult	1						
		Child	1						

Appendix C

Table A5. The Smoothing Parameters and MAPE.

	The Registered Vehicle	Vehicle Sales	Casualty
w1	0.91	0.95	0.95
w2	0.95	0.05	0.68
MAPE	0.71%	6.67%	2.67%

Appendix D

Table A6. Sensitivity Analysis.

Variable	Change	Scenario 1 (t = 10)	Scenario 2 (t = 20)
Initial market penetration rate	1%	0.483	0.396
	3%	0.519	0.474
	5%	0.542	0.514
	7%	0.560	0.542
	9%	0.575	0.563
Maximum market penetration rate	16.70%	0.553	0.532
	18.70%	0.547	0.523
	20.70%	0.542	0.514
	22.70%	0.537	0.507
	24.70%	0.534	0.500
Price of front center airbag	$500	0.650	0.617
	$550	0.591	0.561
	$600	0.542	0.514
	$650	0.500	0.475

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